Demonstration of an Airborne Software Reprogrammable Payload

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ABSTRACT

A Software Reprogrammable Payload (SRP) is comprised of a Software Defined Radio (SDR) which is deployed on a mobile platform, such as an airplane or unmanned aerial vehicle (UAV), and includes a library of user-selectable applications. SRPs are useful because software applications can be written and changed, when necessary, to facilitate communication between ground users when other forms of communication are not available. Additionally, SRPs allow a user to switch software applications dynamically. In this paper, an SRP is demonstrated through flight on a Cessna Skymaster. The demonstrated software radio used GNU Radio, and included the following applications: analog relay with interference mitigation, Automatic Identification System (AIS) data collection and downlink, and a software router.

1. INTRODUCTION

Researchers in the field of Software Defined Radio (SDR) seek to replace analog radio components with software, which increases flexibility through increased programmability [1]. An airborne SDR, which can facilitate beyond line-of-sight (BLOS) communication between distant users, can be referred to as a Software Reprogrammable Payload (SRP.) The SRP Technology Airborne Feasibility Evaluation (STAFE) was a flight demonstration of software-defined radio technology. This demonstration was a first step in the Naval Research Laboratory's effort to develop effective, functional SRPs for the war fighter.

This paper describes a project which demonstrated an SRP using three software applications. The first is a full-duplex analog relay with interference mitigation, in which the SRP relays voice between two RF5800M-MP radios. The relay uses two transmit frequencies and two receive frequencies, allowing for two users. It mitigates interference by notch filtering a moving interference tone. Relays can be helpful for ground users without line of sight to close a communication link.

The second application performs Automatic Identification System (AIS) [2] collection and downlink. The International Maritime Organization (IMO) and various countries require large vessels in international or coastal waters to carry an AIS transponder. The transponder transmits ship information, including Maritime Mobile Service Identity (MMSI) number, position, course, and speed at regular intervals. The AIS application on the STAFE payload collects and demodulates AIS data. After collection, it downlinks the AIS data to a ground user.

The final application is a software router, where SRP routes digital data between ground users by retransmitting at the appropriate frequency.

In addition to the computer hosting these applications, the payload included radio frequency (RF) hardware, analog to digital and digital to analog converters, and an FPGA.

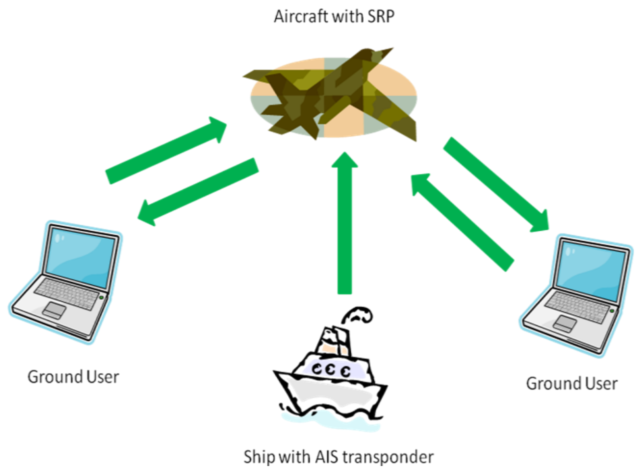

Figure 1: Illustration demonstrating communication between ground users, ships, and the SRP.

2. SYSTEM AND HARDWARE

For this demonstration, GNU Radio [3], an SDR API, was installed and run on a notebook computer with a 2.0 GHz clock. Prior to processing in software, the SRP collects information at 162 MHz for the AIS application and at frequencies between 400 and 500 MHz for the analog relay and digital router applications. On the transmit side, analog voice and digital data are sent to ground users at frequencies between 400 and 500 MHz. Ettus Research's Universal Software Radio Peripheral (USRP), which is designed for use with GNU Radio, was coupled with necessary amplifiers and filters to complement processing performed in software. In the software router application, two USRPs were used to support two digital channels. Figure 2 provides a block diagram of the system hardware.

A low noise amplifier, the Mini Circuits' ZX60-33LN+ helped to reduce the noise figure of the receive paths. The AIS receive path benefitted from three cascaded low noise amplifiers. A Mini Circuits' ZHL-5W-1 power amplifier amplified to 5 W, allowing the SRP's transmitted signal to close its link.

AIS data was collected using a Comant CI 292-1 antenna for data collection, cut to 47 cm to receive at 162 MHz. The Comant CI 275antenna was used for UHF applications. Comant's antennas are specifically designed to be mounted on an aircraft.

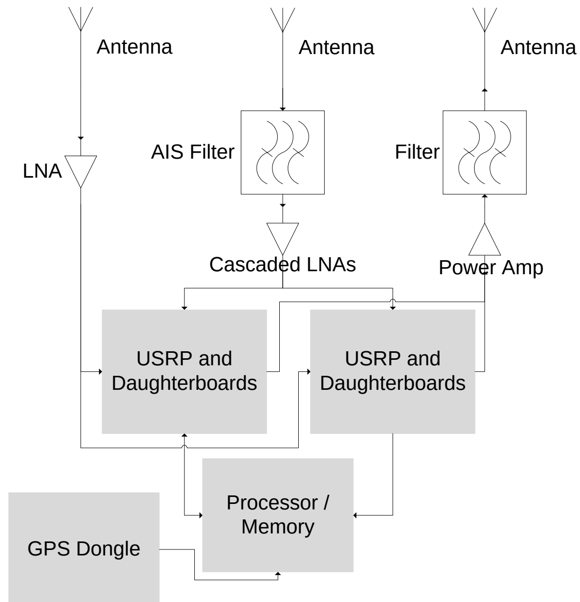

Figure 2: Block diagram of the STAFE payload.

Additional flight hardware included power supplies, AC to DC power converters, and a BU-353 USB GPS receiver, which tracked the payload's position in real time. Information on payload position from the GPS receiver was downlinked to ground users.

To demonstrate the router application, USRP ground stations were constructed with hardware mostly identical to the payload. The ground stations can be hooked up to any computer with GNU Radio for operation. Antennas used for ground users included common quarter wave monopoles and conical antennas. A 100W power amplifier, the Mini Circuits ZHL-100W-52-, driven by a signal generator, was also used on the ground to generate the interference tone for the interference mitigation application.

3. SOFTWARE

The software effort for STAFE required completion of three major applications: full duplex analog relay with interference mitigation, AIS collection and downlink, and IP router. Support software was written to collect downlinked data and allow text-based chatting between users to demonstrate the IP router. All software was written in Python and all applications which required interaction with the USRP utilized the GNU Radio API.

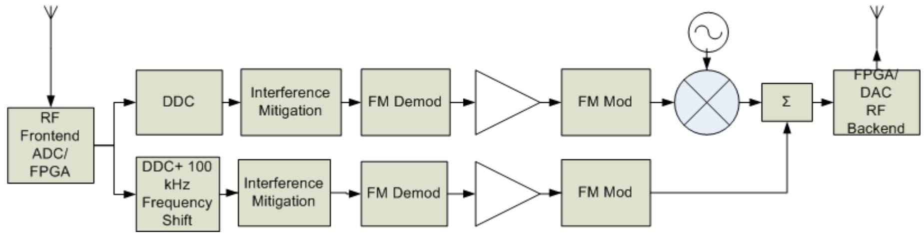

Figure 3: Relay with interference mitigation application.

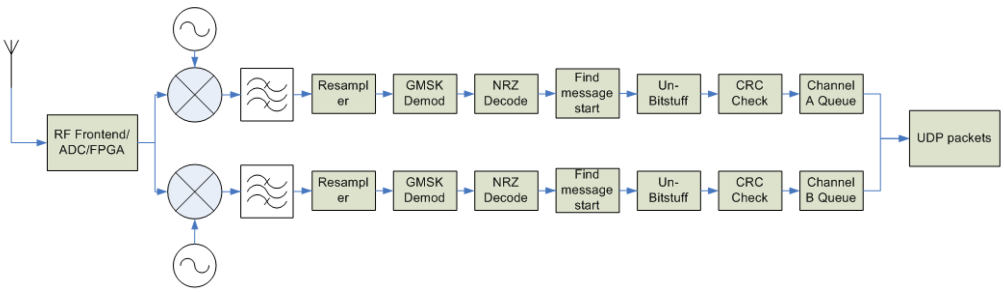

Figure 4: AIS application.

3.1 Full Duplex Analog Relay with Interference Mitigation

This application required that the two users communicate using separate tx and rx frequencies, the payload communications be full duplex, and that the application removed an interfering tone from its input frequency so that interference is not relayed to ground users.

For this application, signals were passed through the front end, down-converted, frequency shifted, and then passed through the interference mitigation component of the algorithm. The interference mitigation algorithm repeatedly scans the spectrum surrounding the signal and places a narrow notch filter over the frequency component with highest amplitude. In the case where there is no interfering tone in the spectrum, the notch filter is normally placed over some part of the signal being received, but it is narrow enough that the effect on the signal is negligible. When an interference tone is present, the filter is deep enough to remove it from the signal with minimal degradation, negating the effect of the the interference. Figure 3 illustrates this application.

3.2 AIS Collection and Downlink

AIS broadcasts originate from ships and provide identification and other ship information, such as position and velocity. The AIS application receives AIS broadcasts from ships, decodes them and outputs them in standard NMEA format. The AIS application collects broadcasts on both AIS channels, 161.975 MHz and 162.025 MHz, and broadcasts the demodulated, but unparsed, data to ground users for logging.

A block diagram for the application is shown in figure 4. When energy from the antenna is passed through the analog to digital converter (ADC), two copies of the digital signal are passed through mixers to do fine tuning for the two AIS channels. The signal is then resampled to achieve the correct bitrate for AIS and passed through a GMSK demodulator. The signal is then passed through a NRZI decoder, an unbitstuffer, and a cyclic redundancy check. The NMEA message is then constructed and the message is put into a queue. Messages from both channels are packed into UDP packets and broadcast using the GNU Radio Tunnel application or another broadcast program derived from Tunnel, such as the IP router application.

3.4 IP Router

The IP Router application routes IP traffic between multiple users through a central hub. The purpose is to demonstrate beyond line-of-sight (BLOS) digital communication by placing the router in an aircraft in view of ground users who do not have direct line of sight to each other.

The IP Router application uses the Tunnel application, which is included with GNU Radio, along with two USRPs to generate two channels handling IP traffic. The two channels are bridged using standard routing in the Linux kernel. Each channel has a dedicated subnet and can support up to 255 users, in theory. However, since no timing scheme was implemented to avoid interference between users, the practical limit on number of users per channel is much lower, depending on the type of traffic generated by the users. Flight testing focused on one user per channel, but preliminary ground testing included multiple users per channel. A block diagram of the application is given in figure 5. The majority of the code lies in the packet TX and RX modules which are included with GNU Radio. These modules are implemented in Tunnel. Tunnel creates virtual network interfaces using the TUN/TAP driver to allow the operating system to pass IP data as if the radio hardware were a wired network. For the IP Router application, two instances of tunnel are created, and their associated virtual network devices are assigned IP addresses on different subnets. A routing table is employed to allow the kernel to route traffic between the two Tunnel instances.

For two ground users to communicate using the Router Application, each sets up an instance of Tunnel on a computer connected to a USRP. The IP traffic is packetized and modulated, passed through a digital to analog converter (DAC) and received by the IP Router. The IP Router forwards the packet to the user to whom it is addressed.

4. AIRBORNE DEMONSTRATION

The team chose to use an airplane for the demonstration. Unlike a blimp or aerostat, airplanes provide the ability to fly at high speeds and to test the payload from varying distances.

Boschma Research, Inc. provided the Naval Research Laboratory (NRL) a Cessna C337 Skymaster for the airborne demonstration. The Skymaster is a small airplane which can fly at speeds down to 100 knots and altitudes up to 10,000 meters. Boschma Research added AC power through a battery with an inverter, allowing for the payload to draw up to 1 kW of power. Figure 5 illustrates the rack and shelves containing the airborne payload. One rack shelf holds the power amplifier, 2 AC to DC converters, and 2

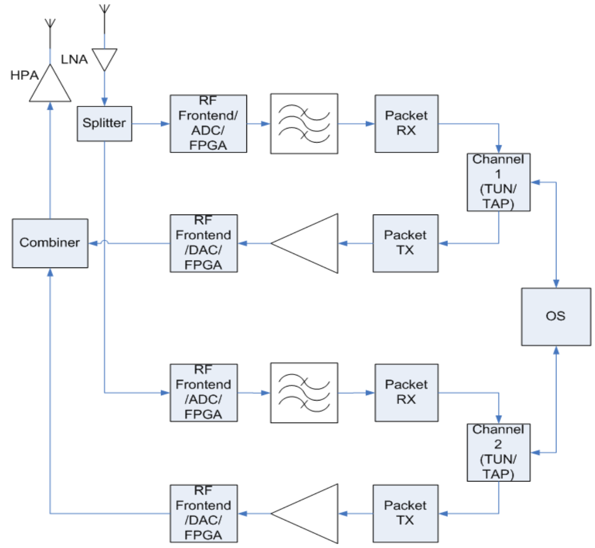

Figure 5: IP Router Application.

EMI filters, while the other rack shelf holds 2 USRPs, an AIS filter, 4 LNAs, and a power combiner.

Both UHF and VHF antennas were originally mounted on the bottom of the aircraft. After finding through testing that proximity of the two UHF antennas greatly affected the receive sensitivity of the system, a fourth antenna was mounted on top of the aircraft to separate the transmit and receive antennas by metal, providing greater electromagnetic isolation between the antennas. For the first campaign, the transmit path used the bottom UHF antenna, while the receive path used the top UHF antenna. For the second flight campaign, this configuration was reversed.

During the airborne demonstration, the aircraft traveled up and down the bay in lines parallel to the coast and about two miles east of NRL's Chesapeake Bay Detachment (CBD), which allowed for minimal free space path loss. The aircraft then flew to waypoints further from NRL-CBD. Waypoint pairs are listed in table 1.

The last pair of waypoints describes an 18 mile long line that is about 15 miles away from NRL-CBD when the aircraft is abeam. Therefore, the airplane flew to distances about 23 miles away from NRL-CBD. At times, variations were flown that were not exactly on these waypoints. In moving between parallel lines, data was collected for lines perpendicular to the bay.

Table 1: Waypoint pairs for airborne demonstration.

Northern Waypoint in Pair	Southern Waypoint in Pair
38°45'49.30"N, 76°29'7.36"W	38°33'37.22"N, 76°29'7.36"W
38°47'25.44"N, 76°25'51.65"W	38°31'40.69"N, 76°25'51.65"W
38°47'25.44"N, 76°20’36.18"W	38°31'40.69"N, 76°20’36.18"W
38°47'25.44"N, 76°14'45.98"W	38°31'40.69"N, 76°14'45.98"W

The first flight campaign demonstrated relay with interference mitigation and AIS applications. The second flight campaign added the software router with chat application. Most flights were at an altitude of 3000 feet, so that the aircraft could move freely while avoiding other air traffic.

5. RESULTS AND ANALYSIS

In this section, results and analysis for each application will be considered individually.

5.1 Relay Application with Interference Mitigation Results

The Relay application with interference mitigation worked consistently when the payload was within about 10 miles of the ground stations, and intermittently out to 14 miles. The application was tested with two Harris RF-5800M radios on the ground as well as an Agilent signal generator and a 100 watt RF amplifier. The interference mitigation algorithm accurately tracked tones near the transmit frequency of one user and removed them so that the second user could hear transmissions clearly.

The limiting factor for the maximum distance between the ground user and payload over which clear communication was possible was antenna placement on the aircraft. Late in the development of the relay application, it was found that the always-on nature of full duplex operation was a detriment to the receiver’s sensitivity, raising the noise floor by 20 – 30 dB. Introducing a bandpass filter between the amplifier and the transmit antenna helped marginally, but it was found that only greater antenna separation could lower the noise floor sufficiently.

As mentioned earlier, the aircraft had three places for UHF antennas to be mounted; two were on the bottom, separated by about 3’, and one was on the top were the wing attached to the fuselage. Although the configuration with one antenna on the top and one on the bottom of the aircraft significantly improved the noise floor for the receive path, whichever antenna was mounted on the top of the aircraft was prone to blockage by the wing, and even with clear line of sight, the geometry was not optimal. Had antenna placement been more flexible, ground testing and link analysis indicate that the application would have worked over significantly longer distances.

5.2 AIS Results

The AIS application was demonstrated during both flight campaigns and performed consistently well. In a dataset collected on 18 November, 2008, the farthest vessel was 144 miles, while the farthest track was at 131 miles. Tracks are defined as sequences of two or more messages from a single source. 174 unique MMSI numbers were detected. Vessels could be observed in the Atlantic Ocean, on the Delaware River, in the Chesapeake Bay, and on the Potomac River.

The AIS application performed very well, as vessels from throughout the payload’s line of sight were detected. The application’s performance was fairly consistent and its requirements were met.

5.3 IP Router Results

Although the purpose of the IP Router application was to demonstrate communication between ground users with IP traffic, the application was tested by periodically polling the airborne payload for its GPS coordinates. Since a successful request meant error-free transmission both to and from the aircraft and the path lengths for both transmissions were well known, this method is a valid performance metric. All communications with the payload used user datagram protocol **(**UDP**)** so that link quality could be better characterized; transmission control protocol **(**TCP**)** will resend packets to guarantee arrival.

A flight test of the application on 17 November, 2008 lasted 73 minutes (4,380 seconds) and 1978 GPS packets were collected. The payload was queried for GPS as quickly as it could send it, which was slightly more than a second since two GPS messages, GPGGA and GPRMC, both being updated at 1 Hz, were required. Of the 4380 second flight, collected GPS accounts for 1978 seconds. This indicates a 45% success rate for two-way communications. It was noticed that the payload would respond consistently when flying abeam the ground station out to 10 miles but would be more unresponsive during turns and when the aircraft was at the farthest points in its flight path.

Additionally, the application was tested using a chat program written specifically for the experiment. This program used UDP along with a simple acknowledgement and retransmit scheme. Because the chat program tried to retransmit failed packets 10 times, higher success rates were achieved.

During this demonstration there was no retransmission of messages with bad checksums. Implementing error correction could significantly improve this application's reliability.

6. CONCLUSION

The STAFE program demonstrated the utility of the SRP for military communications and signal collection. The program exercised a single payload built from commercial components with three diverse applications. The flight demonstrations provided the team with valuable insight for future SRP designs. In the future, robust coding techniques and alternative antenna designs and placement can be utilized to improve link performance.

7. REFERENCES

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