Software-Defined and Cognitive Radio Technology for Military Space Applications

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ABSTRACT

Command of the RF spectrum is essential to current and future Air Force operations, and space operations are no exception to this statement. Current military satellite assets provide unique capabilities to the warfighter, particularly communications and broadcast services such as GPS. But even as demand for these services soars due to expectations driven by commercial capabilities, spectrum allocation is at best remaining constant and in danger of contraction due to re-allocations. Furthermore, military systems, including military space systems, must be able to operate in adverse environments, including adversarial environments, which commercial systems do not accommodate. Finally, there is continual pressure to provide more capability at less cost to efficiently manage budgets. These driving forces have led the Air Force Research Laboratory's Space Vehicles Directorate (AFRL/RV) to initiate a new research effort in the development and application of software-defined and cognitive radio technology for military space applications. This paper will present selected research activities at AFRL/RV in the arena of software-defined and cognitive radio technology for military space-based applications. Current efforts include development of software-defined radio controlled satellite ground-stations, networked ground station operations for increased efficiency of operations, as well as research into new radio control algorithms and methods of dynamic waveform reconfiguration for satellite applications. The paper will include a summary of progress and results to date as well as a discussion of future areas of research.

1. Introduction

Software-Defined and Cognitive Radio (SDR and CR, respectively) platforms have been the subject of much research and development in academic, commercial, civil, and military applications. Military applications for wireless RF technology range from sensor systems (e.g., radar) to communications. These systems nearly always have requirements for operating in an adversarial spectral environment (e.g., intentional vice unintentional interference). Depending how the radio system is planning on being deployed, there can also be significant constraints on the available size, weight, and power (SWaP) available to the RF subsystem to provide the needed capabilities. And finally, military spectrum allocations are continually under pressure from commercial interests due to the fact that conflict is not a persistent activity, resulting in the perception that the allocations are not being efficiently utilized.

Dealing with adversarial communications environments has been a subject of a great deal of work, and current anti-jam approaches such as Direct Spread Spectrum (DSS) or Frequency-Hopping (FH) waveforms are able to provide effective communications in the presence of intentional jamming by adversaries; but these approaches pay for this ability in terms of the data rate (either by running a system at a chip rate vice a data rate for direct spread spectrum

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approaches or by utilizing a very small amount of the allocated spectrum bandwidth instantaneously, which reduces the achievable Shannon data rate). A number of authors have proposed the use of SDR/CR technologies for dealing with adversarial and jamming environments in recent years (see, for example, [1, 2, 3, 4] and references therein).

The ability to reduce the SWaP requirements for radio systems can be viewed in two ways, either as a direct reduction keeping subsystem performance constant or by providing increased performance (say, for example, multi-mission capability) within a constant SWaP target. The ability to provide a number of waveforms for different missions (e.g., radar ranging + communications) in a single RF subsystem with lower SWaP impacts than the two individual subsystems would be an example of this. Recent investigations and progress in this area can be found in, for example, [5, 6].

Efforts directed at improved use of RF spectrum have focused on efficiency in the use of allocated spectrum (e.g., the so-called "white spaces" in the allocated spectrum space). There has been a massive amount of research in the application of SDR, and more frequently CR, technologies to this problem to look at "secondary users" that work in a non-interference mode with spectrum allocated to primary users. Excellent summaries of progress here can be found in [7, 8].

The efforts to date surrounding the above issues have primarily been focused on terrestrial and/or airborne domain platforms and deployments of SDR and CR technologies. However, all of the above issues are extremely relevant to space-based platforms, in some cases (such as SWaP constraints) critically so. The space environment has a number of challenges not present in air and/or terrestrial applications (e.g., the need for radiation-hardened electronics, severe limitations on electrical power due to solar-based sources, little or no ability for recovery of test equipment in the case of failures, etc. etc.). Space-based research and development efforts have been initiated by NASA [9, 10], the US Naval Research Laboratory [11], and efforts by the European Space Agency (ESA) [12, 13, 14, 15, 16], but these efforts will not address all the required developments and experiments necessary for a determination of the utility of SDR/CR technologies in military space applications.

To complement the efforts by these organizations, AFRL Space Vehicles Directorate has initiated a research effort aimed at the research, development, and application of SDR and CR technology to the problems of satellite communications, including traditional space-based relay, satellite commanding, and satellite cross-links. AFRL and partner UNM-COSMIAC have set up two ground stations used to conduct satellite communications experiments. Partnering with the European Space Agency (ESA), the University of Vigo (Spain), and California Polytechnic Institute, AFRL and UNM-COSMIAC have volunteered ground station assets to aid in the development of the Global Educational Network for Satellite Operations (GENSO).

This paper will document recent results of this research effort as well as to provide a status of current efforts. The remainder of the paper is organized as follows. Section 2 will summarize the GENSO amateur-radio satellite ground-station network, and Section 3 will provide a description of the SDR-controlled satellite ground stations used in the present work. Section 4 will discuss recent efforts to provide Universal Software Radio Peripheral (USRP) compatible python implementations of AX.25 data link protocols used in amateur satellite radio, while

Section 5 will present some of the recent results testing these protocols in the laboratory. The paper concludes in Section 6 with a look at next steps and future efforts.

2. GENSO: Networking for Amateur Radio Satellites

In response to the ever increasing demand for small space assets, the European Space Agency created a program called the Global Educational Network for Satellite Operations (GENSO). The first iteration of this system was put online for developers in 2010. The current iteration of the software implementation for control of GENSO ground stations is release 1E, produced in support of the latest launch of CubeSats under the NASA Educational Launch for Nanosatellites (ELaNa) mission. Since many of the ELaNa satellites (16 in the ELaNa four mission) are placed in lower altitudes (325km), it is critical to download as much data as quickly as possible prior to satellite re-entry. This GENSO [17, 18] system is a network of amateur radio ground stations that volunteer to be part of the hub-spoke GENSO ground-station network designed to take advantage of the geographic diversity of the participating stations to allow more downlink accesses as satellites orbit the globe than would be obtained with a single ground station that a satellite owner might construct. The operational concept behind GENSO is that the ground stations around the world can be utilized to perform "bookings" whereby data in the form of Ax.25 packets can be downloaded anytime a satellite passes over a partner ground station. This data can then be passed to the satellite owner for decoding and processing. For many missions such as the COSMIAC Trailblazer mission [19], the total satellite lifetime is measured in months, and thus the most possible data to the ground is essential.

One objective of the current efforts is to integrate Software Defined Radio controlled ground-stations into the GENSO network, thereby achieving complete end-to-end control of scheduling and ground station hardware reconfiguration via software and computer control. Integration of an SDR into the GENSO system would provide many benefits. A SDR can be programmed to emulate multiple radios that already exist as a part of the supported hardware drivers list but are no longer available for sale and can be procured for less than the original hardware equipment. The SDR can also support a broader frequency range and more modulation schemes than that of any single radio currently available as a part of approved equipment in the GENSO database.

3. AFRL-UNM-COSMIAC SDR Ground Stations

The primary ground station used in this work is capable of transmitting and receiving. It has antennas for the 2 meter, 70 centimeter, and 12 centimeter bands. The ground station uses the standard GENSO hardware in Table 1 and successfully operated as a node on the GENSO network in that configuration. The station is also equipped with two USRP2 radios.

Table 1: Satellite Ground Station Equipment

Component	Model
Radio	Icom IC-910H
Modem	Kantronics KPC-3+
Antenna rotator	Yaesu G-5500
Antenna controller	Yaesu GS-232B
SDR Platform	Ettus Research USRP2

A custom program in GNU Radio has been developed to operate the USRP2, antenna rotators, and antenna polarization relays. The software communicates with a satellite tracking server on the network in order to obtain information on the position of the satellite in the sky and its expected Doppler shift. A custom GNU Radio block was developed which controls the antenna rotator over a serial interface. The Doppler shift obtained from the tracking server is used to adjust the frequency of the USRP2 to compensate for the Doppler shift created by the motion of the satellite. The antennas each contain a relay which switches between right-hand and left-hand circular polarization. A custom GNU Radio block was developed to control these polarization relays by using the general-purpose I/O (GPIO) pins on the USRP2.

The software radio at this ground station has successfully received and demodulated FM signals from amateur satellites in LEO, including AO-27, AO-51, and HO-68. These satellites transmit in the 70 centimeter band. The software required to demodulate additional waveforms, including AX.25, is discussed in Section 4 of this paper. The integration of this software into GENSO could allow the USRP2, antenna rotator, and antenna relays to be controlled remotely and new modulators or demodulators to be added remotely.

The Ettus Research, Inc. USRP1 and USRP2 software radio platforms are both comprised of a Field Programmable Gate Array (FPGA) and a variety of daughter boards which act as the receiver front end of the radio. The radios are controlled using Python code which runs on the computer connected to the radio. These programs may be generated using a graphical interface in GNU Radio Companion (GRC) or may be written by hand. The programs specify the actions taken by the radio. For example, these programs may specify modulators, demodulators, filters, and converters, resulting in a highly dynamically configurable communications system.

4. AX.25 Waveforms for USRP2

The data link protocol of digital data sent over wireless communications has traditionally required both a radio and a Terminal Node Controller (TNC) device. With SDR, not only can the A/D and D/A signal processing be done, but also the data link layer protocol of the communications package can be achieved with no additional hardware needed.

Amateur radio operators utilize the AX.25 data link layer protocol for their packet radio networks. AX.25 is derived from the X.25 suite and designed specifically for the use of amateur radio operators [20]. AX.25 occupies the first, second and sometimes the third layers of the OSI networking model, and is responsible for transferring data (encapsulated in frames) between nodes and detecting errors introduced by the communications channel. AX.25 is often used with a TNC that implements the KISS [21] mode framing. KISS mode framing is not a part of AX.25, nor is it sent over the air. It merely serves to encapsulate protocol frames in a way that can be successfully passed over a serial link between the computer and the TNC. The KISS framing is derived from Serial Line Interface Protocol (SLIP), and makes many of the same assumptions, such as there only being two "endpoints" involved in the conversation.

Python code originally written for the USRP1 and released by amateur radio operator IZ2EEQ was modified and adapted for the USRP2 platform for the present work. These modifications enable the USRP2 to modulate data at the transmitting end and demodulate data at the receiving end of the communications link at both 1200 bps and 9600 bps. This code was rewritten to be compatible with the USRP2 or other SDR which uses universal hardware device (UHD) drivers. The move from a UDP USRP2 interface to the UHD interface was necessary because of updates made to GNU Radio and the drivers. In order to format the existing code, Engineers generated the flowgraph diagram in GRC to get the top-block.py file. The top-block was then manually edited to add gr-packetradio and the console sink required to display the received data. This process was executed for each baud rate (1200 and 9600)

5. Experimental Results

The testing phase of this project has been accomplished in the 2m and 70cm amateur radio bands. Operational testing of the receiver code was done by running the program with the USRP2 and receiving AX.25 packets sent from both a local land-based amateur repeater station (APRS) and from a handheld Kenwood TH-D72 radio at 1200 baud. The 9600 baud rate was operationally tested by receiving the down link from FalconSat-3, a United States Air Force Academy's small satellite, and a ICOM-910H radio connected to a Symek TNC2H-DK9SJ TNC which operates at 9600 baud. Engineers also conducted a frame error rate test between the USRP2 and ICOM-910H hardware radio which was connected to the Kantronics KPC-3 Plus operating at 1200 baud. The results of this frame error rate test are summarized in Table 2, below. The same test has been done for the 9600 baud rate utilizing the ICOM-910H and the Symek TNC2H-DK9SJ. Results of this test are also presented in Table 2. The transmit portion was tested using the Kenwood TH-D72 radio and the ICOM-910H set up as the receiving stations.

Table 2: Frame Error Rates

Bitrate	Transmitter TNC	Receiver	Number of frames	Frequency	Spacing Between Frames	Medium	Attenuation	Frame Error Rate
1200	ICOM/ Kantronics	USRP2	61	435M	2 sec	coax	60 dB	0.066
1200	ICOM/ Kantronics	USRP2	61	145M	2 sec	coax	60 dB	0.082
1200	ICOM/ Kantronics	USRP2	1000	145M	1 sec	coax	60 dB	0.238
1200	ICOM/ Kantronics	USRP2	1000	145M	1 sec	coax	60 dB	0.135
1200	USRP2	ICOM-910H	100	435.3M	1 sec	Antenna	~36 dB	0,00
9600	Kenwood TH-D72	USRP2	1000	435.3M	0.1 sec	coax	70 dB	0.492
9600	Kenwood TH-D72	USRP2	100	435.3M	2 sec	Coax	70 dB	0.24
9600	USRP2	ICOM-910H	100	435.3M	1 sec	Antenna	~36 dB	0.00

The next set of testing was a bit error rate (BER) test to see how many bits were dropping in the frames sent in the test above. A frame error will occur if even one bit is dropped out of the total frame. BER was tested by setting up two USRP2s and eliminating all AX.25 formatting, resulting in a transmission of bits over frequency shift key (FSK) modulation at 1200 baud, and Gaussian shaped FSK modulation at 9600 baud. Engineers replaced the vector source (AX.25 format) with a vector source containing a known bit sequence into GRC on the transmit side of the link. At the receiver, the demodulated signal was placed ito file sink. This file was imported into MATLAB and compared to the known bit stream. The results of this comparison can be seen in Table 3, below. The UHD sources and sinks for the USRP2 only support sample rates which can be reached using a limited number of decimation and interpolation operations. The modulator and demodulator systems require a sample rate of 256 ksps, which was chosen for ease of implementation on the USRP1. However, 256 ksps is not supported by the UHD source/sink, therefore a 200 ksps source/sink was fed into a 32/25 rational resampler to produce a 256 ksps signal. The results in Table 3 that use this combination of a 200 ksps source/sink and a rational resampler are denoted “yes” in the “Resampling” column. However, this resampling increases the error rate of the system.

Feeding the modulator/demodulator 255.1502 ksps (which is supported by the UHD source/sink) instead of 256 ksps lowers the bitrate to 1196 bps, but drastically improves the BER when testing between two USRP2s. Because of this offset from 256 ksps that is required by the current modulator and demodulator, the testing of the BER between USRP2 and common hardware radios goes up. Engineers currently are working on methods to correct this incompatibility.

Table 3: Bit Error Rates for AX.25 Protocols implemented on USRP2 hardware

Bitrate	Transmitter	Receiver	Number of Bits	Frequency	Spacing	Medium	Attenuation	Resampling	Bit Error Rate
1200	USRP2	USRP2	2300	435M	continuous	Coax	40 dB	yes	3.90%
1200	USRP2	USRP2	2300	435M	continuous	Antenna	~36 dB	yes	3.74%
1196.0166	USRP2	USRP2	2300	435M	continuous	Antenna	~36 dB	no	0%
1196.0166	USRP2	USRP2	4027300	435M	continuous	Antenna	~36 dB	no	0%
9600 FSK	USRP2	USRP2	3201600	435M	Continuous	Antenna	~36 dB	no	0%

6. Current Status & Future Work

Currently, efforts are devoted to the development of Python code that will be used to interface with the USRP2 to achieve integration into the GENSO program. Once the code is complete, it will allow the USRP2 to be recognized by the GENSO Network server by emulating the communications data response commands of the ICOM-910H radio (and eventually other hardware radios). The GENSO server will then be able control the USRP2s modulation scheme and set its frequency using the same commands as it would use to control the ICOM-910H.

Topics of future work will include rework of the modulator and demodulator in GRC to adjust the bit rate to flow at an exact rate of 1200 baud instead of 1196.0166 as seen above, development of an algorithm to enable cognitive operation of the USRP2 for future experiments with military application, and the expansion of the testing frequency range to include L and S-bands to allow experimentation with the NASA Communications, Navigation and Networking re-Configurable Testbed (CoNNeCT) space flight experiment planned for launch in 2012 [22].

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