Experimental Analysis of Radio Communication Capabilities of Multiple Autonomous Surface Vehicles

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***Abstract*—Autonomous exploration and rescue vehicles have been gaining wide interest over the past few years. Nowadays, demonstrations showed that those vehicles can fly, dive, surf, or drive while carrying out missions autonomously in some specific scenarios. Monitoring vehicles during missions is a crucial and challenging task to avoid the unnecessary cost of losing vehicles or potential accidents. In this paper, we present a cheap yet effective way for monitoring and communicating with autonomous vehicles over long distances by using off-the-shelf 900 MHz modems namely RFD900+ and high gain antennas. Although the 900 MHz band has been around for over two decades, no complete analysis exists providing guidelines to use off the shelf modems for point-to-point and multi-point communications. Our main contribution is to provide experimental analysis of the communication capabilities in point-to-point and multi-point scenarios in both line of sight (LOS) and non line of sight (N-LOS) using an affordable setup ($70 per modem). Experiments were carried out using autonomous surface vehicles (ASVs) as remote nodes and computers as Ground Control Stations (GCSs).**

I. Introduction

The rapid advancement in sensor modalities enables fleets of robots to carryout their missions autonomously and efficiently by maintaining reliable communication links between them and base-stations [1]. Robots nowadays are more sophisticated in terms of exploration capability (drive, fly, and dive autonomously) based on sensory data. However, monitoring exploring robots during a mission is still crucial to minimize potential loss (financially or injury in case of accidents). Hence, it is essential to provide low latency, reliable, and robust communication channels to ensure continuous and effective monitoring of autonomous robots during missions. The desirable range along with the number of nodes are the key factors that define the frequency band (VHF, UHF, SHF, etc.) to be used in the radio spectrum for communications. Several other factors contribute to degrading the quality of communications, such as, but not limited to, environmental noise and weather outdoors, and walls, obstacles, and spectrum overlap indoors.

Various technologies are widely used nowadays and have proven their effectiveness in communications. Some examples of these types of communications that can be seen in our daily lives are, Wi-Fi, Wimax, Zigbee, Bluetooth, etc. Although most of these wireless technologies allow bi-directional communications, they differ in several technical aspects such as communication range, bandwidth, data rate, latency, and are prone to noise. Additionally, an important aspect to consider is the cost factor. Therefore, driven by these observations, our work was done in an effort to use cheap off-the-shelf 900 MHz modems to test their capabilities for long range communications among a fleet of autonomous vehicles. It is worth mentioning that there exists 900 MHz industrial solution for long distance communication, e.g., AWK-3191 Series[1]. The aforementioned series can cover up to 30 km in line of sight (LOS) at 6 Mbps for point-to-point connection and 5 km in LOS for point-to-multi-point at the same rate. The cost for such a device ranges between $1999 - $2199.

Fig. 1. Jetyaks equipped with RFD900+ modems.

This paper presents a performance evaluation that can be used as a guide to understand the capability and reliability of long range communications. Such a study can then be used to establish a better network for a team consisting of multiple robots in marine environments, where network infrastructure might not be available and long range distance communication is necessary. We focus on communicating in the ISM Band (900 MHz) when experimenting indoors and outdoors, because of the low-cost/weight of the hardware, and the potential to cover longer ranges with better penetration through obstacles than higher frequencies. In particular, we use cheap, off-the-shelf Radio Frequency (RF) modems – Open Source RFD900+[2] (widely used for peer-to-peer telemetry communications). Several indoor and outdoor experiments

[1]https://www.moxa.com/doc/brochures/Brochure-AWK-3191.pdf/
[2]http://store.rfdesign.com.au/rfd-900p-modem/

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show how different network configurations affect the quality of communication in terms of latency, range, data rate and RSSI (Received Signal Strength Indicator) value. Specifically, in indoor environments we assume stationary robots due to limited space. In outdoor environments, experiments were conducted by mounting RFD900+ hardware on a fleet of Autonomous Surface Vehicles (ASV) masts (expanding on the WHOI Jetyak [2]); see Fig. 1. Different experimental dimensions, including the number of robots and the network topology with a base station, have been evaluated. The main contribution of this paper is to give an insight of the different setups that can be easily adopted when monitoring autonomous vehicles using basic hardware and how to optimize and tune parameters to achieve higher throughput and range. We also provide a fruitful comparison between the quality of communications in LOS vs. N-LOS in point-to-point and multi-points connections.

The rest of this paper is organized as follows. Related work is provided in Section II. Section III details the experimental setup including the platforms, dimensions, and metrics used. Results are given and discussed in Section IV. The paper concludes in Section V with discussion regarding future work.

II. Related Work

Several works exist that utilize wireless communications among a fleet of autonomous vehicles. These works provide systems for communicating with robots and base station over different bands of the RF spectrum. Hayat *et al.* [3] demonstrated in their work the feasibility of maintaining links between multiple drones and base stations in single and multi-hop manner. Their work showed promising results by adopting the Wi-Fi band (802.11n, ac) for communications, although communicating in Wi-Fi band is limited in range up to a couple of hundred meters. Asadpour *et al.* [4] provided a thorough analysis of micro unmanned aerial vehicle networks in the physical and media access control (MAC) layers. In their testbed, the authors employed ad-hoc Wi-Fi 802.11n for high-speed traffic and long-range XBeePro over $2.4\,\mathrm{GHz}$ as the control channel. Morgenthaler *et al.* developed the UAVNet prototype that forms a flying wireless mesh network [5]. Results showed 6.3 times higher throughput in flying wireless mesh nodes than a ground-based network approach. In [6], Kimball *et al.* have successfully built an Autonomous Surface Vehicle (ASV) that can acquire oceanographic data in shallow or dangerous water. The authors used 3D Robotics $900\,\mathrm{MHz}$ radios for communications with a computer operated by a human and were able to achieve up to $1\,\mathrm{km}$ range to communicate with a single ASV. Additionally, Beard *et al.* [7] used the $900\,\mathrm{MHz}$ bidirectional link between a single Unmanned Aerial Vehicle (UAV) and a laptop (Ground station) where the laptop up-links trajectory commands to the UAV which, in turn, down-links positioning and status data at $20\,\mathrm{Hz}$ to the laptop.

A complete analysis in point-to-point and multi-points communications among autonomous vehicles using $900\,\mathrm{MHz}$ band for long range communications is still missing, gap that this work addresses.

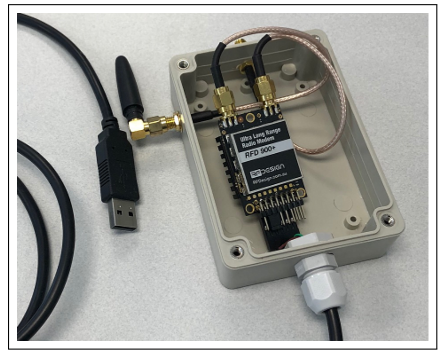

Fig. 2. RFD900+ modem installed in a waterproof box, connected by FTDI cable.

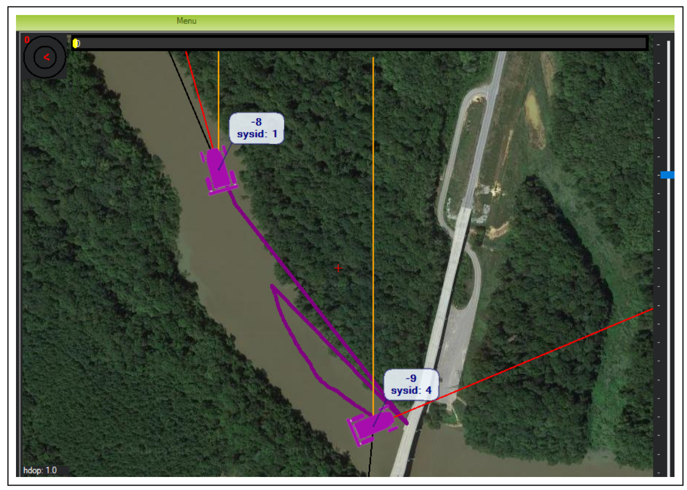

Fig. 3. Live monitoring of 2 ASVs communicating with 1 GCS at the Congaree river in South Carolina using Mission Planner (Ground Control Software).

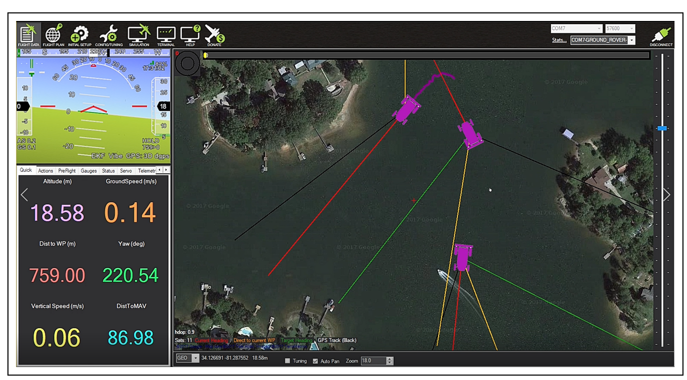

Fig. 4. Live monitoring of 3 ASVs deployed at Lake Murray. Data was collected from various experiments where each ASV was connected to a separate GCS operating on different Net IDs, and this illustration where all were monitored by a single GCS. All BSs were connected to laptops stationed at shore running Mission Planner software for monitoring and data collection.

III. Experimental setup

To evaluate the capabilities of long range communications using 900 MHz band in both point-to-point and multi-point scenarios, we first need to take a look at the various parameters that can be adjusted by the user. These parameters are closely related and can greatly affect the performance of the communication. Table I lists the available and configurable parameters in the RFD900+ modems as well as the default (out of box), minimum, and maximum value for each parameter.

TABLE I
RFD900+ CONFIGURABLE PARAMETERS WITH THEIR MINIMUM, MAXIMUM AND DEFAULT (OUT OF BOX) VALUES

Parameter	Description	Default	Max	Min
Format	EEPROM Version	—	—	—
Serial Speed	Serial data rate (unit: kB)	57	115	2
Air Speed	Data rate (unit: kB)	64	250	2
Net ID	Network ID	25	499	0
Tx Power	unit: dBm	20	30	0
ECC	Error correction code	0	1	0
Mavlink	Mavlink frame & report	0	1	0
Op Resend	Opportunistic resend	0	1	0
Min Freq	In kHz	915	927	902
Max Freq	In kHz	928	928	903
Num Channel	Frequency hopping channels	20	50	5
Duty Cycle	Percentage of transmission	100	100	10
LBT RSSI	Listen before talk	0	1	0
Manchester	Manchester encoding	0	1	0
RTS/CTS	Request/Clear to send	0	1	0
Node ID	Unique ID for each node	2	29	0
Node Dest	Remote ID	65535	29	0
Sync Any	Broadcast feature	0	1	0
Node Count	Total number of nodes	2	30	2

A. Platforms

We adopt an ASV from the WHOI project [2] custom-modified in our lab to serve as remote autonomous nodes. The RFD900+ modems were mounted on the mast (Fig. 1) of each ASV to minimize any interference that may be caused by other on-board electrical and electronic components, *e.g.*, GPS module, Gyroscope, Compass, Accelerometer Sensors.

B. Dimensions

Many factors are crucial to take into consideration when evaluating wireless communications. The desired range, number of nodes, surrounding noise, and obstacles between transmitters and receivers are the most common and widely used to analyze communication quality. The aforementioned factors can be considered environmental. In the following, we detail our experimental setup and the consideration we took for running our tests.

1) Hardware: We employ half wave dipole antennas approximately 3 dBi gain with omni directional radiation pattern. It is reported on the RFD900p manufacturer data-sheet that depending on the antennas installed, communications can be carried for up to 40km in case of LOS[3]. Hence, we adopt such high gain antenna to be used in BSs and ASVs to validate this claim.

[3]http://files.rfdesign.com.au/Files/documents/RFD900/20DataSheet.pdf/

Fig. 5. Electronics box of the ASV, which contains controllers and sensors, including GPS and Arduino. Each of the components can be a source of noise.

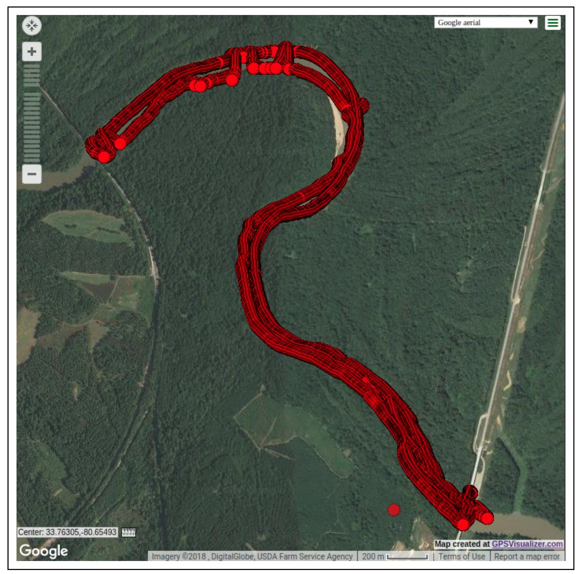

Fig. 6. GPS traces of the four ASVs during a deployment at the Congaree river in N-LOS.

2) Number of nodes: We can summarize our experiments into two main categories: A point-to-point and multi-point scenarios. The first scenario consists of one ASV and one Base Station (BS), equipped with the same RFD900+ modem, connected to a laptop through a serial to USB cable (see Fig. 2). In the multi-point scenario, several setups are tested, where one ASV broadcasts to two separate BSs to emulate multiple GCSs monitoring the same vehicle (Fig. 3). Another setup consists of multiple ASVs monitored by a single BS at the same time (Fig. 4).

3) LOS vs. Non-line of sight (N-LOS): We explicitly consider scenarios under LOS and N-LOS as experimental dimension, to see how robust the quality of communication is.

Fig. 7. GPS trace-path of deployed ASV on Lake Murray to evaluate communication between BS and ASV in LOS. Yellow traces represent low latency, orange represent ASV executing way-point missions, and blue traces evaluate the quality of communication and range limitation.

C. Metrics

We collect two sets of data, telemetry logs (T-logs) and binary (Bin) logs. Both of these types of logs contain mostly the same data from the ASV sensors and modules. However T-logs gets streamed live to the GCS/BS using the RFD900+ modems and the Bin logs get stored locally for collection later. Therefore, different information can be extracted from these logs depending on the type of evaluations. For instance, T-logs provide channel metrics such as RSSI, Noise, and receiving error for Local and Remote nodes Figures 3 and 4, which define the Link quality between transmitters and receivers, while Bin logs are more reliable for obtaining sensitive data (*i.e.*, GPS traces) due to local logging in the ASVs on-board storage Figures 6 and 7.

1) Noise: Several types of noise are well known to have a detrimental impact on the quality of the wireless communications, degrading the quality of the communication link: data transfer rate as well as communication range can dramatically drop, especially when operating outdoors. Examples of common types of noise are environmental noise – *e.g.*, weather – and hardware – *e.g.*, thermal, noise from the ASV's engine magneto. Also, in case of multiple nodes communicating at close distance, each node can be considered a noise source to its neighbor. For simplicity, we categorize the noise measured at GCS and ASV into *local noise* and *remote noise*.

2) RSSI: A positive value that represents the strength of the signal. It is different than Received Signal Strength (RSS) which defines the actual strength value of the signal represented by a negative value.

3) Rx error: Represents the error rate in receiving data over air, *i.e.*, packets that didn't pass CRC check.

4) Distance: The distance between transmitter and receiver which can be ASV or BS.

D. Scenarios

In this section, we describe the scenarios to collect data, according to the dimensions just mentioned. All scenarios can be categorized based on the location where the experiments were conducted. As said, a key factor when dealing with wireless communication that have a great impact on the link-quality is the presence of LOS between communicating nodes. Therefore, we pick two locations namely Lake Murray and Congaree River, to represent communicating in LOS and in N-LOS respectively as follows:

1) Lake Murray (LOS): Lake Murray is about 50,000 acres of open space with minimal obstacles. Therefore, we choose to conduct experiments at this location due to convenience (close to our lab) and optimal conditions (minimal obstacles). Here we setup our scenarios to evaluate the maximum range that can be covered when deploying ASVs in LOS environment, while maintaining reliable monitoring. In particular, we run the following experiments:

i) A pair of one ASV and one BS.
ii) Two pairs of one ASV and one BS.
iii) Three pairs of one ASV and one BS.
iv) Two ASVs connected to one BS, and one ASV connected to a separate BS with different Network-ID.

2) Congaree River (N-LOS): We nominate the Congaree River to run and collect data in a N-LOS scenarios. The winding path of the river and bushy surroundings make this an optimal location for testing and evaluating the quality of communication when there is no visible path between the BS and ASVs (Fig. 6). We conduct several experiments that are different than the ones at the lake. More complicated scenarios were run at the river to verify the accuracy of the results. Intuitively one can expect to run smoother experiments at the lake than at the river due to space limitation and surrounding obstacles. Hence, we start with one pair of BS and ASV as a point-to-point scenario. Then, we introduce several (up to three) ASVs to the network totaling four ASVs and three BS connected to two laptops as follows:

i) One ASV and One BS forming a point-to-point scenario.
ii) One ASV broadcasting to two BSs at the same time, where each BS is connected to separate GCS representing an ASV being monitored by multiple GCSs.
iii) Two ASVs connected to one BS.
iv) Two pairs of one ASV and one BS, where each pair is assigned with different Network-ID.
v) Two ASVs connected to one BS, and one ASV connected to a separate BS at the same time but with different Network-ID.
vi) Two pairs of one ASV connected to one BS, and two ASVs connected to one BS totaling four ASVs in the water and three BSs connected to two GCSs (laptops).

In the aforementioned experiments, T-logs were collected at the corresponding GCS as they were live-streamed. The Bin logs were setup to be stored locally at each ASV and were collected from a 4 GB SD-card located in Pixhawk boxes (Fig. 5) upon the end of all experiments. Several key observations and notes regarding the results are discussed next.

IV. Summary of Results and Discussion

In this section, we provide an inclusive summary of all results obtained from conducting experiments on Lake Murray and Congaree river.

It is worth mentioning that it takes a significant amount of time to carry such field experiments due to loading and hauling ASVs, setting up and configuring parameters, unexpected technical issues, collecting data and perform analysis. Here, we highlight the main observations from the analysis and provide a discussion that guides future setups. Figures 8 and 9 show an analysis of one scenario at the lake and the river respectively.

A. Impact of number of ASVs

By setting up a point-to-point communication, *i.e.*, one ASV and one BS, we observed a low latency and reliable communication in the lake and the river. We configured the nodes to communicate at the maximum available data rate *i.e.*, $250\,\mathrm{kbps}$. As for the duty cycle, we kept the ASV at 100% transmission cycle since we cared about monitoring the ASV. The BS was given the node ID 0, the ASV node ID 1, and they were both configured to communicate with each other by setting up the node destination variable Table II. When another ASV joins the network (with the same configuration), a drastic change to RSSI values is observed, as shown for example in Figure 10. Nodes can no longer communicate with BS or among themselves. We started from the maximum values that allowed by the modems then worked our way down until we were able to upload missions and monitor all ASVs at the BSs. For instance, we altered the data-rate to be at 128 kbps and cut down duty cycle to 40% for each ASV and 20% for the BS. Additionally, we configured all the node to communicate in a broadcasting behavior by assigning the following values: node destination = 65535, SYNC any = 1, and RTS/CTS = 1. Fig. 11 shows the RSSI and Noise values of the configuration that gave the best results in our experiments in point-to-point and multi-point cases.

B. Impact on range

Experiments conducted at the river, in a N-LOS environment, showed a reliable monitoring of multiple ASVs (up to 3, monitored by 2 BSs) for up to $1\,\mathrm{km}$ range. The same configuration provided a range up to $5\,\mathrm{km}$ at Lake Murray in a LOS environment. Also, as expected, the range extends with the fewer number of ASVs in the network due to the absence of noise created by neighboring nodes. We also noticed decreasing data rate results in an increase of the range but at the cost of the amount of data to be exchanged.

C. Discussion

Although RSSI, from the physical layer perspective, is one of the most valuable metrics that can define the quality of communication, several other metrics have to be considered when evaluating the quality of communications. For instance, associating more nodes to the network may increase the value of RSS due to signals colliding. Another important metric is the distance that can be covered. From our experiments,

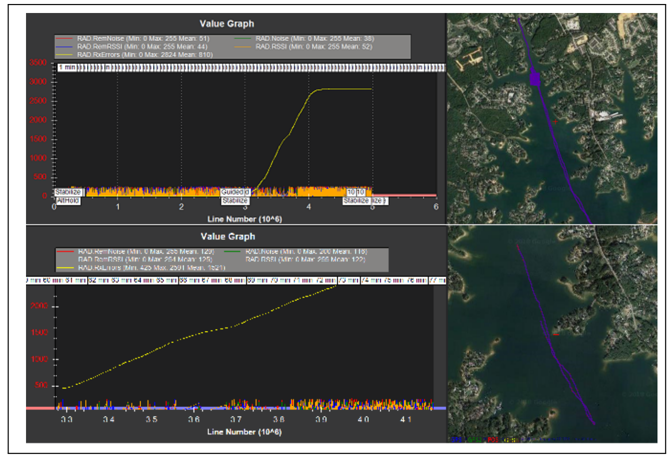

Fig. 8. Analysis example of local and remote RSSI (blue and orange), noise (red and green), and receiving error (yellow) values over distance of a remote (ASV) and a local node (BS) deployed at Lake Murray in LOS. Top map shows the full path and corresponding analysis on the left side of the map. Bottom shows a zoomed in view (segment of path and plot) when accumulated receiving error go beyond 20%.

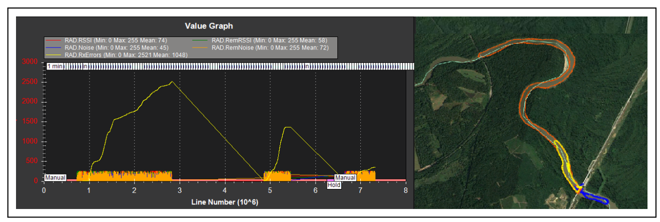

Fig. 9. Analysis of 3 ASVs at the Congaree river with two BSs. Map on the right shows three paths of ASVs. Path colors correspond to quality of communication: Blue-receiving error of less than 20%, yellow-up to 49%, orange- above 50% which considered unreliable for monitoring.

four remote ASVs can be monitored in an open large area more reliably than in a smaller area due to the noise created from neighboring ASVs. Also, it is worth mentioning that trial and error method might be the most effective way when configuring modems for the following reasons. The number of ASVs changes based on the exploring area, environmental factors – *e.g.*, obstacles – other miscellaneous reasons – *e.g.*, antennas type, length, and placement, etc. Therefore, it is hard to find an optimal configuration that can be generalized. On the other hand, we observed an inverse relationship between the number of ASVs vs. maximum possible data rate. Based on the results and analysis, this relation can be defined as follow where n is the number of remote ASVs:

$$\text{Maximum possible Data rate} = 250kbps/(2^n - 1) \qquad (1)$$

V. Conclusions and Future Work

This paper provides an insight of the different configurations that can be used for communicating over $900\,\mathrm{MHz}$ band. We showed how we can utilize off the shelf models, namely RFD900+, to provide bi-directional communications in point-to-point and multi-point setups. Based on the results, a key observation is that using these types of affordable modems

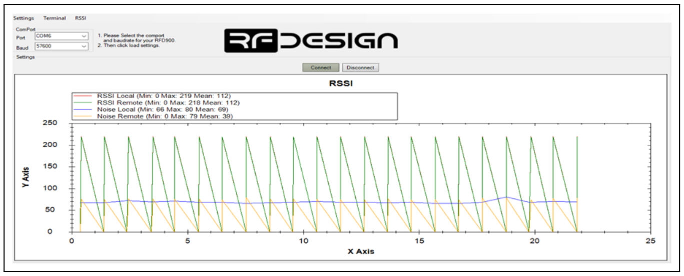

Fig. 10. Initial plot of RSSI and Noise values (Y-Axis) over Time (X-Axis) when a third node (BS or ASV) was added. We can observe the impact of introducing a new node on the quality of communication (RSSI and noise).

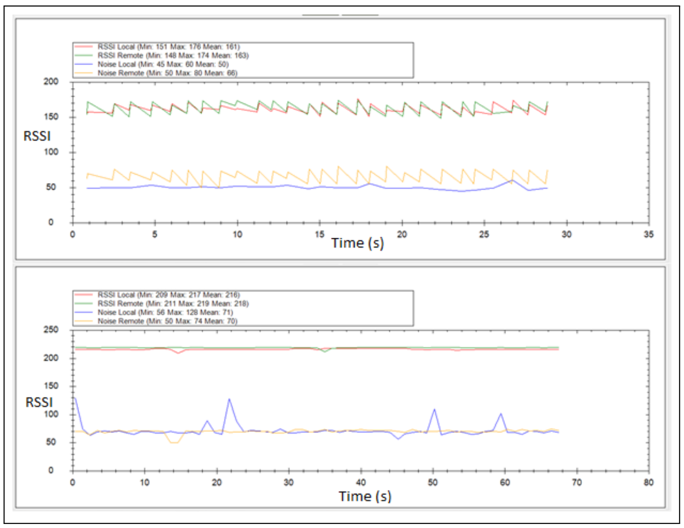

Fig. 11. Plot showing optimal RSSI Vs. Noise values (Y-Axis) over Time (X-Axis) of local and remote nodes (BS and ASV respectively) when communicating in point-to-point (bottom) and multi-point (top) scenarios

can provide long range communications with limited data-rates. It is important to mention that we observed a significant drop in the data-rate when switching form point-to-point communication to multi-point by adding an extra ASV. We observed higher noise that forced us to cut the air-data value by half what it was in a point-to-point configuration. In summary, we tested the capabilities and performance of long range communications using cheap off the shelf modems (approx. $70 per modem), which with some tuning can provide an affordable solution. The viability of this solution depends on the required range and data rate. We showed how the number of actively communicating nodes have the greatest impact to the reliability and quality of communication in terms of the data rate, the receive error rate, and the noise introduced by joining more ASVs to the network. We suggest using a separate network ID when possible to minimize the unintentional noise produced by a neighboring ASV's modem.

Our future research will seek to improve our current communication system. We will consider the construction of a communication map [8] in order to control the ASVs facilitating a communication link to the Ground Control Station while exploring areas larger than the communication ranges [9]. We will also research and experimentally evaluate the maximum number of nodes that can be deployed at once forming a mesh-like network as well as the impact on the range and data rate. Additionally, we will employ and use drones as a communication bridge to extend ASV range from the BS.

TABLE II
RFD900+ CONFIGURATION FOR POINT-TO-POINT COMMUNICATION SCENARIOS WHEN CONDUCTING EXPERIMENTS AT THE LAKE AND RIVER.

Local Node setting -BS	**Remote node setting -ASV**
S0: FORMAT=27	S0: FORMAT=27
S1: SERIAL SPEED=57	S1: SERIAL SPEED=57
S2: AIR SPEED=250	S2: AIR SPEED=250
S3: NETID=36	S3: NETID=36
S4: TXPOWER=30	S4: TXPOWER=30
S5: ECC=0	S5: ECC=0
S6: MAVLINK=1	S6: MAVLINK=1
S7: OPPRESEND=0	S7: OPPRESEND=0
S8: MIN FREQ=915000	S8: MIN FREQ=915000
S9: MAX FREQ=928000	S9: MAX FREQ=928000
S10: NUM CHANNELS=50	S10: NUM CHANNELS=50
S11: DUTY CYCLE=50	S11: DUTY CYCLE=100
S12: LBT RSSI=0	S12: LBT RSSI=0
S13: MANCHESTER=0	S13: MANCHESTER=0
S14: RTSCTS=0	S14: RTSCTS=0
S15: NODEID=0	S15: NODEID=1
S16: NODEDESTINATION=1	S16: NODEDESTINATION=0
S17: SYNCANY=0	S17: SYNCANY=0
S18: NODECOUNT=2	S18: NODECOUNT=2

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