2023
TEST REPORT

TEXAS A&M ENGINEERING
TEEX®
EXTENSION SERVICE

TEEX-Tested Report for

SQUISHY ROBOTICS

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January 15, 2024

TEEX-Tested® Report: Squishy Robotics Stationary Robot and 4-Gas^{PLUS} Sensor Payload Prototype

Submitted to Squishy Robotics, Inc., on behalf of the Texas A&M Engineering Extension Service (TEEX) Testing and Innovation Center (TT&IC):

Date: 15 Jan 2024

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Title: Director, TT&IC

Accepted on behalf of Squishy Robotics, Inc.

Date: February 9, 2024

By:

Printed Name: Deniz Dogruer

Title: Chief Operating Officer

This work was performed under the following financial assistance award 70NANB22H209 from
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Acknowledgements

This TEEX-Tested Report was completed through partnerships with Texas A&M University's Internet2 Technology Evaluation Center (ITEC) and the George H.W. Bush Combat Development Complex (BCDC). ITEC's unparalleled expertise in communications technologies was invaluable to the test design, collection, and analysis of the RF performance data required for this utility assessment. The BCDC team and world class facilities were essential to the operational assessment of the Squishy Robotics technologies.

Summary of TEEX-Tested Results

Feature Tested	Results
System Operation	The stationary robot with a payload can be set up in less than 15 minutes. One person can operate the system.
Reliability	All components operated without failures during the four-month test period.
Sensor data range	Data communications for the 4-Gas^{PLUS} via direct and mesh network provided reliable data at extended distances (evaluated beyond 500 yds line of sight)
Camera feed range	Real time video feed rate fell off at times with intermittent reliability from extended distances (evaluated beyond 300 yds). Video quality was highly impacted by obstructions
Communications interference	Normal disaster scene communications traffic did not interfere with data communications. Short term interference was only noted when within a few feet of the receiver during a keyed mic on a 400Mhz radio.
User Interface (UI)	**NOTE: Squishy Robotics UI was not assessed as part of this TEEX-Tested assessment.** The user interface used for this assessment was an *engineering* version of the Squishy Robots software and was not the version that will be provided upon purchase.
4-Gas detection sensor array	**NOTE: The 4-gas sensor array was not assessed as part of this TEEX-Tested assessment.** The sensor array included with the purchase of 4- Gas^{PLUS} Sensor Payload is a 4-gas sensor that measures O2, LEL, H2S, and CO. The efficacy and accuracy of the 4-gas detector sensor was not evaluated.
Deployment	The stationary robot with the 4-Gas^{PLUS} Sensor payload were deployed by hand placement, ground level toss method, and Uncrewed Aerial System (UAS) drops from fifty feet. Communication devices remained functional with no signs of physical or electrical damage. The system performed as expected.
Battery	The 4-Gas^{PLUS} payload uses rechargeable batteries that operate an average of 60 minutes per charge. The battery charge dissipates at a higher rate with heavy video usage and can be saved by turning the video off.
Recoverability	The stationary robots and payloads can be reused in most circumstances, depending on the reactivity of the contaminant with carbon fiber robotic exoskeleton and payload's protective polyurethane housing

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Texas A&M Engineering Extension Service (TEEX) Testing & Innovation Center (TT&IC) conducts performance assessments in operational environments by experienced professionals and technicians using representative facilities and environments the product is expected to perform in. Operators perform functions that are expected in operational service and assess the products and solutions using the manufacturer's guidelines and instructions to assess performance. TEEX tests follow a process including standards reviews, metrics development, expert panel reviews, test plan and scenario development, and quantitative and qualitative measurements and surveys. This report is a summation of the functionality, reliability, and performance results.

Squishy Robotics' data communications capabilities have been TEEX-Tested$^{(R)}$ based on the specific methodology presented in this report. This report does not constitute an endorsement by TEEX. The TT&IC developed this report for Squishy Robotics' Stationary Robot and 4-Gas$^{\text{PLUS}}$ Sensor Payload. TEEX hereby disclaims and any recipient of this report waives any warranties, whether expressed or implied, including without limitation any implied warranties of merchantability, fitness for a particular purpose, or non- infringement. Any recipient of this report accepts the report "as is" and acknowledges that TEEX has no responsibility or liability to the recipient. TEEX does not in any way endorse the product.

TEEX-Tested® Report for Squishy Robotics LLC
Conducted by:
TEEX Testing and Evaluation Center (TT&IC)
Texas A&M Engineering Extension Service (TEEX)

Distribution: Open

Executive Summary

The Texas A&M Engineering Extension Service's Testing and Innovation Center (TT&IC) conducted a TEEX-Tested® developmental assessment of Squishy Robotics' Stationary Robot with a prototype 4-Gas^{PLUS} Sensor payload, (a.k.a., Squishy Robotics System). This final report provides emergency response and acquisition decision-makers with information regarding the product's operational performance specific to durability and the communications functions. TEEX-Tested assessments follow a similar process to Military Utility Assessments (MUA) to assess the technology's performance in operational settings. Professionals representing the targeted user base participated in the assessment using representative scenarios, appropriate protective distances (a.k.a. stand-off distances), and procedures.

The Squishy Robotics System is a two-component system: the 4-Gas^{PLUS} Sensor payload and the Stationary Robot. The 4-Gas^{PLUS} Sensor payload is a battery-operated sensor array, radio/antenna and multiple small cameras encased in a flexible shell which is suspended in the Stationary Robot. The Stationary Robot is a flexible skeleton frame which provides impact protection to the sensor shell when deployed by an uncrewed aerial system (UAS), thrown by hand, or other means. Data from the sensor and video from cameras are transmitted via radio from the unit to a Chromebook with the Squishy Robotics software installed. This proprietary software provides a graphic representation of the data and communications status. A mesh network consisting of other Squishy robot sensors can also be used to move the data and video around large areas.

This TEEX-Tested assessment was limited to an evaluation of the capability and reliability of the communications function (i.e., radio communications and video streaming) in operational environments. Scenarios were designed to focus on hazardous material missions requiring protective distances between the exclusion and cold zones and included a petroleum/chemical process unit, petroleum/chemical tank farm, a freight train derailment involving a DOT111 tank car, and a subterranean tunnel system. The Squishy Robotics System was deployed by hand or by UAS based on best practices determined by current emergency response personnel.

Proper placement of the Squishy Robotics System using a three-sensor configuration consistent with operational practices was made by emergency response personnel with expertise in current hazardous materials response strategies and tactics. During the evaluation, the laptop receiving the data was repositioned in varying distances to assess the quality and timeliness of data received. Squishy Robotics System is envisioned to be deployed with include 2-3 individual systems, a receiver, and a laptop with the proprietary software installed. The Squishy Robotics System can be contained in a single 27” X 27” X 16” hardened travel case. This case will hold two payload balls attached to two robots (collapsed for storage), a Chromebook laptop, and USB antenna. They can be deployed by hand or dropped from a Group 2 UAS or select Group 1 UAS (i.e., drones with a maximum takeoff weight of 21–55-pounds or select drones with maximum weights of 0-20 pounds).

Radio frequency (RF) Spectrum analysis and data during operations consistently demonstrated that the communications system was reliable and provided operationally safe distances from the scene either directly or through the mesh network when one or multiple sensor robots were deployed in a representative tactical manner. No gas measurements were conducted during our assessment as the specific sensor is being certified separately, as is the user interface. Data communications flowed through and around structures such as tank cars, buildings and complex steel piping and value structures, and in a DoD (Department of Defense) representative tunnel system, representing hazardous gas leaks. Battery life was sufficient for a half-day worth of testing, without live streaming video.

As a result of reviewer feedback and the overall testing, we conclude that the data communications system used by Squishy Robotics 4-Gas^{PLUS} Detection System provides a reliable and realistic pathway for use in operational HAZMAT conditions. SME feedback further concludes that the Squishy Robotics 4-Gas^{PLUS} Detection System would increase mission capabilities and responder and public safety during a hazardous materials emergency by providing data and sentry services at a safe standoff distance allowing informed decisions and planning for response and resolution. The system's packaging, ease of setup, and intuitive operation enables the system to be highly mobile. The attached TEEX-Tested report provides detailed testing and system information.

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Introduction

The following TEEX-Tested report represents findings of operational test results to meet the needs of volunteers and professionals in the fire service. The Texas A&M Engineering Extension Service Testing & Innovation Center (TT&IC) leverages TEEX facilities; national and organization standards; TEEX instructors; TEEX students; and municipal, volunteer, firefighters. The TEEX-Tested mark is TEEX's premier offering for designing and executing testing for disruptive and innovative technologies and is a sign that a technology performs as intended under acceptable, repeatable, and real-world conditions.

This report provides an impartial third-party product evaluation of the Squishy Robotics' Stationary Robot with 4-Gas^{PLUS} Sensor Payload. This assessment was performed according to our seven step TEEX-Tested methodology from July 10 – 13, 2023 at the Brayton Fire Field, Disaster City®, and the George H.W. Bush Combat Development Complex. This report details results from the assessment of the communications function of the Squishy Robotics Stationary Robot with 4-Gas^{PLUS} Sensor Payload (a.k.a. Squishy Robotics System) under operational conditions performed and observed by prospective end-users and scientists.

The Squishy Robotics System consists of a **stationary robot** capable of holding a light payload. For this TEEX-Tested assessment, a **Squishy Robotics 4-Gas^{PLUS} Sensor Payload prototype** was used. Although not assessed during this assessment, the 4-gas sensor array is intended to be used for detecting the presence of and monitoring airborne substances in hazardous materials emergencies. The integrated sensor detects Lower Explosive Limit (LEL) of present combustible gases, Oxygen (O_2), Carbon Monoxide (CO), and Hydrogen Sulfide (H_2S). In addition to the 4-gas array, the 4-Gas^{PLUS} Sensor Payload includes six cameras capable of providing live, streaming video and a Global Positioning System (GPS) for geolocation. Each sensor payload is suspended in the Squishy Robotics Stationary Robot which is constructed of carbon fiber rods, springs, and small diameter cables. This robot provides impact protection to the attached payload, enabling the robot and payload to be thrown by hand or dropped from heights of up to one thousand feet via an Uncrewed Aerial System (UAS).

As no operational field test can include all applications and scenarios that could be encountered, a representative set of testing criteria and conditions were selected and used to collect data, observations, and end user feedback. The sections that follow outline the methodology and test plan utilized during the Squishy Robotics product evaluation, as well as observations, results, and takeaways.

System Components and Setup

The Squishy Robotics System is comprised of multiple hardware and software components designed to deliver prompt and continuous feedback to a command-and-control node. Some system components are standard with the Squishy Robotics package while there are other components that can be added per request. The Squishy Robotics System is contained in a single impact-resistant wheeled 27" X 27" X 16" hardened case containing the following components:

Hardware

Case Components

- Pelican Case

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- Chromebook laptop
- Two Stationary Robots
- Two 4-Gas^{PLUS} Payload modules
- One 32GB Micro SD card for data storage.
- Battery and battery charger for the system.
- DC Adapter
- Chromebook Charger
- Product Guide
- Robot Assembly guide
- Packing list

Accessories and spare parts:

- 11.25-inch payload mounting strings
- V9c Payload Mounting Springs
- 17.5-inch Exterior Strings
- v10c Exterior springs
- Sensor Connector cap with barb connector & tubing

Two Go-Bags that contain the following items:

- Micro USB to USB-A cord
- XBee dongle with 900 MHz Wire antenna
- FPV USB Receiver
- tweezers
- Battery Voltage tester
- Squishy Robotics pen

Figure 1 Two Squishy Robotics Stationary Robots, one Custom payload, and 4-Gas^{PLUS} Sensor payload packed in hard shipping case.

System Setup

Proper rapid deployment of the Squishy Robotics System is possible to complete in austere conditions. A single user can complete setup and deploy the system in less than 15 minutes. All components included in the case are required for the system setup and deployment.

1. The Chromebook is removed from the case.
2. Start the Chromebook
3. Once the Chromebook OS has started, attach the FPV USB receiver and the XBee dongle into the Chromebook’s USB slots.
4. Remove the robot and attached payload from the case.
5. Assemble the robot.
6. Switch the robot to the “on” position.
7. Verify communications between the robot and Chromebook.
8. Repeat for each unit, as needed.
9. Once communications are established, deploy the robot to the desired location either via manual drop or UAS.

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Software

The software used by the Squishy Robotics System is proprietary software designed to provide a graphic display of the data, view the video feed from the embedded cameras, and monitor the communications. The Squishy Robotics software was not assessed during this TEEX-Tested assessment.

Methodology

Scope: The purpose of this evaluation is to conduct an impartial third-party assessment of the Squishy Robotics System in a realistic and safe environment with multiple users of various skill and experience levels. The overall objective is to assess the quantitative and qualitative aspects of the product and its potential training value and purposes. This evaluation is based on the knowledge, experience, and feedback of SMEs and quantitative and qualitative data collected during testing. TEEX follows a testing protocol similar to military utility assessments as depicted in *Figure 2* below.

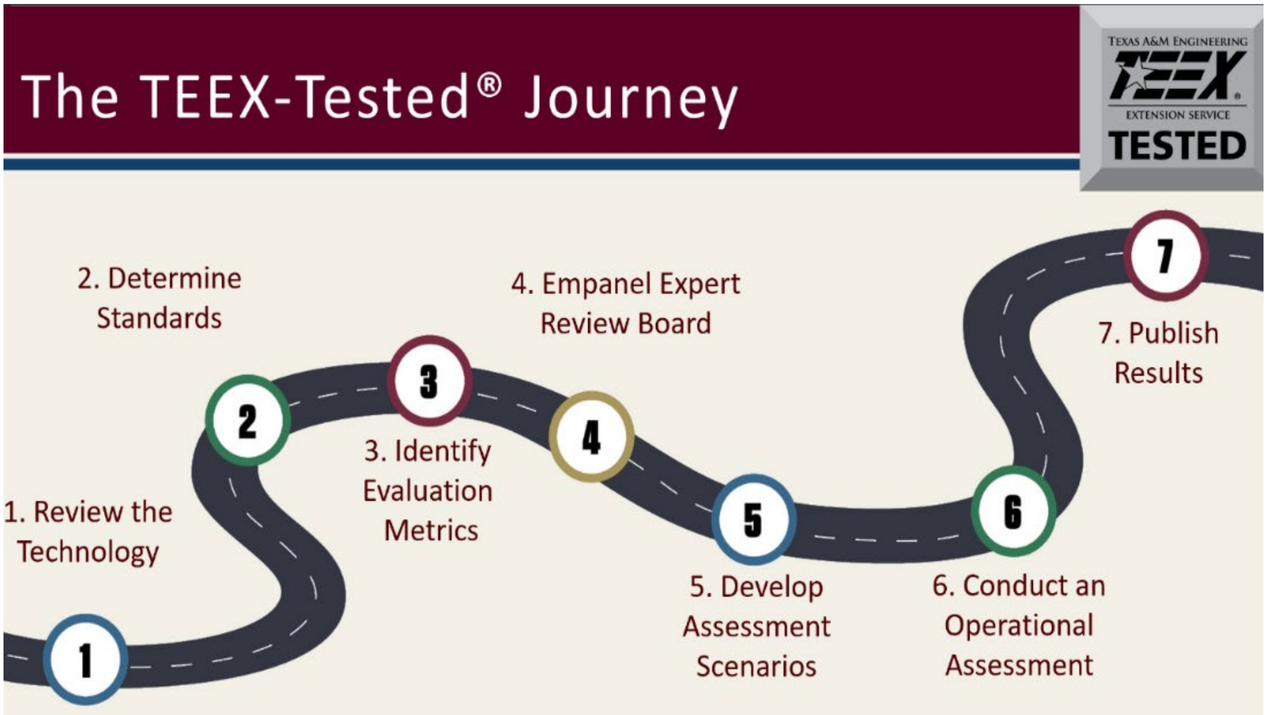

Figure 2 A Graphic Representation of the TEEX-Tested Protocol

<u>Step 1 – Review the Technology</u>: The TT&IC team examined the user manuals and previous tests and analysis regarding mission use and capabilities.

<u>Step 2 – Determine Standards:</u> The TT&IC team determined the standards by which the product would be evaluated and identified applicable evaluation metrics that would allow proper analysis of the technology to be evaluated.

<u>Step 3 – Identify Evaluation Metrics:</u> The TT&IC team, working with engineers from the Internet 2 Technology Evaluation Center, selected applicable quantitative, qualitative, and technology-specific metrics upon which to evaluate the product and developed a customized test plan suited for operational testing of the Squishy Robotics System.

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Step 4 – Empanel Expert Review Board: The panel of SMEs for the evaluation of Squishy Robotics 4-Gas^{PLUS} Detection System consisted of active representatives from the following stakeholder communities: municipal firefighting, HazMat specialists, and search and rescue. Members were selected from three states to provide a diverse representation of policies, procedures, and tactics.

Step 5 – Develop Assessment Scenarios: The TT&IC team created realistic, fair, and impartial testing scenarios leveraging state-of-the art TEEX and Bush Combat Development Complex (BCDC) facilities and appropriate standards and evaluation metrics.

Step 6 – Conduct an Operational Assessment: The TT&IC team conducted operational testing on the product in a realistic and safe training environment with multiple users of various skill and experience levels and collected the resulting data, observations, and end user feedback for analysis.

Step 7 – Publish Results: This comprehensive TEEX-Tested report captures, interprets, and communicates all the relevant data and completes the last step of the protocol.

Location

The evaluation of the Squishy Robotics System was conducted at TEEX's Brayton Fire Training Field Complex, including Disaster City® (figure 4) and the Bush Combat Development Complex (BCDC) Subterranean tunnels (figure 5).

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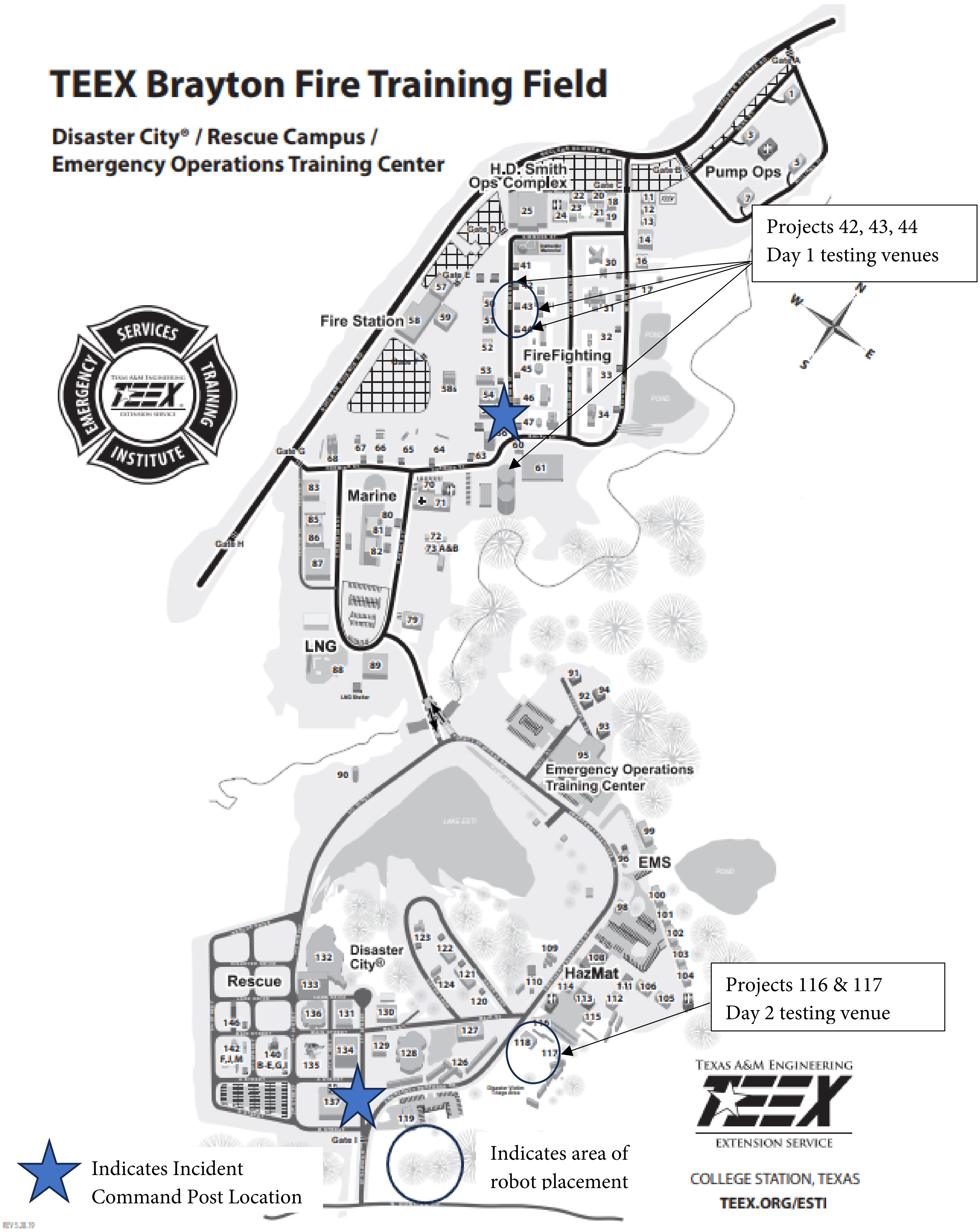

Projects 42, 43, 44
Day 1 testing venues

Projects 116 & 117
Day 2 testing venue

Indicates Incident Command Post Location

Indicates area of robot placement

Figure 3: Overhead Map of the TEEX Brayton Fire-Field and Disaster City

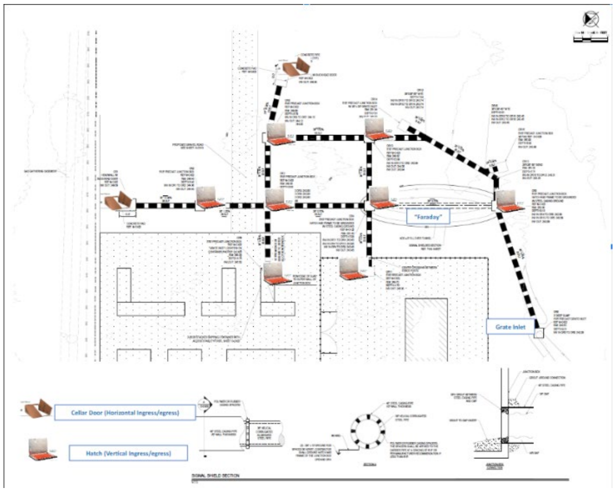

Figure 4 Tunnel System at the Bush Combat Development Complex

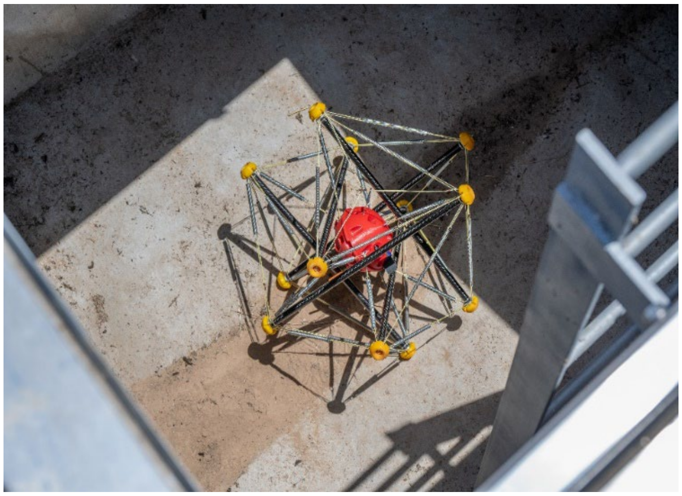

Figure 5 Squishy robot in Subterranean Tunnels at the Bush Combat Development Complex

Test Plan

A detailed test plan was co-developed by the TT&IC staff and ITEC engineers. Squishy Robotics then reviewed and approved the plan. The detailed test plan describing the test strategy, objectives, schedule, and metrics used can be found in Appendix A. The test plan used to evaluate Squishy Robotics System was developed similarly to those used in industry and the military but was tailored to the unique characteristics of this system evaluated in realistic conditions by users of all ability, skill, and experience levels. It was determined that this evaluation would not focus on the specific technical aspects of the hardware and software, but on its performance as an overall system and its purpose and utility. The plan for the testing of Squishy Robotics System was categorized by evaluating the range, durability of the range, and strength of communications between the robots and the established command node.

To accomplish this, Texas A&M University's Internet 2 Technology Evaluation Center (ITEC) conducted three distinct communications tests.

1. **Interference Tests** - This test was used to determine how well the Squishy system performs in the presence of other devices that are also operating in the same band and potentially close to either the robots or the base station. An interferer signal was created in the same band and adjusted in frequency and amplitude relative to the Squishy signals over the course of several tests. This test consisted of two parts:
    a) Adjacent channel interference test – data –the test protocol consists of multiple iterations of nearby interference tests, strong adjacent channel interference tests, and very strong adjacent channel interference tests. The strength of the interference signal was increased by adapting the waveform closer to that of the Squishy Robotic System signal, thus simulating the most probable incident scene signals.
    b) Adjacent channel interference test – video – Similar to the adjacent channel interference test – data, this test protocol includes test consists of multiple iterations of nearby interference tests, strong adjacent channel interference tests, and very strong adjacent channel interference tests.

c) Methodology – The methodology for performing these tests followed this procedure:

   - **Step 1: Baseline** – The ITEC team established the baseline spectrum plot.
   - **Step 2: Nearby Interference** – Using a signal generator, an interferer signal was created with the same amplitude as the Squishy signals and in the same band as the Squish system, but not directly adjacent to the frequencies used by the Squishy robots.
   - **Step 3: Adjacent Channel Interference** – The ITEC team modulated the interferer signal closer in frequency to the robot signals until it is in the adjacent channel space. This situation represents another device, such as another robot deployed along with the Squishy robots, with similar transmit power as the Squishy robots.
   - **Step 4: Strong Adjacent Channel Interference** – The ITEC team increased the power of the interferer signal. This situation represents either another device with higher transmit power than the Squishy system, such as another robot or drone in use in the hazard area that has a stronger transmitter. Or use another device with similar transmit power as the Squishy robots, but physically closer to the Squishy base station than the robots are (so the signal is received with higher amplitude)
   - **Step 5: Very Strong Adjacent Channel Interference** – Finally, the ITEC team increased the power of the interferer signal even further, until the widest parts of the signal encroach on the robot transmissions. While this situation may be unlikely, the team thought it was useful to see what conditions were needed to significantly impact Squishy data communications.

2. **Public Safety LMR Test** - The purpose of the Public Safety LMR Interference Test was to simulate the interference of a Land Mobile Radio (LMR), which is widely used by most public safety personnel. This test was designed to determine if the presence of either a strong transmitter near the Incident Command Post (ICP) (such as a repeater or mobile radio) or a handheld radio located at the Squishy operating position would cause significant disruption to the ability to receive data from the Squishy robots.

3. **Background Noise Test** - The purpose of the noise floor interference test is to determine how much stronger than the noise floor a signal from the robot needs to be for successful reception at the Squishy base station receiver.

   a) This test was used to determine how well the Squishy system performs in the presence of other devices that are also operating in the same band and potentially close to either the robots or the base station. An interferer signal was created in the same band and adjusted in frequency and amplitude relative to the Squishy signals over the course of several tests.

4. **Fire Apparatus Tests**: The purpose of the Fire Apparatus tests was to discern the correct positioning of antennas on a fire apparatus to maximize the communications throughput while using the robot base station while inside a fire apparatus. Due to the large metallic nature of a fire engine, special measures must be taken in order to permit communication. Tests were conducted

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by positioning antennas at various points inside and outside the fire apparatuses, to determine where the antenna is best situated.

5. **Communications Terrain-Obstruction Range Tests** - The purpose of this test was to determine how well the Squishy Robotics system transmits numerical gas sensor and video data in a variety of environments with varying levels of man-made and terrain obstructions that can interfere and/or block communications pathways. To determine the strength and the quality of the wireless signals from the deployed sensors, the percentage of packets received, RSSI values, and sensor payload meshing data were collected from each sensor deployed in various sensor placement configurations. The robot position was recorded via the robot's onboard GPS, base station position was recorded via annotating test locations and later extracting GPS coordinates via google satellite view. In the specific case of the tunnel tests, the robots' GPS was not accurate due to their subterranean emplacement, instead, robots were deployed at the junction between tunnels, and these junction positions were extracted via satellite view.
    a) **Methodology** - The methodology for performing these tests at each testing prop followed this procedure:
        - **Step 1: SME Devised Response Scenario** - Panel of First Responder subject matter experts with hazardous materials response expertise devised an emergency response scenario relevant to each testing prop. Panelists inspected props and discussed factors of the devised response scenario to determine a response plan such as the location of Incident Command and the ideal placement of air monitoring equipment for such a response effort.
        - **Step 2: Baseline Background Noise** - The baseline background noise was measured and recorded as a comparison metric for each test. This data was collected by both ITEC and Squishy Robotics.
        - **Step 3: Baseline Sensor Connectivity** - Three to four Squishy Robotics sensors were positioned at the ideal deployment locations identified by the SME panelists in Step 1. The baseline connectivity data (percentage of packets received, RSSI values, sensor payload meshing data) from each deployed sensor was recorded. This data was collected by Squishy Robotics.
        - **Step 4: Incremental Repositioning of Sensors or Base Station** - The Squishy Robotics sensors were incrementally repositioned, placing sensors further and further from Incident Command until connectivity from each sensor to the Squishy Robotics UI positioned at Incident command was lost and meshing between sensors was not achieved. Connectivity data was recorded for each deployment location for each sensor. In select test conditions where the props did not facilitate very long-range tests, the base station was instead repositioned (carried by hand on a golf cart) to enable testing at further extended distances.

ITEC used the following equipment to conduct these tests:

Spectrum Analysis

- Anritsu S412E LMR Master
- CACI Spectrum Guard

5GHz Interference Generator

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- Radio: Ubiquiti AirFiber Model AF-5XHD, 5Hz Radio
- Antenna: Ubiquiti Model AF-5G23-S45, 5GHz AirFiber Dish, 23dBi, Slant 45

900MHz Interference Generator:

- Radio: Cambium Model PTP 450, 900 MHz Radio
- Antenna: GNS Wireless Model GNS-1529, 900MHz, 12 dBi, Yagi Antenna

Additional detailed information on Radio Frequency (RF) background and the tests can be found in Appendix A: Squishy Robotics RF Test Report.

Sequence of TEEX Testing Events

10 Jul 2023

1. Squishy team meet in lobby of Smith building- Brayton Fire Field
2. Transport team and equipment to Classroom 55 for safety in-brief
3. BFTF (Brayton Fire Training Field) Classroom 55. Safety brief, Panel/SME discussion regarding initial prop/42/43 set up for placement of robots.
4. Set up for testing- Incident Command post outside of classroom 55.
5. T1: Petro/chemical Deployment- Test mesh network hubs with robots within industrial complex (props 43/44).
6. Regroup at Classroom 55 for T2 initial robot placement discussion.
7. T2: Bulk storage tanks- large tanks deployment- Deployment of robots around two large water storage tanks simulating fuel/chem storage.
8. Remote Incident Command post for receiver and analysis to be positioned 50-100 yds from site.
9. Robots and receivers to be moved as required for testing performance distances.

Project 42 Pump Alley Fires *Water Storage Tank used for Day 2* *Project 117 Freight Train Derailment*

Figure 4 Brayton Fire Training Field projects used for testing.

11 Jul 2023:

1. Squishy team meet in lobby of Smith building- Brayton Fire Field
2. Transport team and equipment to Rescue building for safety in-brief.
3. Disaster City/Rescue building classroom TBD. Safety brief, Panel/SME discussion regarding initial prop/116/117 set up for placement of robots.
4. T3: Derailment scenario- measure single robot data from various angles ranges around train/sensor. Deploy additional robots for mesh network measurements (props 116 and 117). UAS overhead for photos. TF-1 Comms truck to provide representative disaster communications.
5. Remote Incident Command post for receiver and analysis to be positioned 200-300 yds from site at the rescue building.

6. The robots were then positioned on Prop 116/116 (freight train derailment) to simulate their actual use in such an incident.
7. Baseline range and throughput data was collected.
8. Interference tests were conducted.
9. Robots and receivers to be moved as required for testing performance distances.

Figure 10: UAS deployment of Squishy Robot

12 July 2023:

1. Squishy team meets at RIC/BCDC for range. Reposition team/equipment to IPG (Innovation Proving Ground) tunnel complex.
2. T4: Underground tunnel deployment- Deployment of robots inside and outside of campus tunnel area in coordination with Texas A&M facilities
3. Remote Incident Command post for receiver and analysis to be positioned under covered area in complex area. Power required.

13 Jul 2023:

1. Squishy team meet at BFTF fire station, building 58.
2. T5: Multi apparatus familiarization and antenna testing- Testing of receiver antenna locations in and around available apparatus. No installations or holes to be drilled. Repositioning receiver inside apparatus for reception and logical use. (requested Siddons-Martin representative)
3. Wrap up at TT&IC (101 Gateway Blvd. suite A, College Station) panel discussion regarding observations.

Analysis and Results

The metrics measured in the TEEX-Tested assessment are grouped into three categories: quantitative metrics, qualitative metrics, and other value considerations. This section details the observations made and the subsequent results of the assessment.

The following section summarizes the testing completed by the Internet2 Technology Evaluation Center (ITEC) at Texas A&M University.

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Quantitative Metrics

The TEEX-Tested quantitative metrics are a set of defined measurements that provide an objective perspective to the evaluation. Quantitative metrics are typically reported using numerical data. ITEC conducted the testing and generates the Squishy Robotics RF Test Report detailing the signal strength, interference testing conducted, among other considerations. Below is synopsis of the significant findings from each of the tests done by ITEC. A complete report including all data gathered by ITEC is provided in Appendix A.

Adjacent Channel Interference Test Observations – The test showed that consumer products do not have the transmitter power or high-gain antennas to generate a large amount of interference. The likely source of interference shown in the test came from other nearby public safety devices. ITEC concluded from this test that the hopping nature of the system is "a definite plus" due to the ability to hop to a different frequency and avoid interference.

Public Safety LMR Interference Test Observations – The operation of Squishy data communications was not significantly impacted by normal use of LMR radio in proximity to the squishy base station, similar to a normal ICP. Data communications with the Squishy base station could be forced to fail by keying up a radio close to the laptop, but performance returned to normal when the radio was moved away.

Background Noise Test Observations - The noise floor was raised repeatedly until the packet reception rate dropped to 10%. This occurred for one of the robot antenna orientations when the robot signals were only 3-5 dB above the noise floor. This is quite a small margin. Given the ability of the robots to automatically create a mesh and relay from one robot through another to reach the base station, the robots should be capable of being deployed even in challenging RF environments.

Communications Terrain-Obstructions Range Tests - These tests showed that a sensor could acceptably communicate numerical data back to the Squishy Robotics UI located at Incident Command under typical operational conditions at ranges from hundreds of 500 - 1500 feet. In some instances, communications were established at even further distances or around large obstacles utilizing the mesh capability of the Squishy Robotics sensor payloads. Specific ranges and performance varied from test to test due to the inherent terrain obstructions (varying from minimally obstructed to highly obstructed) from each test site, and a full compendium of data for these range tests can be found in Appendix B. A selection of top-line representative results is below:

Test	Maximum Range (ft)	Transmission Success	Meshing Status
Water Storage Tank	412	98.7%	Direct
	1093	94.5%	Mesh - 1 Hop
Industrial Plant	443	96.3%	Direct
	2225	46.9%	Mesh - 1 Hop
Train Derailment	954	99.8%	Direct
	1462	96.6%	Mesh - 1 Hop
Underground Tunnel	120	63.8%	Direct
	93	99.5%	Mesh - 1 Hop

Table 1 Select Communications Range Results

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Qualitative Metrics

The TEEX-Tested qualitative metrics are a set of measurements based on operational experience and judgement that subjectively evaluate a product and or its technology. Qualitative metrics resulted in observed categorical descriptive data:

> **Quality of operational /data transmit-receive capability in representative RF spectral and various terrain and structural environments:** Based on the repeated tests in a variety of environments (e.g., train derailment, sloping terrain, subterranean tunnels, extended range between transmitter and receiver (> 1,000 feet) etc.), the panel observing the scenarios agreed that the performance of the Squishy Robotics System video and data communications functions was effective when used in operational environments.
>
> **Realistic positioning of receiver to robots:** During the scenarios, the SME panel used accepted practices in placing the system and base stations to start each assessment. From there, the SME panel moved the Squishy Robotics System (i.e., robots) that often exceeded the specified performance parameters defined by the manufacturer. In most cases, the System performed reliably at greater than stated distances.
>
> **Realistic positioning and relay capability of additional robots in mesh network:** During the multiple scenarios, the team observed instances when individual robots connected to the system. In other cases, situations were observed where individual robots could not connect directly to the base. However, in each instance, the mesh network and relay robots were able to connect and relay the data. It was also noted that the addition of robots extended the range connections.
>
> **Quality of data reception within various apparatus cabin and antenna mountings:** There were no assessments from apparatus. This capability was only demonstrated to the expert panel. However, data was collected from apparatus in the firehouse with internal and external apparatus antennas. The observers noted that reception was reliable inside fiberglass bodies. However, bodies with heavy use of aluminum and steel materials were not consistent. All demonstrations were limited to up to 25 yards.

Other Value Considerations

This category includes critical considerations beyond measurable metrics explaining the perceived value of the system. HAZMAT operational experts concluded that the robots could function as a sentry due to the gas detection and cameras vs using firefighters or HAZMAT personnel monitoring gas levels/changes and recording activity.

User Feedback

Feedback was collected throughout the evaluation period. Also, surveys were administered at the end of each product demonstration session to capture feedback on testing. Surveys were obtained from fire academy instructors, fire academy students, full-time municipal firefighters, and professional forestry firefighters. Additionally, the advisory panel members were surveyed and provided feedback.

Advisory Panel Hands-On Review, Assessment, and Feedback

Battery

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Through feedback from the SMEs, it was found that the battery component was a common response when asked for areas of improvement. While the battery life was commended by some SMEs, others said that increased battery life would be beneficial for more sustained monitoring activities. The SMEs commented that battery life was an issue at certain parts of the testing due to camera use requiring frequent replacement.

Another aspect of the battery that was recommended to be changed was the user friendliness of the battery change. Several SMEs explained that the current battery connection makes changing batteries difficult while wearing gloves during a HazMat scenario.

The final common recommendation among SMEs was to create a visual monitor on the robot and in the user interface regarding the battery level. The concern is that it would be difficult for users in the field to identify the battery level and anticipate change outs.

Large Scale Incidents

The SMEs unanimously agreed that the Squishy robots would be best utilized in large-scale incidents, such as train derailments, industrial HAZMAT releases, or highway incidents. This was the driving requirement for robot placement during the operational assessment at the TEEX Brayton Fire Field and Disaster City.

Size limitations

A concern shared by the SMEs was the size limitations of the current model of the robot. While the SMEs understand the robot's dimensions and reason for its size, there are two main concerns. The first concern is that the robot is too large to fit into small scale scenarios such as an internal spill. The second concern is that the size limitation will be a problem with fitting the robot on the transportation vehicles. Due to the limited space of vehicles such as fire trucks, the bulkiness of the robot package is a potential disadvantage.

Customization

A recommendation shared by several SMEs was to be able to customize the robot to a further extent than already provided by Squishy Robotics. In the feedback the SMEs stated that while it is helpful to have a customizable payload, there are aspects of the robot that could be tailored to individual departments. These include the type of battery, the antennae type, and its attachment method due to the different nature of handling the device on sight.

User Interface

The current user interface for data reception and interpretation was received with mixed reviews. SMEs that had used the system before talked about the ease of use for any end user. However, several other SMEs stated that the user interface was difficult to understand and that the graphics on the screen were not clear. They suggested that the interface align with normal markings and graphics that an average department would utilize with other technologies.

Signal Strength

Overall, the SMEs were extremely pleased with the capabilities of the signal strength of the robots. They were particularly impressed with the strength of the signal when multiple sensors were used in a mesh network across a large disaster scenario.

Multiple SMEs recommended including a signal strength indicator on the robot and on the user interface for ease of use and understanding for the end user.

Rapid Deployment

SMEs were impressed with the rapid deployment of devices. They outlined how quick from unpacking to having a robot deployed on scene was extremely useful, especially for incidents in sensitive locations requiring a rapid response and assessment.

Non-Physical exposure to chemicals

SMEs highly praised the capability and benefits of not having personnel exposed to chemicals due to the remote nature of the device. This was seen as a game changer as no personnel would need to go into a situation without knowing the full extent of the situation.

Conclusions

The Squishy Robotic data communication system performed as advertised in operational environments and scenarios. Despite the expendable, low-cost nature of the communications system, it proved robust in expected disaster incident where numerous radios and devices are in use that could cause interference. Sensor and camera data was available and useful at ranges between a HAZMAT area and normal safe ranges to an on-scene incident command site. This included connecting through its mesh network in and around large metal and concrete objects and terrain features, such as drainage ditches, and through tunnels to an exit hatch. The robots were deployed by hand and by UAS. Active firefighters, HAZMAT and rescue team assessors provided improvement recommendations, while concluding that the system would be effective and highly useful in active HAZMAT detection and incident conditions.

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Appendix A:

Squishy Robotics RF Test Report

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Squishy Robotics RF Test Report

Contents

This work was performed under the following financial assistance award 70NANB22H209 from

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Technical Background: Squishy Robotics Components

The Squishy Robotics System is composed of two main elements:

1. The "Squishy Robotics Stationary Robot with 4-Gas^{PLUS} payload", or 4-Gas^{PLUS} Robot, for short. For brevity, this report will use the term "robot."
2. The Squishy User Interface Base Station is used to view the data and video being sent by the robots. In includes the Communications Status Monitor (CSM), which runs in the background, monitors the status of connectivity with the robots, and reports it using human-digestible metrics. For brevity, this report will use the term "base station."

Multiple robots can be deployed and managed from a single base station. For example, a typical hazmat scenario might involve two to three robots deployed around a spill or leak, all being monitored by a single receiver. This can provide the first responders valuable information about the way direction of travel of the gasses.

Self-Forming Data Mesh

The robots will automatically create a mesh network using the data channel to reach the base station. For example, suppose a robot is deployed in an area that has a poor RF path back to the base station, such as behind a large metal storage tank, or on the other side of a large train wreck, or down a tunnel. In such a case, another robot can be deployed at an intermediate location. It will automatically form a mesh with the initial robot and the base station and function as a relay between the two. This feature proved to be very useful in several of deployment scenarios assessed.

Frequency Bands

The Squishy Robotics System communications between the deployable Squishy robots and the receiver currently operates in the following frequency bands:

- Data: 900 MHz ISM band (902 to 928 MHz)
- Video: 5.8 GHz FPV (First Person Video) band

Squishy Data Communications: Overview

The Squishy Robotics System uses the data communications channel to communicate sensor information plus information about the robot status, such as battery, IMU and GPS data. Data throughput requirements are relatively low and can be customized by the agency using the device.

By default, the robot sends:

- Every second: 4-gas sensor readings, temperature, and alarms
- Every five seconds: GPS location

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The interval between transmissions can be adjusted. For example, a gas reading may be desired every 5 seconds in some cases.

The Squishy Robotics System uses Xbee radios operating in the 900 MHz ISM band for data communications. The choice of the 900 MHz band allows the signal to transmit further and deal with obstructions, such as trees, much better than other band choices for Xbee, such as 2.4 GHz band.

The following configuration was assessed:

Robots:	Digi S3B Xbee with ¼ wavelength whip antenna
Receiver:	Digi S3B Xbee with ½-wavelength dipole antenna attached to the laptop lid

The 900 MHz ISM band is shared with many types of consumer and public safety devices. Examples of consumer devices include cordless phones, baby monitors, and amateur radio. Examples of public safety devices include sensors, navigation systems, amateur radio (coordinated with public safety/emergency management) and other robots.

The tests described in this report help to characterize the data communications performance of the Squishy Robotics System in the presence of other devices in use in the band and in other bands.

Performance Metrics

The Squishy robots insert the number of packets they have sent over the last minute into each packet that they send. The Squishy base station compares the number reported by the robot to the number of packets that it received over the last minute and reports the ratio as a percentage.

In the default configuration, the Squishy Robotics System sends a packet every second, which includes a 4-gas sensor reading, a temperature reading, any alarms that may be present on the robot, and the number of packets set over the last minute.

The Squishy receiver system will divide the number of packets it received by the number of packets reported sent by the robot as a percentage. For the default interval of one reading per second, the percentages indicate the following:

- 100% = 60 of the 60 packets sent by the robot were received
- 50% = 30 of the 60 packets sent by the robot were received
- 10% = 6 of the 60 packets sent by the robot were received

So, for the default interval of one gas reading per second, a receive rate of only 10% still means that six gas readings were received within the last minute. An agency can decide if that is enough data or if they might need to deploy another robot as a relay.

This received packet percentage value will be referenced in the RF test results described below.

Squishy Video Communications: Overview

The Squishy Robotics System uses the video communications channel to send live video from the robot to the receiver. The robot contains six cameras pointed in different directions and cycles the video images sent to the receiver every 1.5 seconds. In this way, the orientation of the robot does not matter.

The Squishy Robotics System uses analog video operating in the 5.8 GHz FPV band for video communications. This band is shared with 5.8 GHz WiFi, 5.8 GHz Amateur Radio, and 5.9 GHz Public

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Safety. In addition to the analog and digital FPV uses, the other users of the band tend to use it for high-speed data transmission.

The following configuration was assessed:

- Robots: Eachine TX805 5.8 GHz FPV Transmitter
- Receiver: SkyDroid 5.8 GHz FPV Receiver

The tests described in this report help to characterize the data communications performance of the Squishy Robotics System in the presence of other devices in use in the band.

Performance Metrics

The video signal is analog and there are no quantitative metrics. Human observation was used to assess if the images were useful.

Radio Frequency Technical Background

The Squishy Robotics System will be deployed by public safety at emergency incidents. It will need to operate within the complex communications ecosystem that exists at incidents in support of first responders. This section describes some of the RF interference challenges that exist and at an emergency incident and forms the background for RF tests that were conducted with Squishy.

Sources of RF Interference at an Emergency Incident

The use of wireless communications continues to expand in public safety. In addition to traditional P25 radio communications, public safety agencies now make use of a variety of cellular, WiFi, Bluetooth, Satellite, and other communications devices, including network devices, sensors, robots, drones, and other communications accessories. This technical background provides a brief overview of the types of RF interference that can exist in an emergency incident. Understanding the sources and types of interference is

Interference at the Incident Command Post

Squishy Robotics' user interface will usually be located at an ICP (Incident Command Post), which will be a safe distance away from the location of the hazard where the robots are deployed. Operating at the ICP subjects the receiver to a wide variety of potential wireless communications sources.

The ICP will contain a variety of communications systems in a variety of RF bands. Depending on the site used for the ICP, any of the following communications systems could be present.

- Public Safety LMR (Land Mobile Radio) systems, such as P25 radios in VHF and UHF
- Cellular (4G, 5G, …) in multiple bands
- WiFi (typically operating in the 5.8 GHz band used by Squishy for video)
- Bluetooth
- Satellite
- Positioning, Navigation and Timing (PNT)
- Cordless phones (perhaps operating in the 900 MHz ISM band used by Squishy for data)
- Amateur radio (high power, and perhaps operating in the 900 MHz and 5.8 GHz bands)
- Industrial IoT sensors (temperature, humidity, vibration, water, movement, …)

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- Drones and robots (air- or ground-based, transmitting audio, video, and sensor info)

As the local hub of communications activity, high power transmitters are likely to exist at or near the ICP, providing a "communications bubble" to support local communications within the incident area and connecting the incident area to other locations and support resources, such as DOCs (Departmental Operations Centers), EOCs (Emergency Operations Centers), other agencies, and the Internet.

These communications assets may be set up in vehicles parked near the ICP or set up in the ICP itself, depending on the need and the situation. Examples include:

- Portable VHF/UHF mobile repeater, outputting 50-100 Watts
- Portable or mobile cellular site, outputting 40 or more Watts.
    - CoLT = Cell on Light Truck; CoW = Cell on Wheels; CRD = Compact Rapid Deployable
- WiFi Access point, output of up to 1 watt through directional antennas
- Satellite backhaul, such as Starlink for Internet access.
- Drones and robots may be set up and evaluated at or near the ICP before deploying to the hazard location.

Individuals performing duties in the ICP will also have radios and other communications devices on their person. Examples include:

- VHF/UHF Radio
    - Mobile radio inside the ICP for primary radio communicator, output 20-50 Watts
    - Individual handheld radios, outputting 4-5 Watts
- Personal cell phones
- Personal WiFi devices
- Personal Bluetooth devices

Interference at the Robot Deployment Location

The Squishy robots are designed to be deployed at the location of the hazard so they can sense and report on the conditions without endangering a human. Depending on the situation, other robots and drones may also be in use at the deployment location. For smaller, localized hazmat situations, it is conceivable that at least an aerial drone might be in use. In fact, the Squishy robot may be deployed by dropping it from a drone. The use of ground-based mobile robots, such as a tracked robot or "robot dog" is also becoming more common. For large, multi-agency responses, there can be dozens of drones in use and multiple robots deployed by several agencies.

Types of Interference

The potential for RF interference from other nearby devices can manifest in many ways. In fact, the other devices do not need to be using the same frequency to create interference. Following are some potential types of interference that can exists from to these communications include:

- Co-channel interference
    - Another device is using the same frequency range or channel as the Squishy Robotics System.
- Adjacent channel interference

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  - Another device is using the channel or frequency range that is immediately adjacent to the channel or frequency range used by the Squishy Robotics System. Since a perfect RF filter does not exist, some of the signal from one channel can bleed over into adjacent channels.
  - If the adjacent channel signal is weak, such as if the other device has low transmit power or is farther away, then the portion of the signal in the adjacent channel that overlaps into the desired channel can be negligible.
  - If the adjacent channel signal is strong, such as if the other device has a higher power transmit or is closer in location, then the portion of its signal in the adjacent channel that overlaps into the desired channel can be significant enough to cause interference.
- Spurious and harmonic emissions
  - Undesirable emissions that are outside the proper bandwidth of the transmitter. The undesirable emissions can be a wider than normal signal or can be emissions on a harmonic (multiple) of the main signal.
  - This type of interference is most often caused by cheap, consumer-grade products, and especially imports that do not adhere to FCC requirements. It can also be caused by higher quality devices that are misaligned or have a failing component.
  - Like adjacent channel interference, this type of interference can come from other devices that are close enough that these unwanted emissions have enough power to interfere with the desired signal.
- Fundamental Overload
  - A signal that is strong enough to induce currents on receiver components, overloading them and degrading their performance.
  - This type of interference can occur from a strong in-band signal, such as another device operating in the same band with a high-power transmitter, or a moderately powered transmitter that is located very close by.
  - This type of interference can also be caused by a much stronger signal that is not even in the same band. For example, transmissions from a much higher power radio in a different band but in close proximity can overload a device's receiver.
- Intermodulation Distortion (IMD)
  - Nonlinearities in a communications system cause two or more signals to mix and generate additional signals (IMD products) occurring at the sums and differences of multiples of those original frequencies.
  - For example, two or more radios transmitting on different frequencies at the same time will cause additional signals to be generated through mixing. These intermod products could land on the same channel as used by the desired device (co-channel interference) or adjacent to that channel (adjacent channel interference). If these IMD products are strong enough, they can interfere with the desired device.
  - For intermodulation interference from in-band signals, third order IMD products such as ($2f_1$-f_2) and ($2f_2$-f_1) are the most troublesome because they have the highest amplitude.
  - For intermodulation interference from out-of-band signals, 2nd order IMD products such as (f_1+f_2), ($2f_1$), ($2f_2$), (f_1-f_2), and (f_2-f_1) are the most troublesome because they have the highest amplitude.

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- Passive Intermodulation (PIM)
    - Intermodulation distortion that occurs in passive devices, such as junctions of dissimilar metals or loose or corroded connectors. PIM can be from both in-band and out-of-band signals.

Frequency Coordination

With the number and variety of wireless devices present at an incident increasing, the need for frequency coordination for all communications devices involved in the incident response is more important than ever. The Communications Unit in the Logistics Section of the Incident Command team performs this function. The frequencies in use by all devices used in the incident are documented on an ICS-205 form.

Incident Command teams usually have a predefined communications plan that includes the devices they use every day plus the devices they might foresee using. These plans are regularly evaluated during typical responses. As novel and innovative devices such as drones and robots are added to the tool set, Incident Command teams will need to update their frequency assignments to accommodate these new devices and to avoid or minimize interference.

Frequency coordination helps to reduce or eliminate many sources and types of interference. But it cannot address all situations. For example, a member of the incident management team who walks into the ICP and keys up their radio right next to other RF devices is likely to cause fundamental overload in those devices, regardless of the frequency plan. Or a device running low on batteries may start to emit spurious or harmonic emissions because its transmitter is operating on the edge of its capabilities. Or a new, uncoordinated robot or drone that is brought to the scene, perhaps by a partner agency, can create one or more of the interference types listed above. Therefore, understanding how well a device behaves in the presence of interference is very important.

Adjacent Channel Interference Test - Data

Test Purpose

The 900 MHz ISM band is home to many devices that could be present at a hazmat or disaster location, including:

- Consumer devices, such as cordless phones, baby monitors, etc.
- Licensed radio services, such as Amateur Radio, which can be operating high power transmitters (up to 1500 Watts)
- Positioning, navigation, and timing (PNT) systems, such as NextNav
- Commercial IoT Sensors, such as temperature, humidity, motion, etc.
- Wireless cameras
- Other commercial and consumer robots

This test was used to determine how well the Squishy Robotics System performs in the presence of other devices that are also operating in the same band and potentially close to either the robots or the base station. In order to do this, an interferer signal was created in the same band and adjusted in frequency and amplitude relative to the Squishy signals over the course of several tests.

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Test Methodology

Step 1: Baseline: Establish the baseline spectrum plot.

Step 2: Nearby Interference: Create an interferer signal of approximately the same amplitude as the Squishy signals and in the same band as the Squish system, but not directly adjacent to the frequencies used by the Squishy robots.

Step 3: Adjacent Channel Interference: Move the interferer signal closer in frequency to the robot signals until it is in the adjacent channel space. This situation represents another device, such as another robot deployed along with the Squishy robots, with similar transmit power as the Squishy robots.

Step 4: Strong Adjacent Channel Interference: Increase the power of the interferer signal. This situation represents either:

- another device with higher transmit power than the Squishy Robotics System, such as another robot or drone in use in the hazard area that has a stronger transmitter.
- another device with similar transmit power as the Squishy robots, but physically closer to the Squishy base station than the robots are (so the signal is received with higher amplitude)

Step 5: Very Strong Adjacent Channel Interference: Increase the power of the interferer signal even further, until the widest parts of the signal encroach on the robot transmissions. While this situation may be unlikely, the team thought it was useful to see what conditions were needed to significantly impact Squishy data communications.

Baseline Conditions

The Squishy robots were set to operate in the lower end of the 900 MHz band. Figure 1 shows the background noise at about -75 dBm. The robot beacon signals can be clearly seen.

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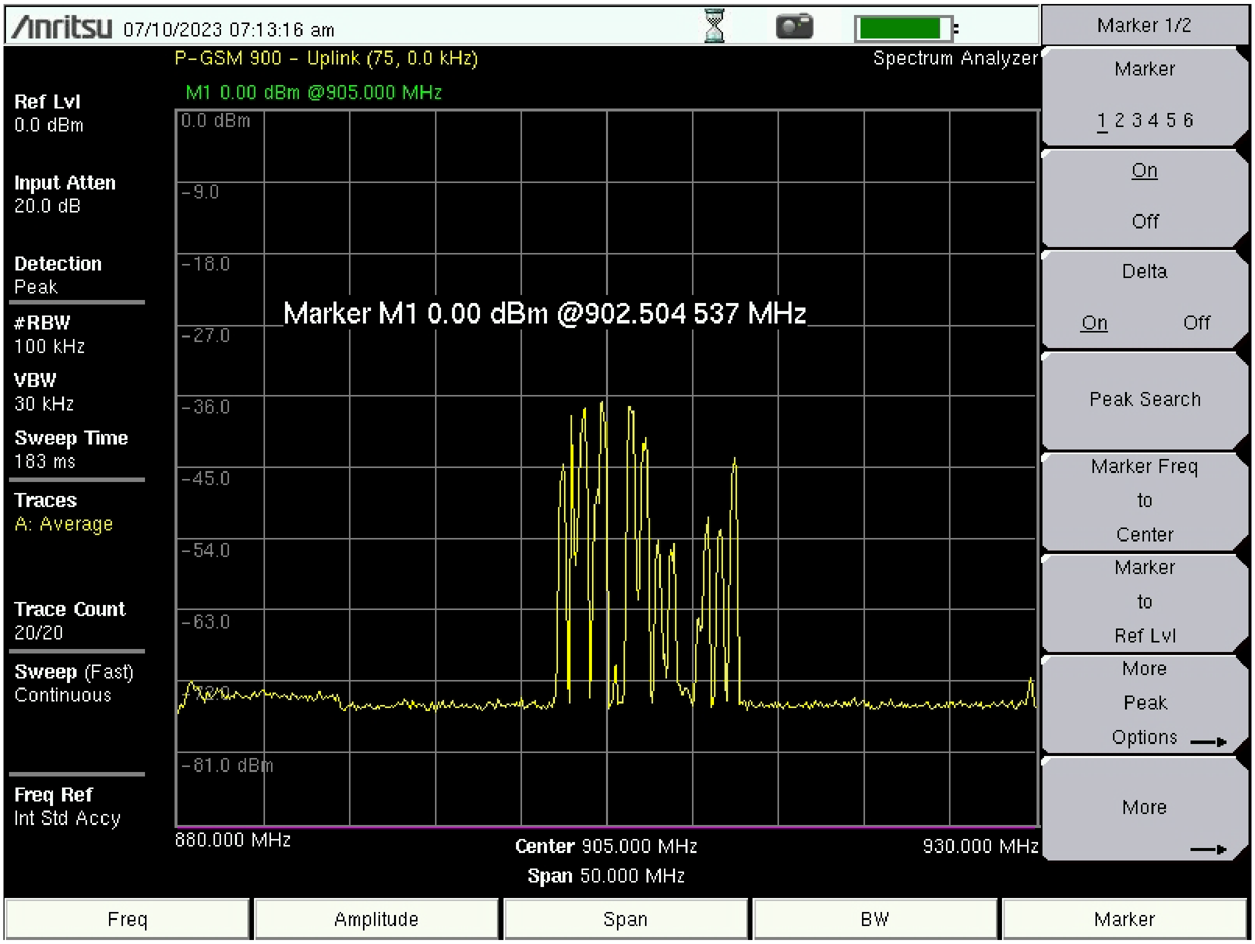

Anritsu 07/10/2023 07:13:16 am

P-GSM 900 - Uplink (75, 0.0 kHz)

Spectrum Analyzer

M1 0.00 dBm @905.000 MHz

Ref Lvl 0.0 dBm

Input Atten 20.0 dB

Detection Peak

#RBW 100 kHz

VBW 30 kHz

Sweep Time 183 ms

Traces A: Average

Trace Count 20/20

Sweep (Fast) Continuous

Freq Ref Int Std Accy

Marker M1 0.00 dBm @902.504 537 MHz

Center 905.000 MHz

Span 50.000 MHz

Figure 1 Spectrum analyzer plot showing baseline conditions.

Interference Tests

A 900 MHz WiFi transmitter with a highly directional antenna was used to generate the interfering signal. The transmitter power level was manipulated to create stronger or weaker signals. And the directional antenna was used to direct the interfering signal at either the robots or the receiver.

Several tests were conducted to determine the impact of such signals on the data communications of the Squishy Robotics System. This report includes a few representative samples of those tests.

Nearby Interference

Figure 2 shows the robots operating at the lower end of the 900 MHz band, from about 902 MHz to 913 MHz. The interference signal is centered at 920 MHz, is 5MHz wide (917.5 – 922.5 MHz) and was set to the same amplitude as the Squishy signals. This left about 5 MHz of clear spectrum between the highest frequency used by the robots and the lower end of the interference signal. No impact on Squishy data communications was observed.

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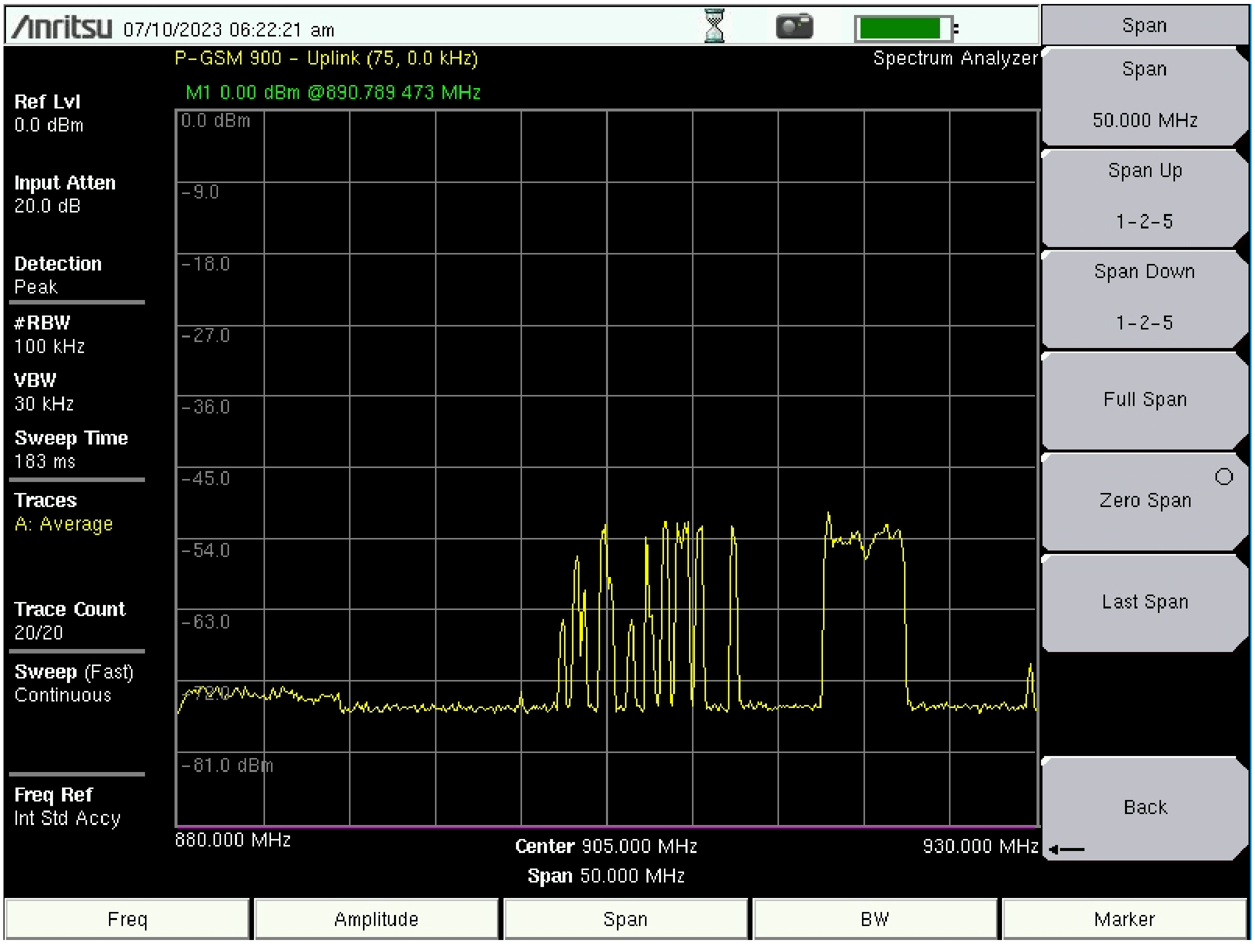


07/10/2023 06:22:21 am

P-GSM 900 - Uplink (75, 0.0 kHz)

M1 0.00 dBm @890.789 473 MHz

Ref Lvl 0.0 dBm

Input Atten 20.0 dB

Detection Peak

#RBW 100 kHz

VBW 30 kHz

Sweep Time 183 ms

Traces A: Average

Trace Count 20/20

Sweep (Fast) Continuous

Freq Ref Int Std Accy

880.000 MHz

Center 905.000 MHz

Span 50.000 MHz

930.000 MHz

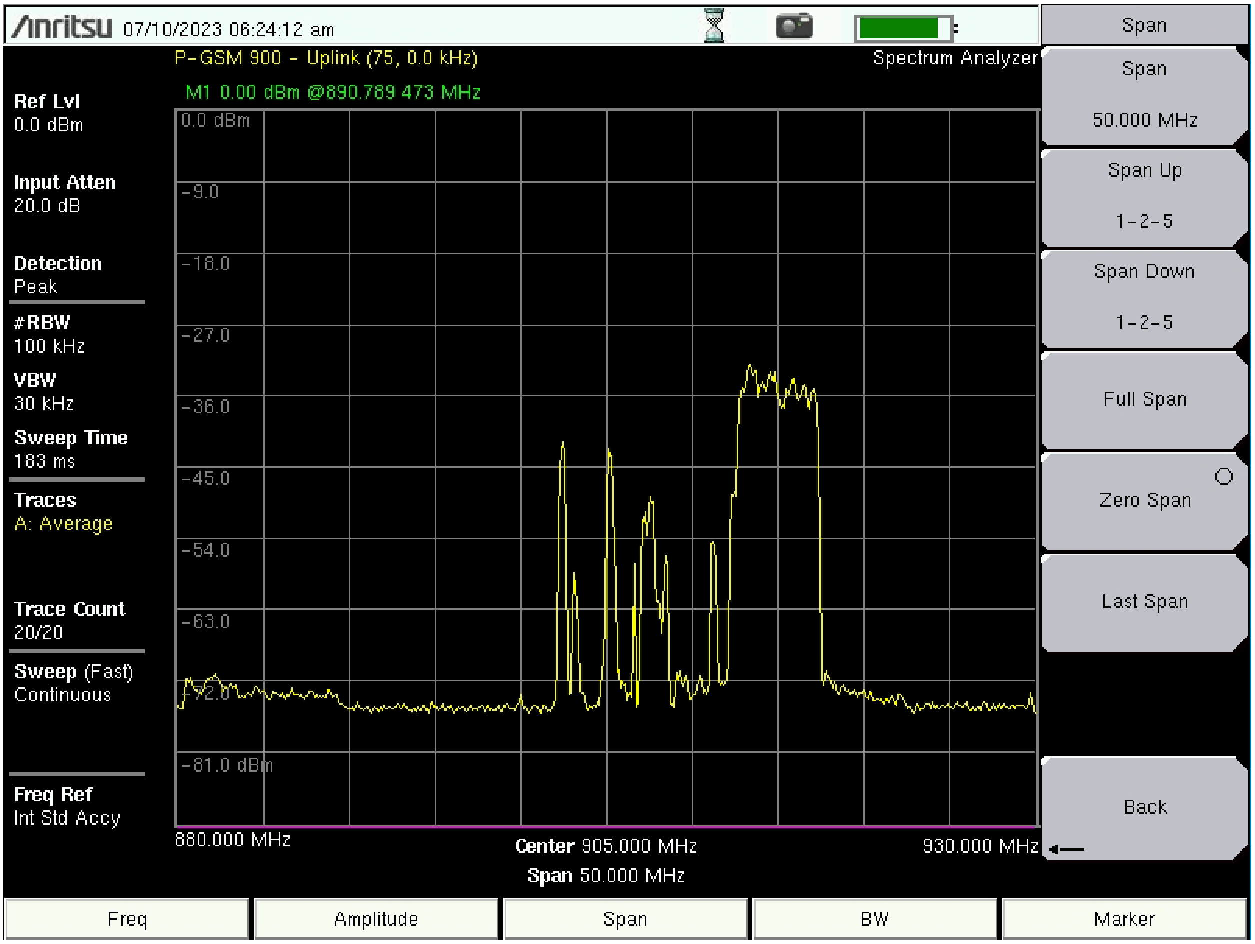
Span 50.000 MHz

Figure 2 Graph of the results of the nearby interference test

Strong Adjacent Channel Interference

Next, several tests were run as the interfering signal was moved closer to the robot signals and the amplitude of the interfering signal was increased.

In Figure 3, the interfering signal is moved to a center frequency of 915 MHz and is 5 MHz wide (912.5 to 917.5 MHz). This puts the lower end of the interfering frequency directly next to the robot signals (which are using from 902 to 913 MHz). The power of the interfering signal was increased to be about 15 dB stronger than the robot signals. This represents a strong adjacent-channel interferer.



Anritsu 07/10/2023 06:24:12 am

P-GSM 900 - Uplink (75, 0.0 kHz)

Spectrum Analyzer

M1 0.00 dBm @890.789 473 MHz

Ref Lvl 0.0 dBm

Input Atten 20.0 dB

Detection Peak

#RBW 100 kHz

VBW 30 kHz

Sweep Time 183 ms

Traces A: Average

Trace Count 20/20

Sweep (Fast) Continuous

Freq Ref Int Std Accy

Center 905.000 MHz

Span 50.000 MHz

Figure 3 Strong adjacent channel interference test results

Under these conditions, data connectivity to the robot was only minimally impacted. Successful packet reception dropped to about 85% on a couple of the robots. For the default setting of one gas reading per second, this represents fifty-one gas readings per minute.

Very Strong Adjacent Channel Interference

Additional tests were performed with interfering signals that were even stronger and that overlapped the frequencies in use by the robots. While this type of strong interference is unlikely to be generated by typical consumer products, it could occur from another public safety robot operating in close proximity.

In Figure 4, the interfering signal remained at a center frequency of 915 MHz and is 5 MHz wide (912.5 to 917.5 MHz). The power of the interfering signal was increased to be about 15 dB stronger than the robot signals.

Note that the interfering signal is now much wider at the bottom, below -63 dBm, than it was in the previous test. This is typically referred to as the “skirt” of the signal envelope. This is allowed in the regulations since the amplitude of this part of the signal is so much less than the main part of the signal. But the skirt of the interferer signal is now overlapping with (and interfering with) the much weaker robot signals, which are also down in the -50 to -60 dBm range.

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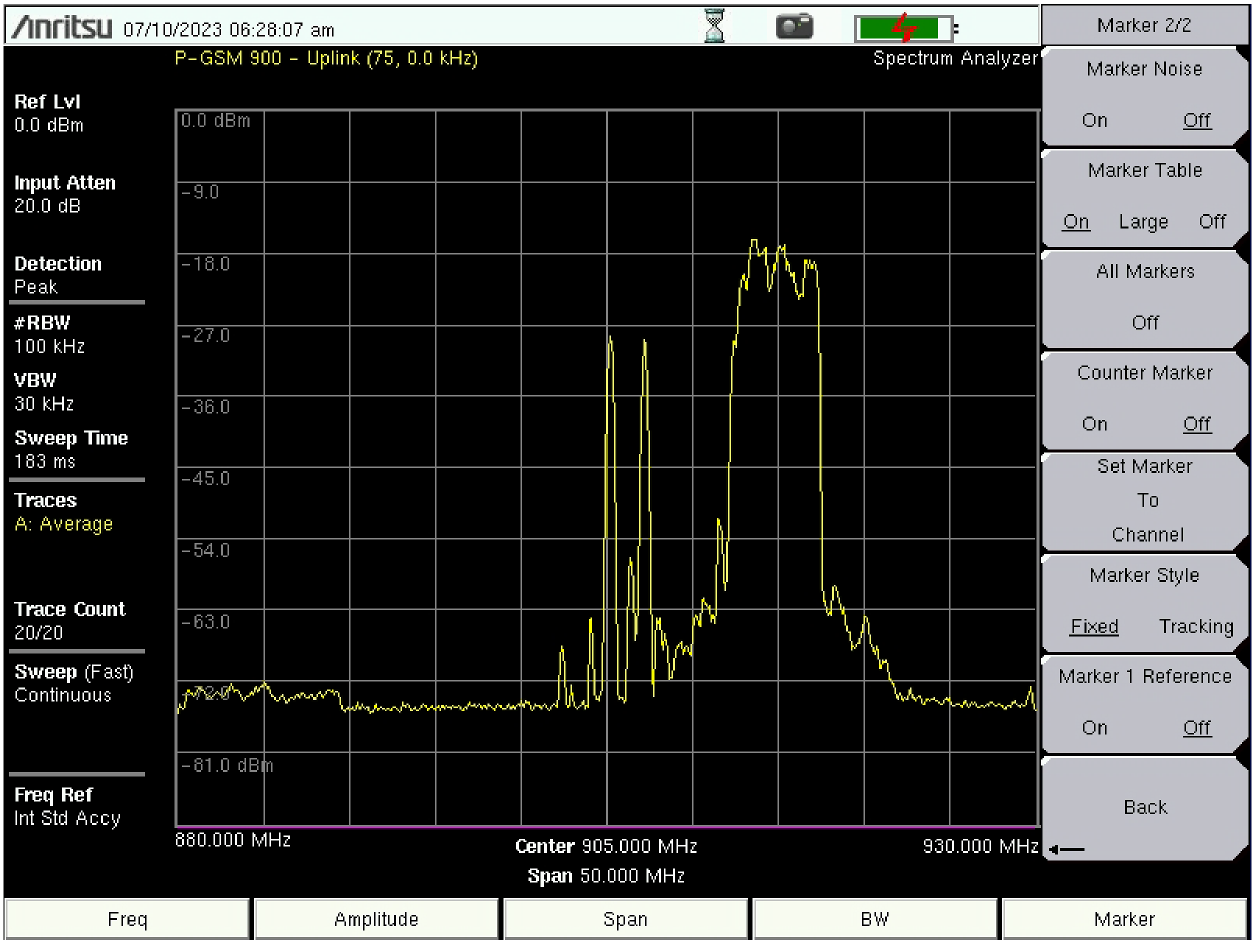

Anritsu 07/10/2023 06:28:07 am

P-GSM 900 - Uplink (75, 0.0 kHz)

Spectrum Analyzer

Ref Lvl 0.0 dBm

Input Atten 20.0 dB

Detection Peak

#RBW 100 kHz

VBW 30 kHz

Sweep Time 183 ms

Traces A: Average

Trace Count 20/20

Sweep (Fast) Continuous

Freq Ref Int Std Accy

Center 905.000 MHz

Span 50.000 MHz

Marker Noise: Off

Marker Table: On

All Markers: Off

Counter Marker: Off

Marker Style: Fixed

Marker 1 Reference: Off

Figure 4 Very strong adjacent channel interference results

Under these conditions, connectivity to robots was impacted. Some had intermittent connectivity while some stayed connected with only about 10-15% successful packet reception. For the default setting of one gas reading per second, this still represents 6-9 gas readings per minute.

Observations and Conclusions

Typical consumer products do not have the transmitter power or high-gain antennas used to generate these interference scenarios. Therefore, the most likely source of interference such as shown here will come from other licensed users and other nearby public safety devices, such as other robots. Proper frequency coordination can avoid or minimize this type of interference.

The frequency hopping nature of the Squishy Robotics System is a definite plus. Even if an interfering signal blocks some of the frequency range in use by the robots, some packets can still make it through as the robot’s transmitter hops to a different frequency.

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Adjacent Channel Interference Test – Video

Test Purpose

The 5.8 GHz FPV (First Person Video) band is used by a variety of drones and robots, ranging from consumer-grade toys to industrial and public safety devices. The band is channelized, as described below. But many of the channels overlap with the unlicensed WiFi band and the amateur radio band. And, depending on the size and nature of an hazmat or emergency incident, there could be several to many drones and robots deployed, including from multiple agencies. So, the ability to operate in close proximity to other FPV and WiFi signals is important.

This test was used to determine how well the Squishy Robotics System performs in the presence of other devices that are also operating in the same band and potentially close to either the robots or the base station. In order to do this, an interferer signal was created in the same band and adjusted in frequency and amplitude relative to the Squishy signals over the course of several tests. In addition, two Squishy robots were configured to operate on adjacent FPV channels.

FPV Video Background

The Squishy Robotics system uses the 5.8 GHz FPV (First Person Video) band to send video from the cameras onboard the robot to the receiver. This band is commonly used for sending video from drones and allows the consumer of the video to see the viewpoint of the drone. This can be extremely useful for public safety to get a first-person view of a remote, possibly hazardous situation.

Table 1 shows the various FPV sub-band channel assignments used by drone equipment. It also shows the range of frequencies allocated to Amateur Radio (the orange line at the top). This is significant because Amateur Radio operators may use much higher power (up to 1500 Watts) than consumer products. At the bottom of the chart, the spectrum used by 5.8 GHz WiFi is shown in blue. The chart also shows useful channel groups which avoid intermodulation interference (grey text at the bottom right).

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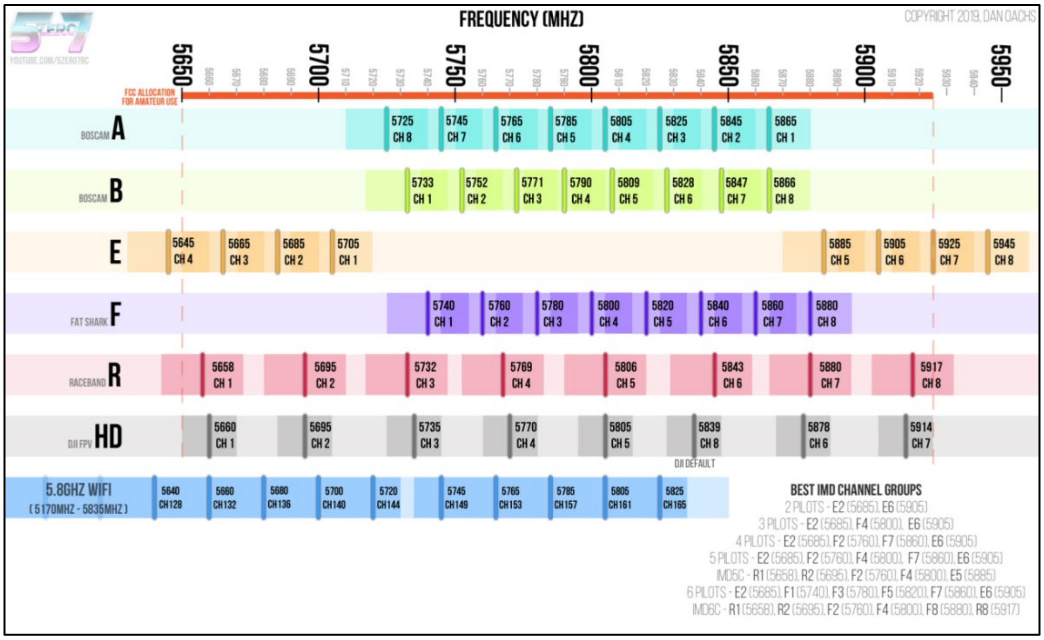

Table 1 First Person Video (FPV) sub-band channel assignments used by drone equipment.

Table 2 shows more details of the Wi-Fi channel assignments in the 5.8 GHz band. Note that Wi-Fi channels may be 20 MHz, 40 MHz, 80 MHz, or 160 MHz wide.

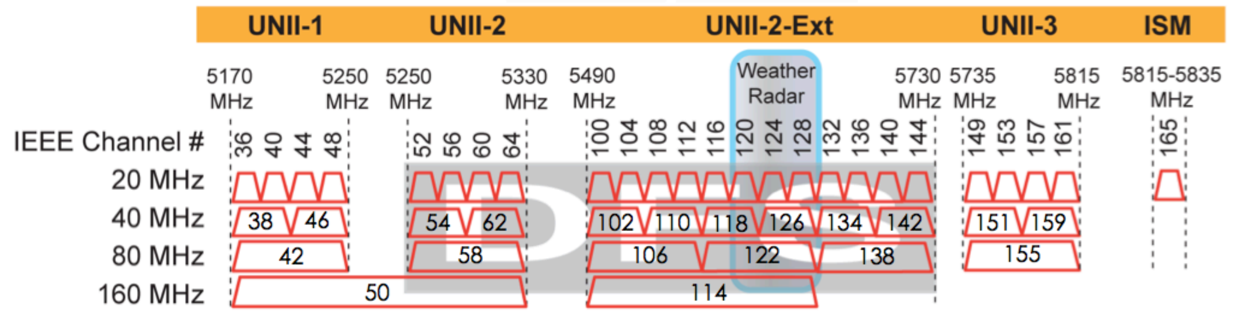

Table 2 Detailed chart of Wi-Fi channel assignments.

Interference Tests

Adjacent Channel Interference

An interference signal was generated using a 5.8 GHz Wi-Fi radio. The interfering signal was configured with a center frequency of 5845 MHz and a channel width of 10 MHz. The transmitter power and antenna direction were adjusted to make the amplitude the same as the Squishy video signal. The Squishy video signal was centered at 5865. The image below shows the two signals, with the interferer on the left and the Squishy video signal on the right.

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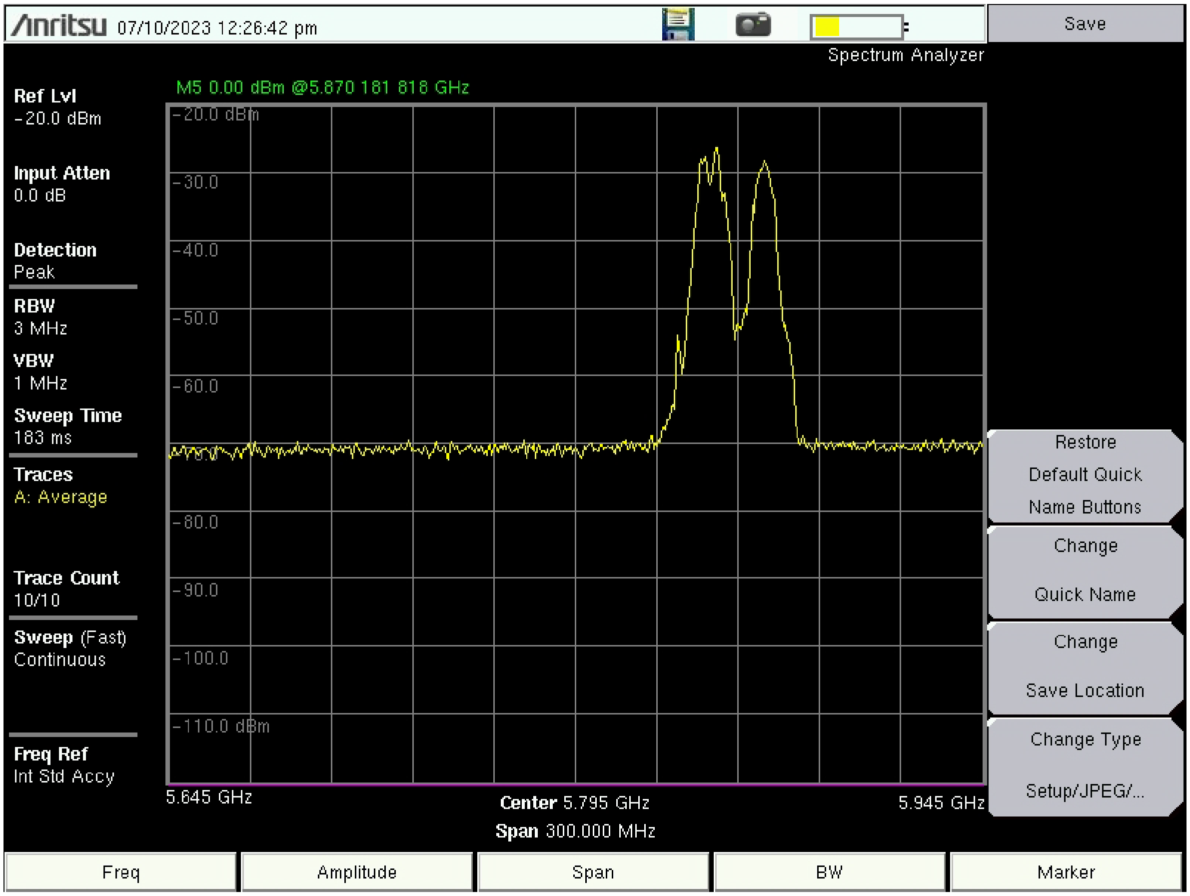

Anritsu 07/10/2023 12:26:42 pm

Spectrum Analyzer

M5 0.00 dBm @5.870 181 818 GHz

Ref Lvl -20.0 dBm

Input Atten 0.0 dB

Detection Peak

RBW 3 MHz

VBW 1 MHz

Sweep Time 183 ms

Traces A: Average

Trace Count 10/10

Sweep (Fast) Continuous

Freq Ref Int Std Accy

Center 5.795 GHz

Span 300.000 MHz

Figure 5 Graphic illustrating signal bleed during interference test

Figure 5 illustrates the two signals bleeding into each other at the skirts (wider areas at the bottom) of the signals. This area of the signal is approximately 30 dB below the signal peaks. So, a major portion of the information in the signal is still undisturbed. The Squishy video image exhibited some flickering and “snow,” but the video contents were still easily discernable.

Overlapping Channel Interference

The interferer signal was made more intrusive. It was configured with a center frequency of 5790 MHz and a 10 MHz wide channel width. The transmitter power and antenna direction were adjusted to make the amplitude the same as the Squishy video signal. The Squishy video signal was configured with a center frequency at 5800 MHz. Figure 6 shows the two signals, with the interferer on the left and the Squishy video signal on the right.

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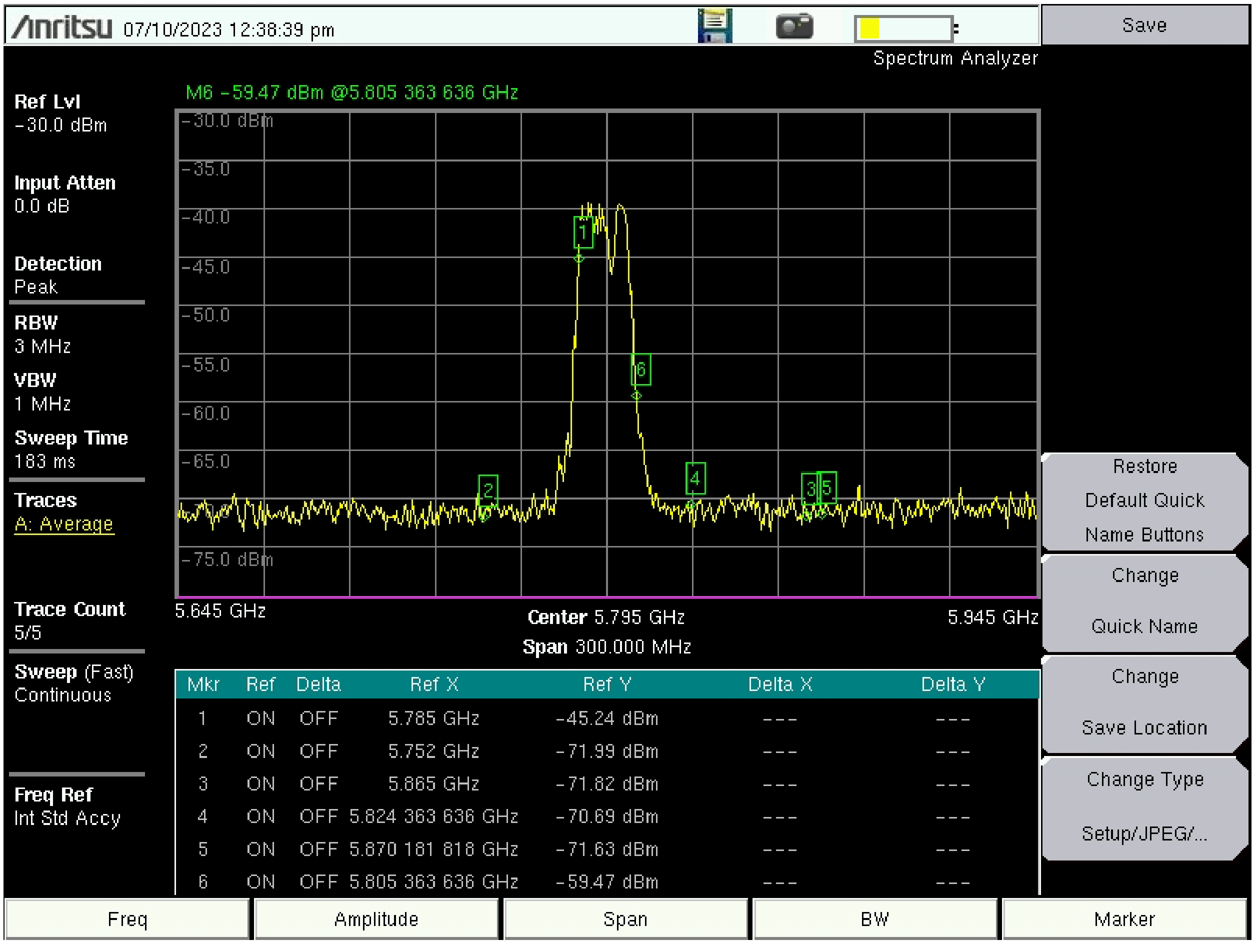

Ref Lvl -30.0 dBm
Input Atten 0.0 dB
Detection Peak
RBW 3 MHz
VBW 1 MHz
Sweep Time 183 ms
Traces A: Average
Trace Count 5/5
Sweep (Fast) Continuous
Freq Ref Int Std Accy
Center 5.795 GHz
Span 300.000 MHz

Mkr	Ref	Delta	Ref X	Ref Y	Delta X	Delta Y
1	ON	OFF	5.785 GHz	-45.24 dBm	---	---
2	ON	OFF	5.752 GHz	-71.99 dBm	---	---
3	ON	OFF	5.865 GHz	-71.82 dBm	---	---
4	ON	OFF	5.824 363 636 GHz	-70.69 dBm	---	---
5	ON	OFF	5.870 181 818 GHz	-71.63 dBm	---	---
6	ON	OFF	5.805 363 636 GHz	-59.47 dBm	---	---

Figure 6 Video interference test with two overlapping signals - the interferer on the left and the Squishy video signal on the right

The interferer signal overlaps about half of the Squishy video signal. Significant flickering and "snow" were observed in the received video signal, making the video contents unusable.

Adjacent Channel Video

The general recommendation for most RF systems is to avoid using adjacent channels when two devices are in close proximity. This is because the wider parts of the signals, which are at much lower power, are still powerful enough to interfere with each other when the devices are near each other. But given a crowded band, and the fact that multiple Squishy robots (and other drones and robots) may be deployed in a localized area, it is feasible that adjacent video channels may need to be used.

Two Squishy robots were configured to use adjacent video channels. A screen capture of the output at the base station is shown below.

Observations and Conclusions

Typical consumer or enterprise products do not have the transmitter power or high-gain antennas used to generate the Wi-Fi interference scenarios. Therefore, the most likely source of WiFi interference such as generated in these tests is from other licensed users and other public safety devices, such as other robots

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and drones, and other WiFi systems deployed at an incident. Proper frequency coordination can avoid or minimize this type of interference.

The Squishy Robotics System produced easily viewable video signals even in the presence of adjacent channel interference from WiFi or adjacent channel video from another Squishy robot. In fact, the ability of the Squishy receiver to accept video streams from two robots on adjacent channels with minimal signal degradation was surprising. This set of tests demonstrated the ability of the Squishy Robotics System to operate in a congested 5.8 GHz band.

Public Safety LMR Interference Test

Test Purpose

Public Safety LMR (Land Mobile Radio) is a major component of public safety communications. It is widely used by law enforcement, fire, medical, search and rescue, emergency management, and others at the local, county, state, tribal and federal levels.

Many of the personnel working within the ICP (Incident Command Post) will have a handheld radio with them which operates on one or more of these frequency ranges. These handhelds typically output 4-5 Watts of power when transmitting. If the ICP is in a remote location that lacks sufficient radio coverage, a communications vehicle containing one or more repeaters may be parked near the ICP to provide local coverage at the incident. These repeaters may transmit 50 to 100 Watts of power.

While these public safety radios are not operating in the 902-928 MHz band used by the Squishy Robotics System, the presence of strong transmitters can cause a receiver to experience fundamental overload, which will degrade the receiver's performance.

This test was designed to determine if the presence of either a strong transmitter near the ICP (such as a repeater or mobile radio) or a handheld radio located at the Squishy operating position would cause significant disruption to the ability to receive data from the Squishy robots.

Texas A&M Task Force 1 (TX-TF1) provided the radios and communications vehicle used in this test. TX-TF1 is one of the twenty-eight federal teams under the Federal Emergency Management Agency (FEMA)'s National Urban Search and Rescue (US&R) System.

Public Safety Frequency Bands

Public safety communications operate in the following frequency ranges:

- 25-50 MHz (VHF Low Band)
- 150-174 MHz (VHF High Band)
- 220-222 (220 MHz Band)
- 410-420 MHz (Federal LMR)
- 450-470 MHz (UHF Band)
- 758-769/788-799 (700 Broadband)
- 768-775/798-805 (700 Narrowband
- 806-809/851-854 (NPSPAC Band)
- 809-815/854-860 (800 MHz Band)

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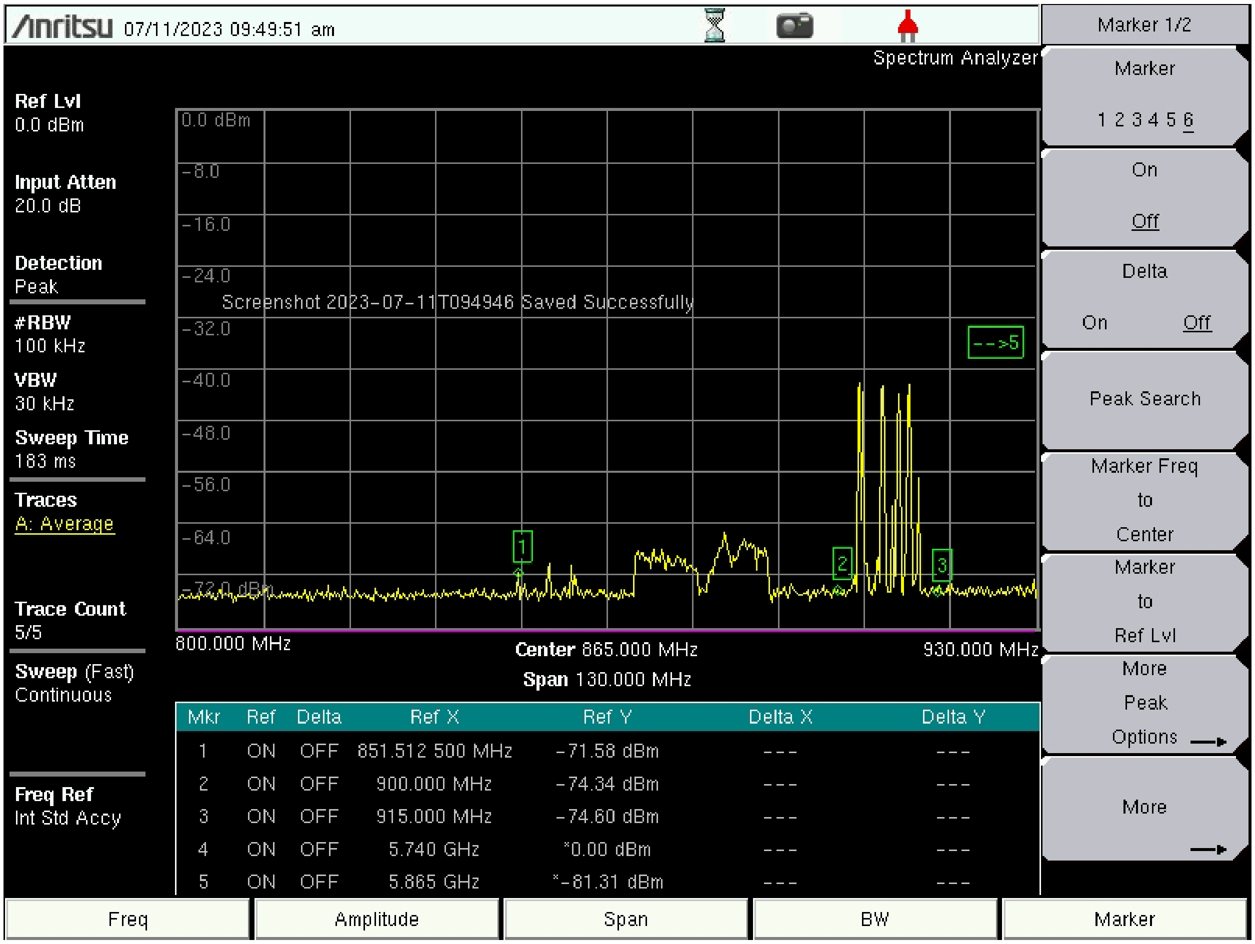
- 4940-4990 MHz (4.9 GHz Band)
- 5850-5925 MHz (5.9 GHz Band)

Baseline Conditions

Figure 7 shows the initial conditions prior to initiating the LMR interference tests. The robots were placed several hundred feet away at a derailed train training prop. Background noise was at about -75 dBm. The robots were set to use the lower end of the 902-928 MHz band. The transmissions of the robots and receiver can be seen in the image below, between markers 2 and 3.



Ref Lvl 0.0 dBm
Input Atten 20.0 dB
Detection Peak
#RBW 100 kHz
VBW 30 kHz
Sweep Time 183 ms
Traces A: Average
Trace Count 5/5
Sweep (Fast) Continuous
Freq Ref Int Std Accy
Center 865.000 MHz
Span 130.000 MHz

Mkr	Ref	Delta	Ref X	Ref Y	Delta X	Delta Y
1	ON	OFF	851.512 500 MHz	-71.58 dBm	---	---
2	ON	OFF	900.000 MHz	-74.34 dBm	---	---
3	ON	OFF	915.000 MHz	-74.60 dBm	---	---
4	ON	OFF	5.740 GHz	*0.00 dBm	---	---
5	ON	OFF	5.865 GHz	*-81.31 dBm	---	---

Figure 7 LMR Baseline Conditions

Interference Tests

Four types of tests were run using 400 MHz and 800 MHz radios:

- Handheld radio operated by the Squishy operator near the Squishy base station.
    - 400 MHz transmitting at 5 Watts.
    - 800 MHz transmitting at 4 Watts.
- Mobile radios located in Texas A&M Task Force 1 communications vehicle parked approximately fifty feet away from the Squishy base station.
    - 400 MHz transmitting at one hundred Watts.

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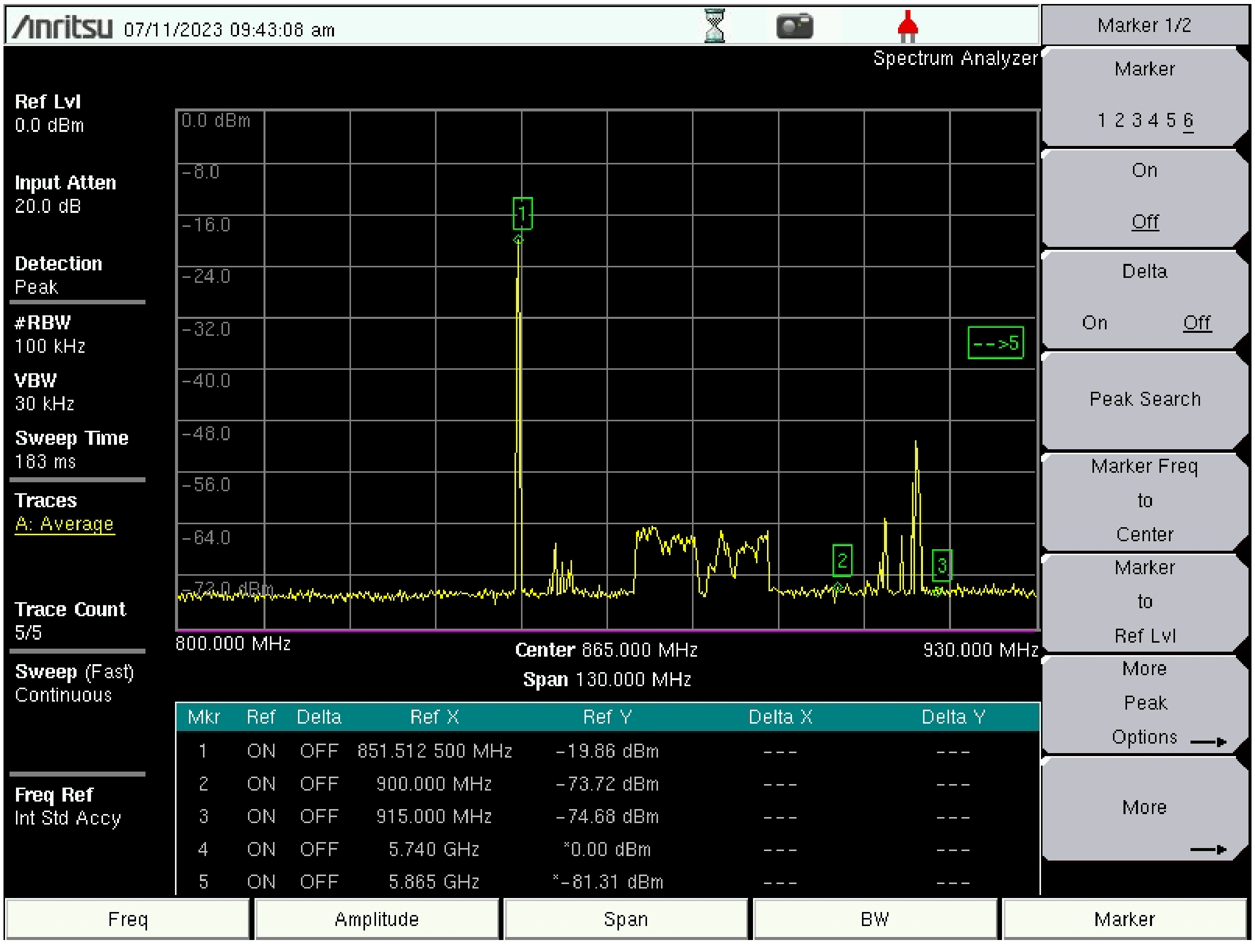
- ○ 800 MHz transmitting at 40 Watts.

Figure 8 shows one of the 800 MHz tests. The 800 MHz signal can be seen at marker one. The robots are between markers 2 and 3.



Ref Lvl 0.0 dBm

Input Atten 20.0 dB

Detection Peak

#RBW 100 kHz

VBW 30 kHz

Sweep Time 183 ms

Traces A: Average

Trace Count 5/5

Sweep (Fast) Continuous

Freq Ref Int Std Accy

800.000 MHz **Center** 865.000 MHz 930.000 MHz

Span 130.000 MHz

Mkr	Ref	Delta	Ref X	Ref Y	Delta X	Delta Y
1	ON	OFF	851.512 500 MHz	-19.86 dBm	---	---
2	ON	OFF	900.000 MHz	-73.72 dBm	---	---
3	ON	OFF	915.000 MHz	-74.68 dBm	---	---
4	ON	OFF	5.740 GHz	*0.00 dBm	---	---
5	ON	OFF	5.865 GHz	*-81.31 dBm	---	---

Figure 8 800 MHz LMR Interference test

Several tests like this were run using 800 MHz LMR.

Figure 9 shows one of the 400 MHz tests. The 400 MHz LMR signal can be seen at marker four. The robot transmissions are located between markers 2 and 3.

Ref Lvl 0.0 dBm

Input Atten 20.0 dB

Detection Peak

#RBW 100 kHz

VBW 30 kHz

Sweep Time 1.5 s

Traces A: Average

Trace Count 5/5

Sweep (Fast) Continuous

Freq Ref Int Std Accy

Center 665.000 MHz

Span 530.000 MHz

Mkr	Ref	Delta	Ref X	Ref Y	Delta X	Delta Y
1	ON	OFF	851.512 500 MHz	-73.63 dBm	---	---
2	ON	OFF	900.000 MHz	-73.38 dBm	---	---
3	ON	OFF	915.000 MHz	-72.87 dBm	---	---
4	ON	OFF	419.272 727 MHz	-14.78 dBm	---	---

Figure 9 400 MHz LMR test

Once again, several tests like this were run using 400 MHz.

No measurable impact to the Squishy data communications was observed when the interfering signal was generated by:

- Mobile radios in the TX-TF1 comms vehicle parked about fifty feet away.
  - One hundred Watt 400 MHz
  - 40 Watt 800 MHz
- Handheld radio operated at least 5-6 feet away.
  - 5 Watt 400 MHz
  - 4 Watt 800 MHz

If the 5 Watt 400 MHz handheld radio was held very near to the base station (within a few feet), and keyed up (put into transmit mode), the LMR signal would overload the Squishy base station's receiver and cause loss of connectivity. The 4 Watt 800 MHz radio interfered with the Squishy Base Station's background noise measurements, but not the connectivity throughput rates. This was not surprising and occurs with most other RF devices, as well.

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Observations and Conclusions

The operation of Squishy data communications was not significantly impacted by normal use of LMR radio in proximity to the Squishy base station, such as would be at an ICP. Data communications with the Squishy base station could be forced to fail by keying up a radio in very close proximity to the laptop. But performance returned to normal when the radio was moved away.

Background Noise Test

Test Purpose

The further a robot is from the base station, the weaker its signal will be when it reaches the base station. And the more communications equipment that exists at the ICP, the higher the noise floor will be at the base station. To, the purpose of the noise floor interference test is to determine how much stronger than the noise floor a signal from the robot needs to be for successful reception at the Squishy base station receiver.

Baseline Conditions

Baseline signal measurements were made prior to introducing interference. The first step for measuring the baseline consisted of measuring the background noise level with all transmitters turned off. Next, the signal levels received from Squishy robots were measured after enabling the transmitters on the robots, which caused them to start beaconing in search of the base station.

Baseline Background Noise Level

The background noise at the ICP test location was measured for the entire 900 MHz ISM band (902 MHz to 928 MHz). The spectrum analyzer was set to a resolution bandwidth of 30 kHz to allow a fast sweep of the entire band (183 ms/sweep). Figure 10 shows that the background noise condition was uniform across the entire band at approximately -80 dBm.

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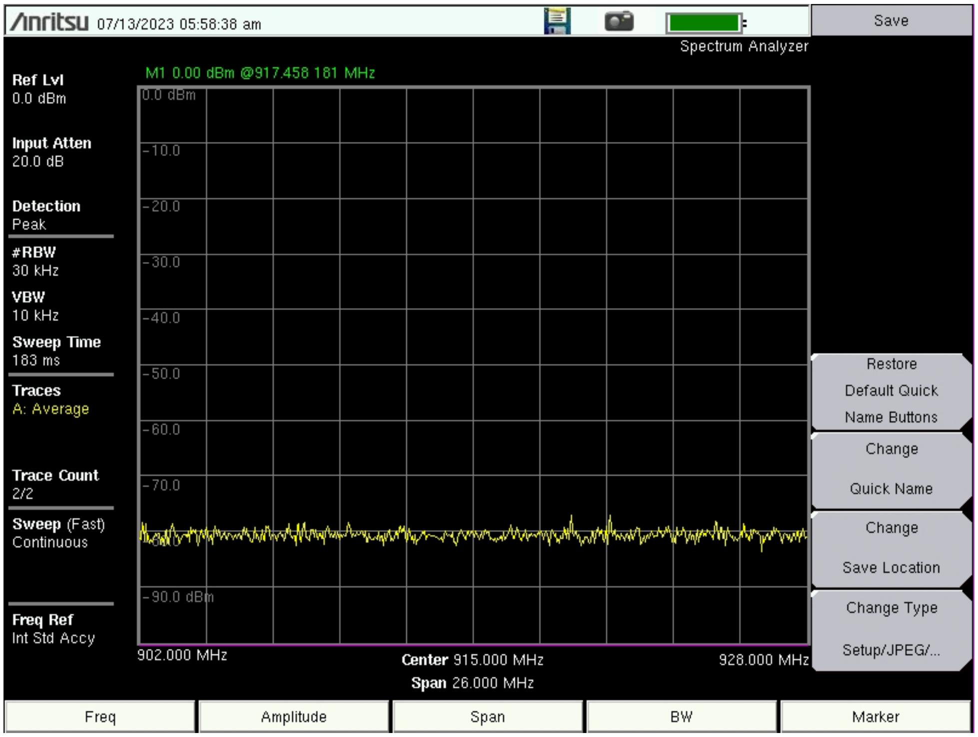

Anritsu 07/13/2023 05:58:38 am

Spectrum Analyzer

M1 0.00 dBm @917.458 181 MHz

Ref Lvl 0.0 dBm

Input Atten 20.0 dB

Detection Peak

#RBW 30 kHz

VBW 10 kHz

Sweep Time 183 ms

Traces A: Average

Trace Count 2/2

Sweep (Fast) Continuous

Freq Ref Int Std Accy

Center 915.000 MHz

Span 26.000 MHz

Figure 10 Background noise test

Baseline Received Signal Level from Robots

The Squishy robots were turned on and started to beacon to discover the base station. They were set to use frequencies in the upper end of the band. Since the Squishy radios perform frequency hopping, the spectrum analyzer was set to max hold to capture the beacons as the frequency values changed. Figure 11 shows that the beacons from the robots peaked at about -30 to -35 dBm.

In a real deployment, the robots would be stationed further away from the base station receiver, resulting in weaker signals received at the base station receiver and a lower signal to noise ratio to defeat with additional noise. Several such configurations were evaluated, as described elsewhere in this document. But such tests introduce other variables, such as obstructions, multipath, and other, external noise sources that could hamper the repeatability of this test. So, this test used a simpler physical configuration to focus on interference from background noise and minimize other variables.

Baseline Signal to Noise Ratio (SNR)

The Signal to Noise Ratio (SNR) is a key metric used to compare the level of the desired signal to the level of background noise. It is expressed as the ratio of the Power of the signal to the Power of the Noise, where the power is typically measured in Watts:

$$\mathrm{SNR} = P_{\mathrm{signal}} / P_{\mathrm{noise}}$$

SNR can be expressed in decibels as:

$$\mathrm{SNR_{dB}} = 10\log_{10}\left(P_{\mathrm{signal}} / P_{\mathrm{noise}} \right)$$

When the signal and noise measurements are already in decibels, then:

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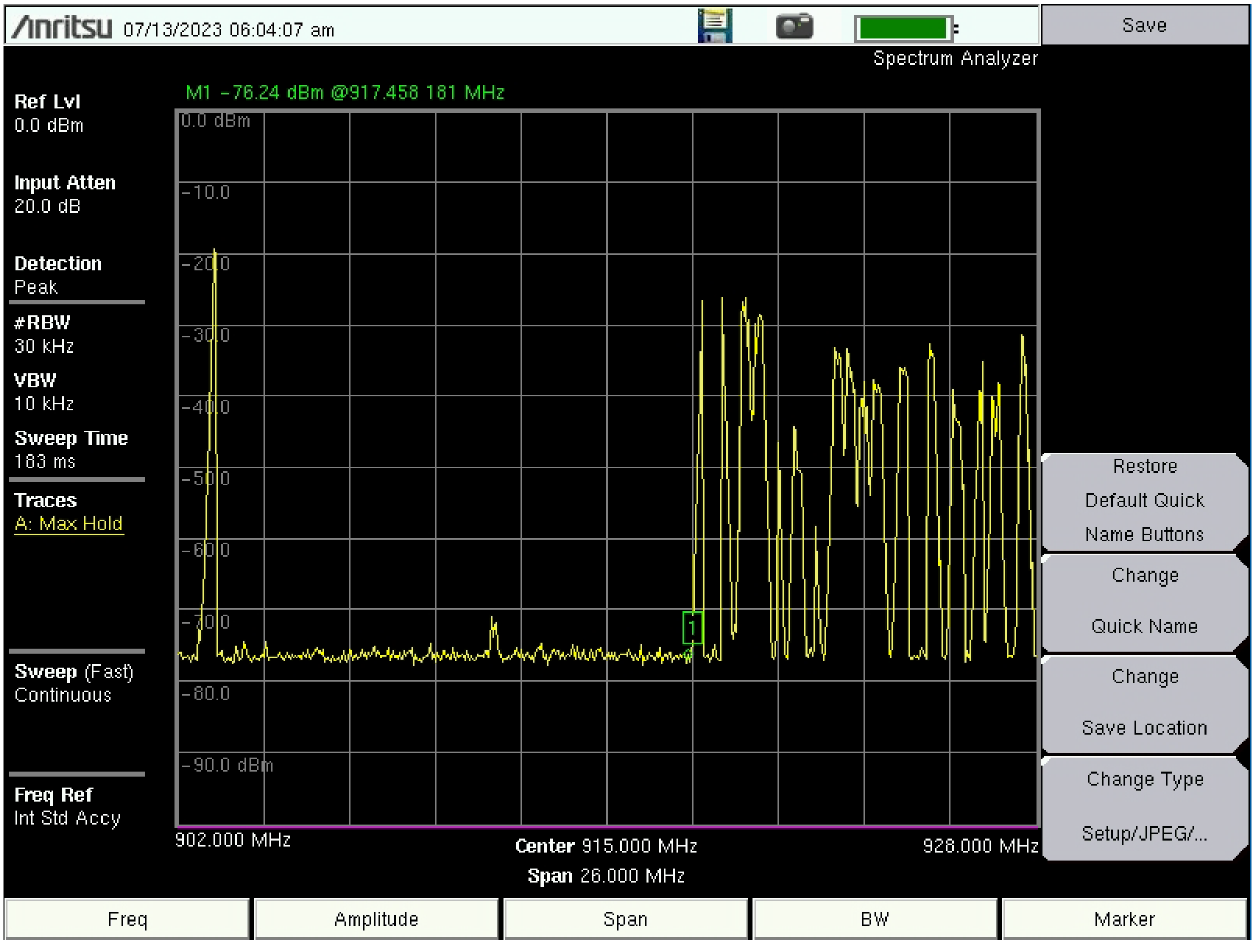
$$SNR_{dB} = P_{signal,dB} - P_{noise,dB}$$

For initial baseline measurement, the background noise level was approximately -80 dBm. The Squishy robot beacon signals were received at the ICP test location at approximately -30 to -35 dBm. So, subtracting the noise from the signal level, we get an SNR_{dB} of approximately 45 to 50 dB.



07/13/2023 06:04:07 am

Spectrum Analyzer

M1 -76.24 dBm @917.458 181 MHz

Ref Lvl
0.0 dBm

Input Atten
20.0 dB

Detection
Peak

#RBW
30 kHz

VBW
10 kHz

Sweep Time
183 ms

Traces
A: Max Hold

Sweep (Fast)
Continuous

Freq Ref
Int Std Accy

Center 915.000 MHz
Span 26.000 MHz

Figure 11 Baseline signals from robots

Interference Tests

As determined in the previous baseline measurements, the margin to overcome in the test scenario is 35 to 40 dB.

One way to conduct this type of test would be to move the robots further and further away from the base station, thereby causing their received signal to be weaker and weaker. Repeatability using that methodology is difficult because terrain, obstructions, and other sources of interference located further away can impact the measurements, making them less valid for other locations.

For maximum repeatability, these interference tests were constructed as follows:

- The robots were located a short distance away from the base station receiver.
- A spectrum analyzer was placed on the table next to the Squishy base station to measure the local RF condition and signals received from the robots at the Squishy base station.

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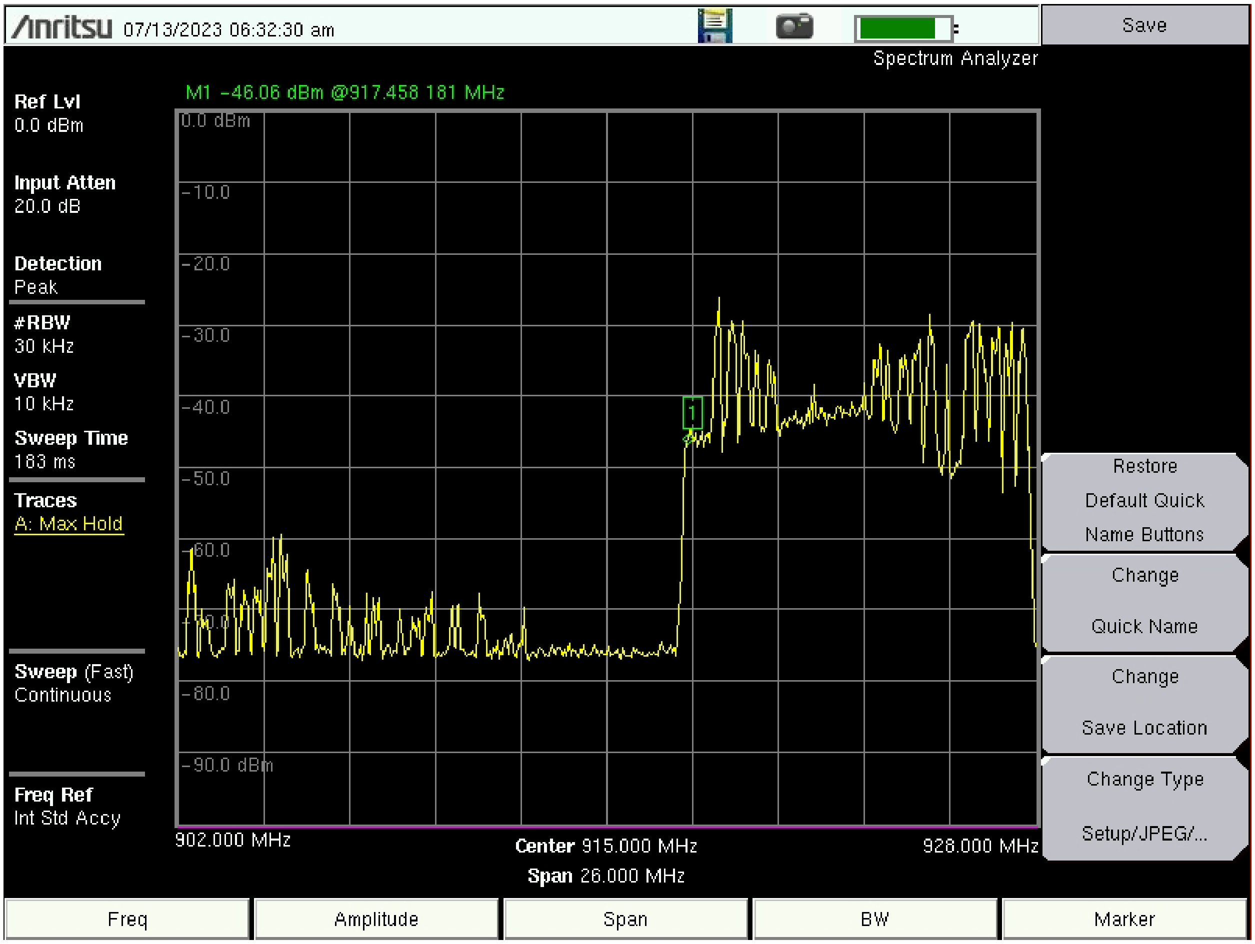
- Since the Squishy robots use the 900 MHz band for sending sensor data, a 900 MHz WiFi Access Point radio was used to generate broadband interference. The Wi-Fi signal is wide and flat, making it suitable for raising the noise floor across the section of the band used by the robots.
- The Squishy robots were configured to use the upper end of the 900 MHz band. So, the interference radio was set to a center frequency of 922 MHz and a channel width of 10 MHz, thereby creating a shelf of noise from 917 to 927 MHz.
- A directional antenna was attached to the interference radio. By adjusting the direction of the antenna and the power level of the transmitter, the amount of interference seen at the Squishy base station could be adjusted in as small as 1 to 2 dB increments.
- The interference radio was powered on and a series of measurements were made as the noise floor was gradually raised.

10dB Margin

Figure 12 shows the background noise level in the upper portion of the band has been raised by about 40 dB to approximately -43 dBm. The robot beacon signals are peaking at about -35 to -30 dBm. Therefore, the signals received from the robots were only 10dB above the noise floor.



07/13/2023 06:32:30 am

Spectrum Analyzer

M1 -46.06 dBm @917.458 181 MHz

Ref Lvl 0.0 dBm

Input Atten 20.0 dB

Detection Peak

#RBW 30 kHz

VBW 10 kHz

Sweep Time 183 ms

Traces A: Max Hold

Sweep (Fast) Continuous

Freq Ref Int Std Accy

902.000 MHz

Center 915.000 MHz

Span 26.000 MHz

928.000 MHz

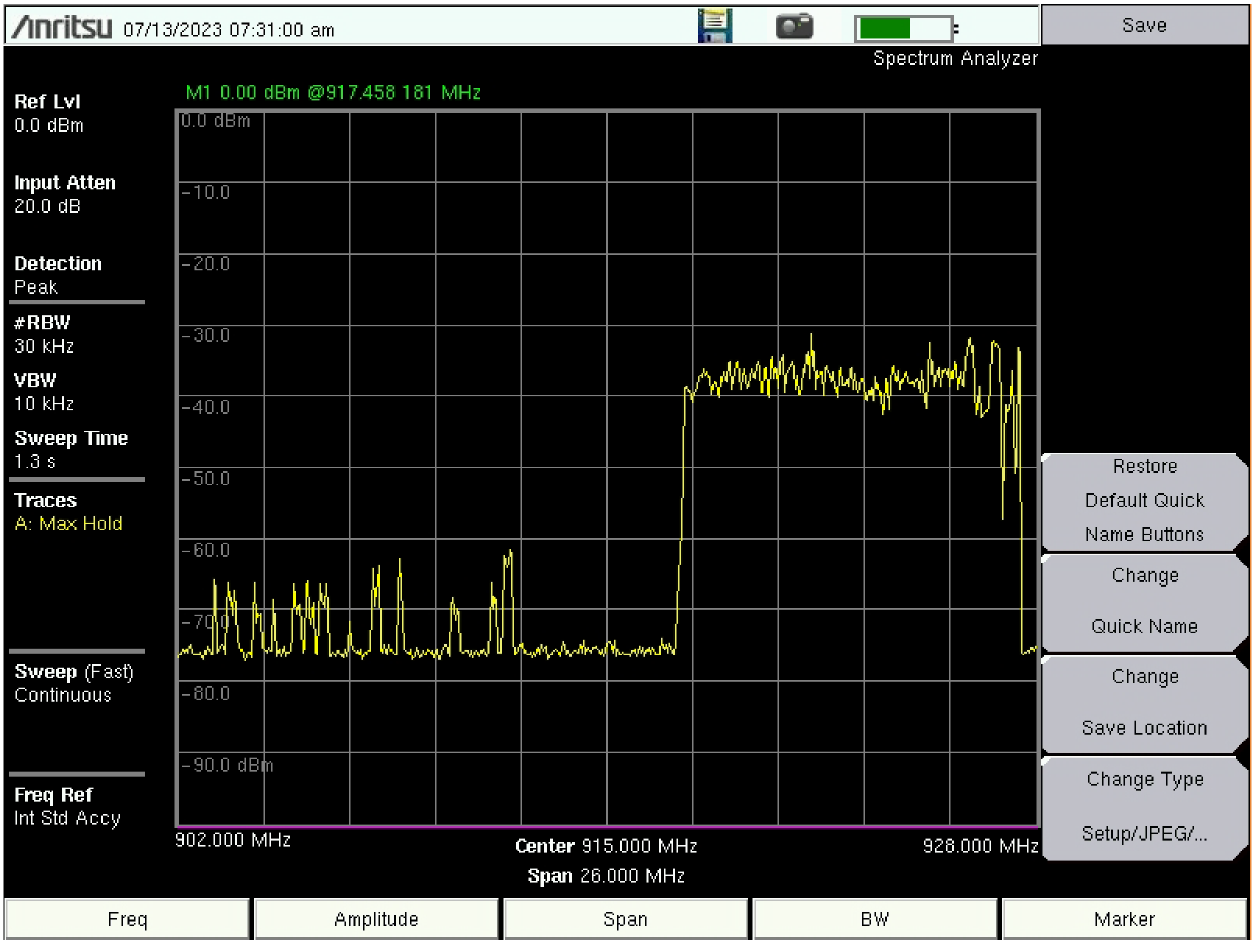
Figure 12 Interference test @ 10dB margin

Under these conditions, the Squishy receiver recorded a successful packet delivery rate from the two robots of 98% and 86%, respectively. Recall that the robot sends a 4-gas reading every second. So, the two measurements mean:

- 98% packet reception means that 59 readings were received in the past minute.
- 86% packet reception means that 52 readings were received in the past minute.

5-7 dB Margin

The interference signal was adjusted to bring the noise floor up to approximately -37 dBm. As a result, the peaks of the Squishy robot beacon signals were only 5-7 dB above the noise floor. Figure 13 illustrates the beacon signal spikes are still visible above the noise.



Anritsu 07/13/2023 07:31:00 am

Spectrum Analyzer

M1 0.00 dBm @917.458 181 MHz

Ref Lvl 0.0 dBm

Input Atten 20.0 dB

Detection Peak

#RBW 30 kHz

VBW 10 kHz

Sweep Time 1.3 s

Traces A: Max Hold

Sweep (Fast) Continuous

Freq Ref Int Std Accy

Center 915.000 MHz

Span 26.000 MHz

Figure 13 Beacon signal spikes @ 5-7dB margin

Under these conditions, the valid packets measured from the two robots was 70% and 98%, respectively. The discrepancy is accounted for by the difference in antenna orientation that was previously observed. Recall that by default the robot sends a 4-gas sensor reading every second. So, the two measurements mean:

- 98% packet reception means that 59 readings were received in the past minute.
- 70% packet reception means that 42 readings were received in the past minute.

3-5 dB Margin

The interference signal was adjusted to bring the noise level up to approximately -35 dBm. As a result, the peaks of the Squishy robot beacon signals were only 3-5 dB above the noise floor. In Figure 14, the beacon signal spikes are just barely visible above the noise.

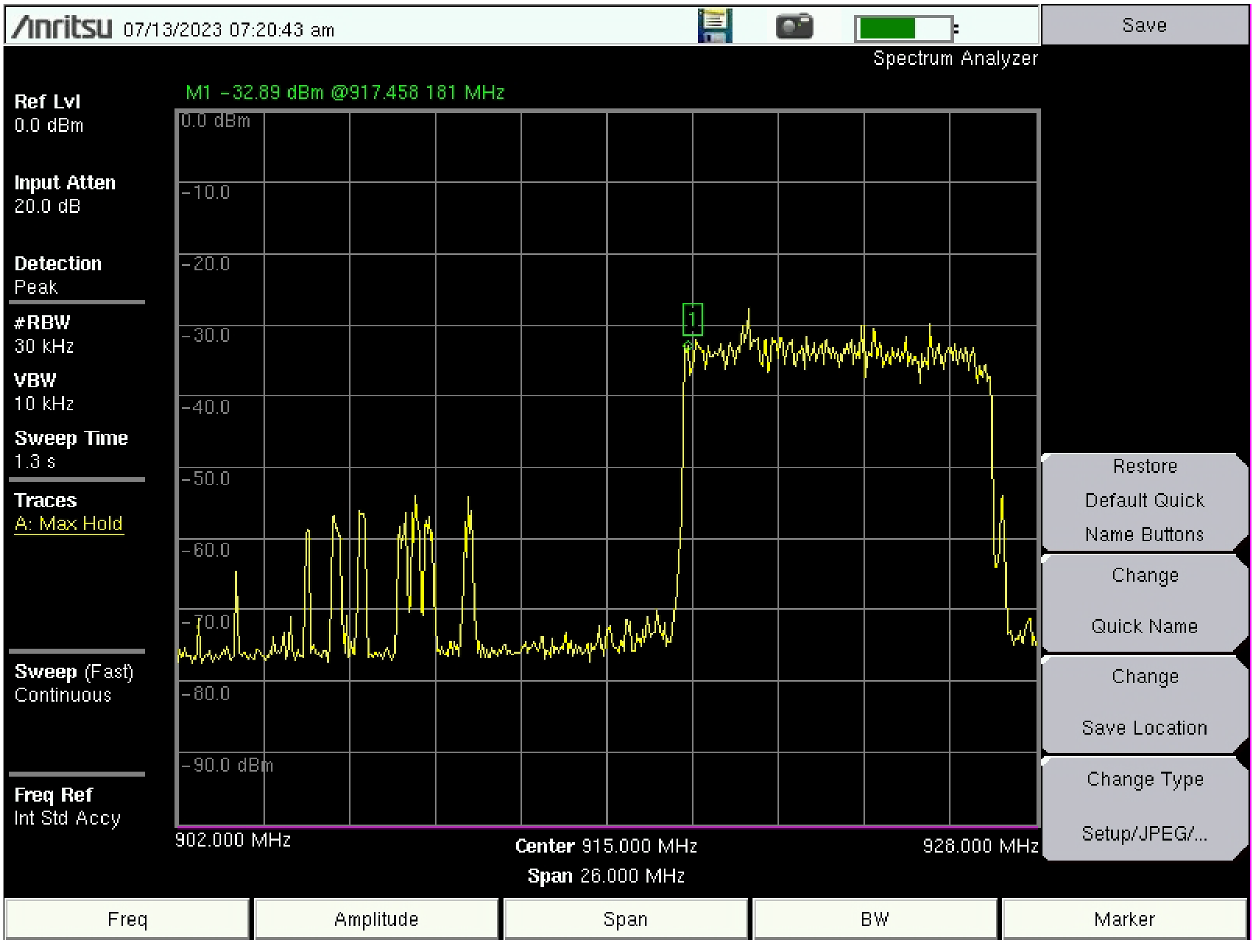

/\nritsu 07/13/2023 07:20:43 am
Spectrum Analyzer
M1 -32.89 dBm @917.458 181 MHz
Ref Lvl 0.0 dBm
Input Atten 20.0 dB
Detection Peak
#RBW 30 kHz
VBW 10 kHz
Sweep Time 1.3 s
Traces A: Max Hold
Sweep (Fast) Continuous
Freq Ref Int Std Accy
Center 915.000 MHz
Span 26.000 MHz

Figure 14 Interference tests 3-5 dB Margin

Under these conditions, the valid packets measured from one of the robots was only 10%, while the other robot was at 82%. The discrepancy is accounted for by the difference in antenna orientation that was previously observed.

Recall that by default the robot sends a 4-gas sensor reading every second. So, the two measurements mean:

- 82% packet reception means that 49 readings were received in the past minute.
- 10% packet reception means that 6 readings were received in the past minute.

Observations and Conclusions

The noise floor was raised repeatedly until the packet reception rate dropped to 10%. This occurred for one of the robot antenna orientations when the robot signals were only 3-5 dB above the noise floor. This is quite a small margin. And given the ability of the robots to automatically create a mesh and relay from

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one robot through another to reach the base station, it means that the robots should be capable of being deployed even in very challenging RF environments.

About Internet2 Technology Evaluation Center (ITEC)

Since 2004, the Texas A&M University ITEC has focused on evaluating emerging technologies and their real-world applications for critical communications, infrastructure, and data interconnectedness. As an applied research center, ITEC has been instrumental in the development of Next Generation 911 (NG 911), public safety broadband technologies, cyber security enhancements for mission critical networks, and industry collaboration events and exercises aimed at proving next generation interoperable communications. Texas A&M ITEC convenes government, industry, practitioners, and academia, creating collaborative teams to identify problems, define solutions, and get technologies in the hands of first responders and other front-line professionals for test and evaluation. The aim of every effort is to advance the practical use of communications technologies to benefit communities, public safety, and national security.

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Appendix B:

Communications Terrain-Obstruction Range Test Report

This work was performed under the following financial assistance award 70NANB22H209 from

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Communications Terrain-Obstruction Range Test Report

Testing Overview

Technical Background

Squishy Robotics' sensor platform provides impact resilience that safeguards a sensor payload within an outer tensegrity (tensional integrity) structure. Although the sensor payload can be customized with different sensors, the standard 4-Gas^{PLUS} sensor payload is a multi-modal sensor optimized for situational awareness in Hazardous Materials (HazMat) operations. This payload is equipped with LEL, O_2, CO, H_2S sensors, six cameras, and GPS and can communicate chemical sensor and visual data to remote response teams in real-time. The sensor payload's mesh networking capabilities enable transmission even in areas with no cellular coverage and/or in zones with communications infrastructure damage. Sensors can be deployed from aerial vehicles, dropped by machine, or manually thrown, tossed, or placed into position.

Fig. 1: Drone carrying a 4-Gas^{PLUS} sensor

The Squishy Robotics 4-Gas^{PLUS} sensor is specifically intended to perform an initial assessment of a HazMat scene to provide situational awareness to first responders, enabling them to make better and more appropriate decisions. With the Squishy Robotics platform, first responders can rapidly position sensors into locations to improve situational awareness—enabling downrange deployment without the need for responders' physical intervention in potentially dangerous areas. Manual deployment is also useful enabling sensors to be thrown over walls, around corners, or into inaccessible rooms. Numerical chemical sensor and visual data are communicated back to response teams remotely, in real-time, via one of several different communications pathways. Many of these pathways are not reliant on existing communications networks, which may be unavailable in an emergency response scenario.

Fig. 2: Squishy 4-Gas^{PLUS} sensors deployed in petro/chemical plant environment.

The ruggedized Squishy Robotics' Sensor Platform enables the rapid deployment of sensors to provide additional data to First Responders. However, deployment of sensors is only the first step

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to improving situational awareness. To truly improve situational awareness and support data-driven decision making, this time-critical, life-saving data needs to be communicated back to First Responders. This communication of data consists of both the reliable transmission of data to first responders (often in less-than-ideal situations) and the presentation of data in a way that is easily digestible and actionable.

Testing Objectives

The purpose of this test was to determine how well the Squishy Robotics system transmits numerical gas sensor and video data in a variety of operationally relevant environments with varying levels of man-made and terrain obstructions (such as rubble piles, derailed train cars, tunnels, structures) that can interfere and/or block communications pathways.

To determine the strength and the quality of the wireless signals from the deployed sensors, the following data were collected from each sensor deployed in various sensor placement configurations:

- Packet Throughput - Percentage of data packets sent by the transmitting sensor which were received by the receiver (i.e., laptop situated at the Incident Command Post)
- RSSI values - Received Signals Strength Indicator values to assess the strength of the signal received by the receiver (i.e., the laptop situated at the Incident Command Post) from deployed sensors
- Sensor GPS - Global Positioning System data to identify the location of deployed sensors
- Sensor Data Mesh Route - Indication of communication pathway from sensor to the laptop situated at the Incident Command Post (i.e., if data was being sent directly from sensor to the laptop, or if meshing occurred and which sensor(s) data was being pushed through)

Testing Goals

The overall objectives of this testing included the development of a Communications Connectivity Status Monitoring (CSM) Software to enable first responders with the ability to accurately assess connectivity status and strength beyond connected and not connected. Data and analysis from this testing will support the development of the CSM to determine ideal placement of sensors (and repeaters) for data transmission, detect potential interference from other devices, and mitigate interference through using instructions on how to change wireless bands used by the sensor payloads.

Method

Development of the Testing Plan

Emergency responses take place in vastly varying locations, often in areas with inadequate communications infrastructure. Based on the terrain of the response location and the possible presence of obstructions from man-made structures, the transmission of data from sensors deployed during a response effort to First Responders and incident commanders may be degraded. The effect of terrain on the transmission of data can vary from very minimal (i.e., outdoors with very few line-of-sight obstructions), to very significant (i.e., indoors, subterranean environments, or across extended ranges).

Emergency response scenarios were developed based on actual and probable emergency response events or situations. The SME panel developed each scenario as an example of an emergency incident with the use of the Squishy Robotics' 4-Gas$^{\text{PLUS}}$ sensors. The three scenarios represent the response options and tradeoff adjustments that first responders make when faced with terrain- or topography-related issues that can hamper response efforts. These scenarios motivated the development of the TEEX Testing plan and the identification of props and testing locations sites.

Scenario 1: Transport Related HazMat Scenario

Common response protocols require the rapid assessment of the scene to identify the potential hazard and risks, as well as establish continuous air monitoring of the response location and surrounding area. Oftentimes this requires a first responder to suit up in PPE (often a Level A HazMat Suit) and go into the crash area to install air monitoring equipment, assess the scene, and retrieve cargo manifests. Air monitoring is continuously used to assess the danger of a fuel/air explosion. Finally, depending on circumstances, steps may be taken to mitigate the scene, by closing valves, plugging leaks, grounding the chassis of the tanker, and de-fueling the tanks.

Fig. 3: Simulated tanker car train derailment

In this scenario, a fire department drone would deploy the Squishy Robotics 4-Gas$^{\text{PLUS}}$ sensor—dropping the sensor near to and downwind of the site of the leak/spill to perform the air monitoring and visual assessment missions. In such a transport scenario, the main communications challenge is range, as the Fire Truck and Incident Command Post (ICP) may be hundreds to thousands of yards distant from the site. Secondly, small obstructions such as trees, bushes, crash wreckage, Jersey barriers, and noise abatement barriers may interfere with communications. To perform the remote sensing mission successfully, communications must be guaranteed to transmit data.

Scenario 2: Industrial Plant HazMat Leak

Industrial chemical and petroleum plants are complex structures with steel structures and piping throughout. This scenario was designed to test communications reliability and ranges when Squishy Robotics 4-Gas^{PLUS} sensors are deployed within large metal structural areas. This environment causes electronic spectrum reflection, multi-path, blockage and scattering, affecting quality of data and range of the signal. Sensors could be deployed by hand, ground robot or UAV to provide initial situational awareness and gas detection and monitoring within a plant without endangering personnel.

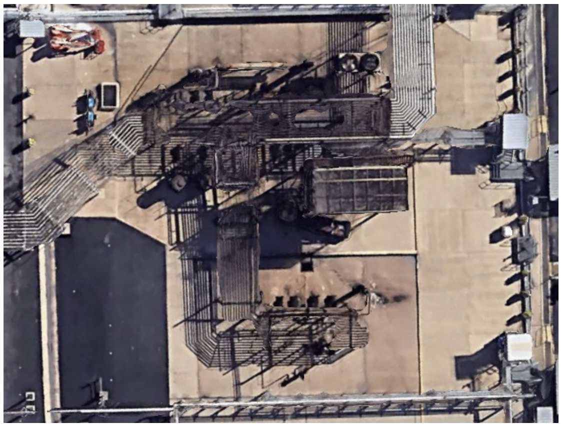

Fig. 4: Simulated Industrial Plant

Scenario 3: Industrial Storage Plant HazMat Leak

Chemical leaks in storage facilities are challenging environments where overhead observation and deployable sensors can be beneficial to quickly locate the source and product that is leaking. This is especially true in a nighttime situation.

Squishy Robotics 4-Gas^{PLUS} sensors deployment around and within the tank area was envisioned to provide basic situational awareness through its cameras and chemical sensors during the initial assessment phase. A ground-level view from within the tank farm, as opposed to a view from above the tank farm, may determine the source of the leak and monitor the area better than airborne in many situations.

Fig. 5: Simulated Chemical Storage Facility

In terms of communications challenges, this scenario was significant but did not require extreme range (estimated at 300 yards). Obstructions, such as concrete retaining walls and other storage tanks full of various liquids create multiple signal and data challenges.

Scenario 4: Confined Space Rescue

Tunnels and shafts create a difficult environment for rescue due to the communications and monitoring challenges. The communications daisy chain offered by a mesh network provides the means to “bread crumb” sensors and communications relays deep inside tunnels.

In this scenario, Squishy Robotics 4-Gas^{PLUS} sensors were deployed by hand into subterranean tunnels through access points and into tunnel junctions. The assessment tested video and sensor data connectivity throughout the tunnel system and to outside Squishy Robotics 4-Gas^{PLUS} sensors and/or relays to an incident command post. The scenario demonstrates the capability to detect and monitor gas levels and provide video of the structure for situational awareness, possible leak points and rescue planning.

Fig. 6: Tunnel, interchange

Fig. 7: Tunnel Access Point

Selection of TEEX Testing Props/Sites

Considering the scenarios listed above, representative operationally relevant testing props available at the TEEX Brayton Fire Training Field (Disaster City) and the Bush Combat Development Complex were selected. Testing props were selected to provide a variety of natural and manmade terrain obstructions, ranging from minimal to significant obstructions. The testing props selected are listed in the table below, from the minimal to significant obstructions.

Representative Response	Testing Prop/Site	Terrain-Obstructions Present
Train Derailment / Transportation Related HazMat Incident	Freight Train Derailment: Props 116/117	Minimal: outdoor response, natural terrain features such as drainage ditches and sloping terrain
Industrial Plant	Petro/chemical Plant: Props 42/43	Mid-level: outdoor response, man-made obstructions from surrounding metal and concrete structures
Storage Tank Farm	Bulk Storage Tanks	Mid-level: outdoor response, man-made obstructions from concrete structures and storage tanks
Underground Tunnel / Confined Space	Subterranean Tunnels: Bush Combat Development Complex	Significant: subterranean response, man-made obstructions from concrete tunnels

Methodology

The methodology for performing range tests at each testing prop was as follows:

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- **Step 1: SME Created Response Scenario** - Panel of First Responder subject matter experts with hazardous materials response expertise developed an emergency response scenario relevant to each testing prop. Panelists inspected props and discussed factors of the devised response scenario to determine a response plan such as the location of Incident Command and the ideal placement of air monitoring equipment for such a response effort.
- **Step 2: Baseline Background Noise** - The baseline background noise was measured and recorded as a comparison metric for each test. This data was collected by ITEC and Squishy Robotics.
- **Step 3: Baseline Sensor Connectivity** - Three to four Squishy Robotics sensors were positioned at the ideal deployment locations identified by the SME panelists in Step 1. The baseline connectivity data (percentage of packets received, RSSI values, sensor data mesh route) from each deployed sensor was recorded. This data was collected by Squishy Robotics.
- **Step 4: Incremental Repositioning of Sensors or Base Station** - The Squishy Robotics sensors were incrementally repositioned, placing sensors further and further from Incident Command until connectivity from each sensor to the Squishy Robotics UI positioned at Incident command was lost and meshing between sensors was not achieved. Connectivity data was recorded for each deployment location for each sensor. In select test conditions where the props did not facilitate very long-range tests, the base station was instead repositioned (carried by hand on a golf cart) to enable testing at further extended distances.

Results

Stationary tests represent tests where deployed 4-Gas^{PLUS} sensors and the ICP were situated at operationally relevant locations based on Subject Matter Expert input. Mobile tests were then conducted to maximize the transmission distance tested by the expedient of moving the ICP Laptop or deployed 4-Gas^{PLUS} sensors via a golf cart and may be less operationally representative than the fixed tests. The following sections present high level results from each testing prop/site.

Freight Train Derailment (Props 116/117, minimal terrain obstructions)

Fig. 8: Prop 116/117 Freight Train Derailment

Fig. 9: SME panelists discussing response scenario and sensor placement locations

Fig. 10: 4-Gas^{PLUS} sensor placed near identified potential leak site

Fig. 11: 4-Gas^{PLUS} sensor in drainage ditch to monitor for run-off

Test	Maximum Range (ft)	Transmission Success	Meshing Status
Stationary	943	95.6%	Direct
	809	96.3%	Mesh - 1 Hop Mesh 187 ft from sensor in culvert (no direct line of sight) to sensor with line of sight
Mobile	824	95.1%	Direct
	1460	***94.6%***	***Mesh - 1 Hop*** ***Mesh 759 ft from sensor deployed on perimeter to sensor with line of sight***
Train Derailment, Numerical Data Transmission Props 116/117, Minimal Obstructions			

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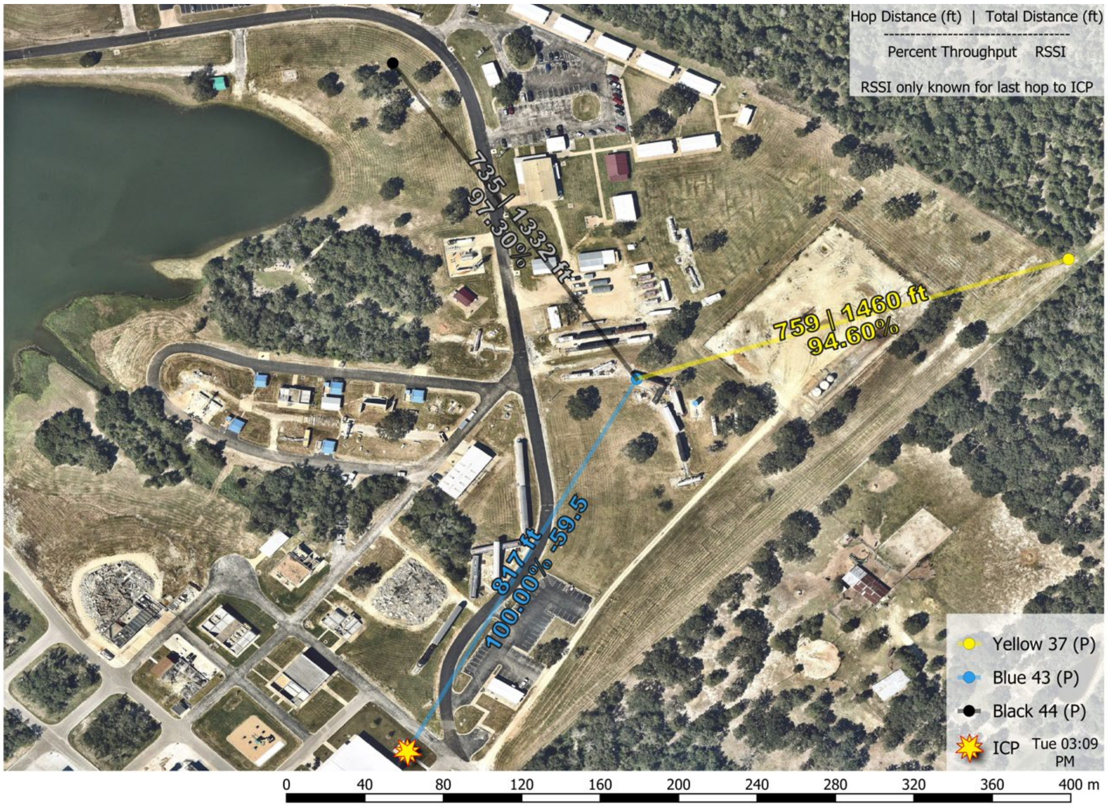

Fig. 12: Longest transmission range of 1460 ft recorded at Train Derailment prop (indicated in bold italic in table); achieved through 1-hop mesh

Petro/Chemical Plant (Props 42/43, mid-level terrain obstructions)

Fig. 13: Petro/Chemical Testing Prop

Fig. 14: SME panelists discussing response scenario and sensor placement locations

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Fig. 15: 4-Gas^{PLUS} sensor placed near potential leak site

Fig. 16: 4-Gas^{PLUS} sensor strategically placed in location surrounded by metal

Test	**Maximum Range (ft)**	**Transmission Success**	**Meshing Status**
Stationary	607	98.1%	Direct
	432	100.0%	Mesh - 1 Hop Mesh from sensor on ground to sensor on tower to avoid piping network
Mobile	851	89.1%	Direct
	2225	***46.9%***	***Mesh - 1 Hop*** ***Mesh 303 ft to sesnor on slightly higher terrain with better line of sight***
Petro/Chemical Plant, Numerical Data Transmission Props 42/43, Mid-Level Obstructions			

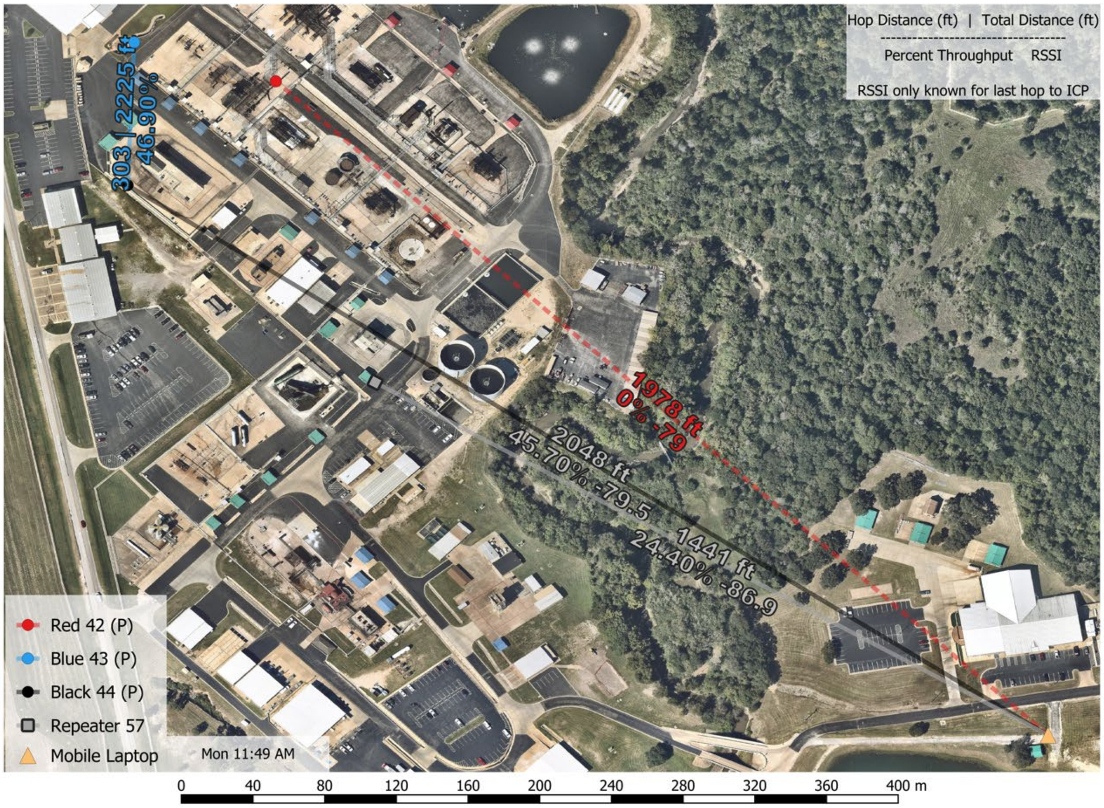

Fig. 17: Longest transmission range of 2225 ft recorded at petro/chemical plant testing prop (indicated in bold italic in table); achieved through 1-hop mesh

Bulk Storage Tanks (mid-level terrain obstructions)

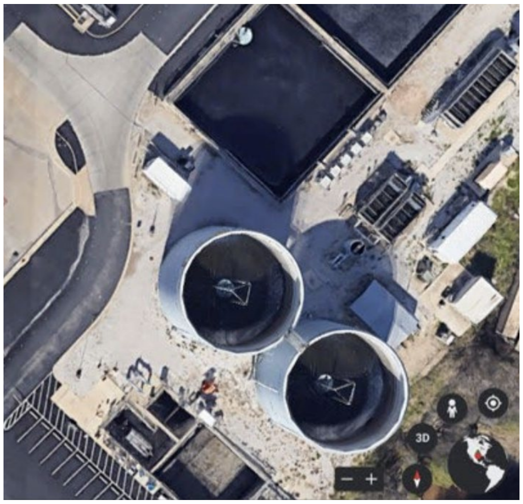

Fig. 18: Bulk storage tank testing prop

Fig. 19: SME panelists discussing response scenario and sensor placement locations

Fig. 20: 4-Gas^{PLUS} sensor deployed behind water storage tank

Fig. 21: RF interference data collection set-up at water tank storage testing prop

Test	**Maximum Range (ft)**	**Transmission Success**	**Meshing Status**
Stationary	412	98.7%	Direct
Mobile	855	53.7%	Direct
	1093	***94.5%***	***Mesh - 1 Hop*** ***Mesh 227 ft from sensor behind water tank to sensor with better line of sight***
Bulk Storage Tanks, Numerical Data Transmission Mid-Level Obstructions			

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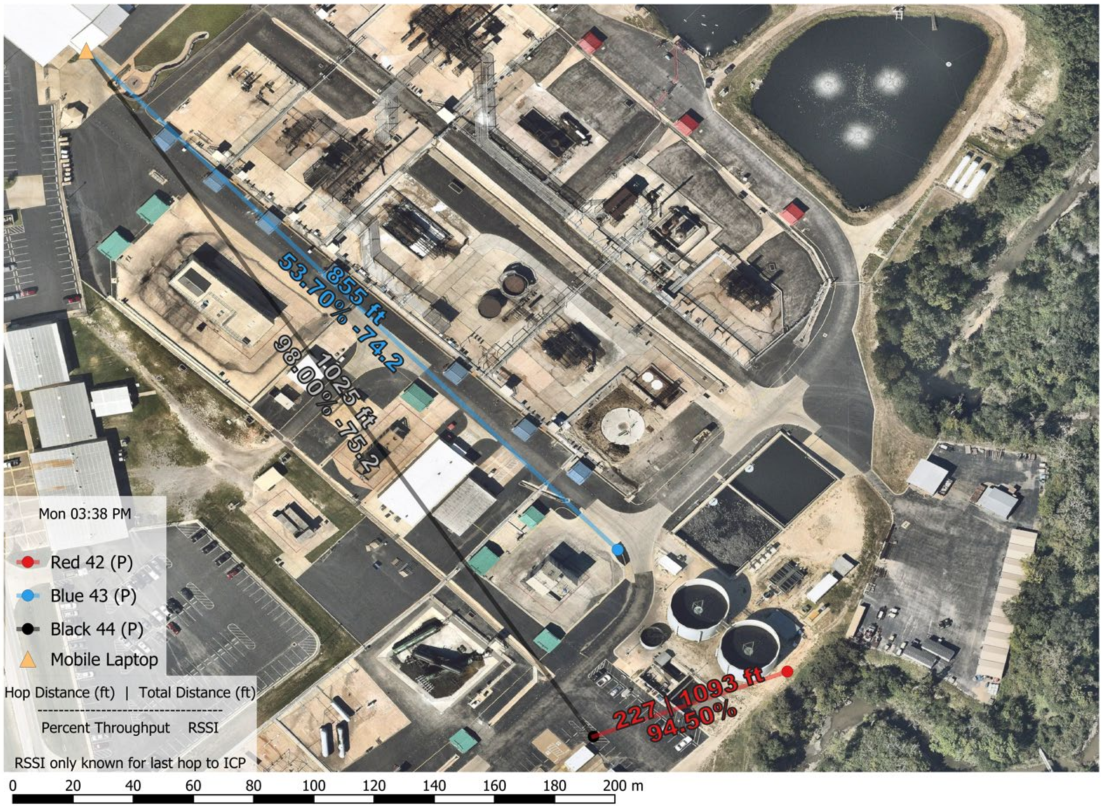

Fig. 22: Longest transmission range of 1093 ft recorded at Bulk Storage Tanks prop (indicated in bold italic in table); achieved through 1-hop mesh

Subterranean Tunnels (Bush Combat Development Complex, significant terrain obstructions)

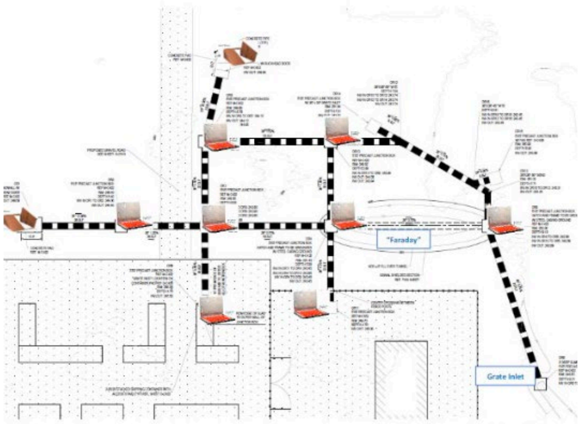

Fig. 23: Map of subterranean tunnels and Bush Combat Development Complex

Fig. 24: SME panelist assessment of response and sensor placement locations

Fig. 25: 4-Gas^{PLUS} sensor deployed at entrance of subterranean tunnel

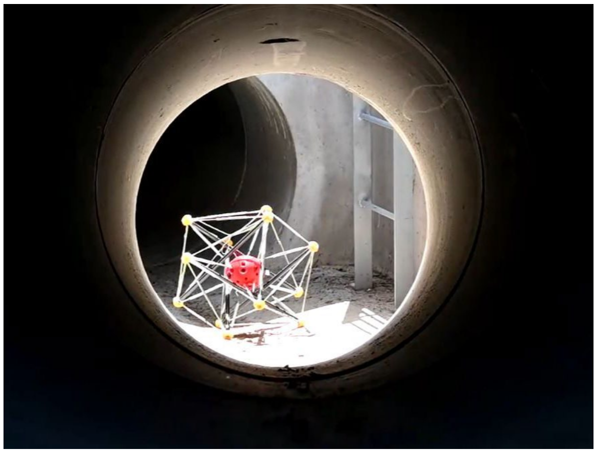

Fig. 26: 4-Gas^{PLUS} sensor deployed in subterranean tunnel

Test	Maximum Range (ft)	Transmission Success	Meshing Status
Stationary	62	97.7%	Direct Sensor in tunnel with shielding to simulate 20 ft deep tunnel in dirt
	83 ft	93.4%	Mesh - 1 Hop Mesh from sensor in tunnel to sensor at bottom of manhole access ladder
Mobile	77	98%	Direct Sensor at bottom of access ladder
	1717	***15%***	***Mesh - 2 Hops*** ***Mesh from sensor deep in tunnel network through intermediate sensor to sensor at ground-level exhaust port to ICP on hill***
Subterranean Tunnels, Numerical Data Transmission Bush Combat Development Complex, Significant Obstructions			

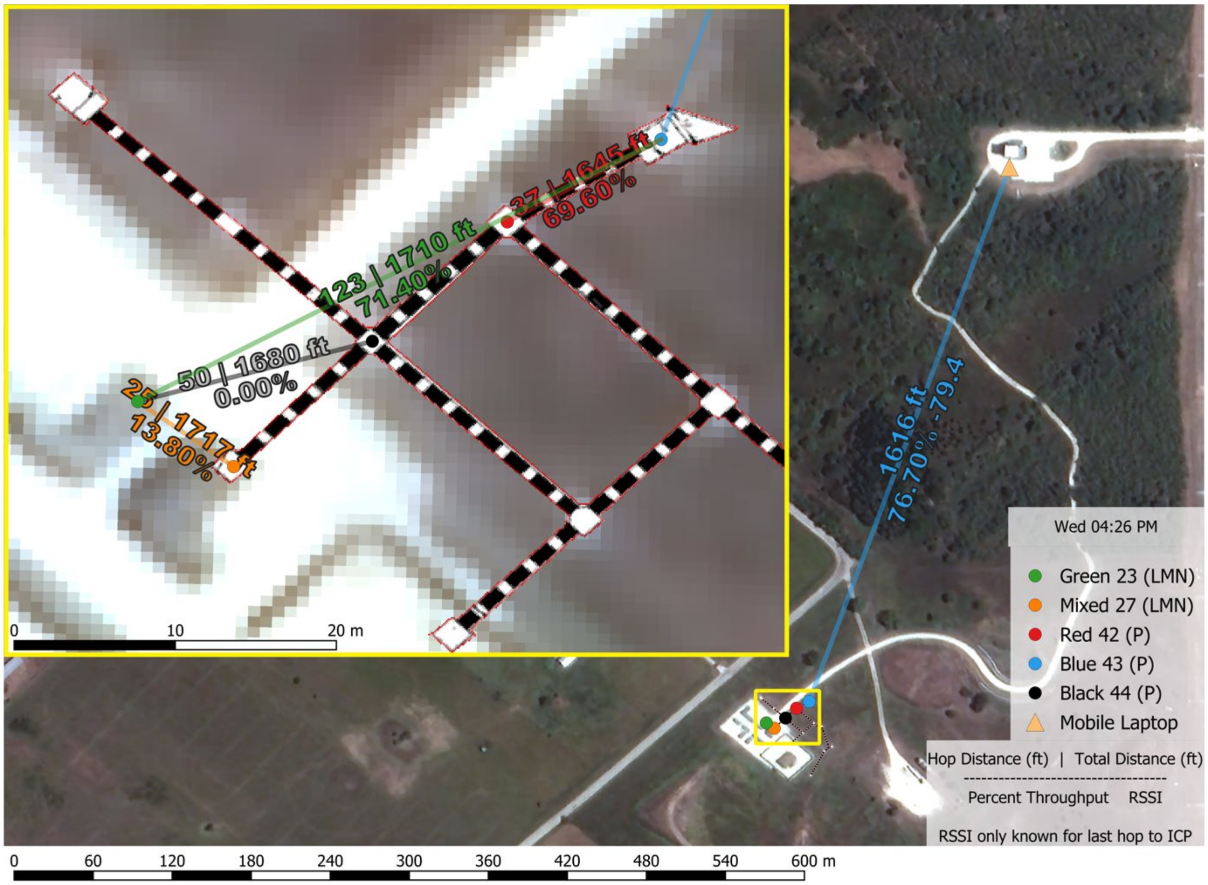

Fig. 27: Longest transmission range of 1717 ft recorded at subterranean tunnel complex (indicated in bold italic in table); achieved through 2-hop mesh

Summary

Communications terrain-obstructions range tests in a variety of operationally relevant environments showed that the Squishy Robotics 4-Gas^{PLUS} sensor could acceptably communicate numerical data back to the Squishy Robotics UI located at Incident Command under typical operational conditions at ranges from hundreds of 500 - 1500 feet. In some instances, communications were established at even further distances or around large obstacles utilizing the mesh capability of the Squishy Robotics sensor payloads. Specific ranges and performance varied from test to test due to the inherent terrain obstructions (varying from minimally obstructed to highly obstructed) from each test site.

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