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Rapid Prototyping Interface for Software Defined Radio Experimentation

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by

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Abstract

This thesis focuses on a user-friendly software-defined radio (SDR) development workflow for prototyping, research and education in wireless communications and networks. Specifically, a Simulink^{TM}interface to the Universal Software Radio Peripheral 2 (USRP2) SDR platform is devised in order to enable over-the-air data transmission and reception using a Simulink signal source and sink, in addition to controlling a subset of the hardware resources of the USRP2 platform. Using the USRP2 as the RF front end, this interface will use Simulink for software radio development and signal processing libraries of the digital baseband component of the communication transceiver design. This combination of hardware and software will enable the rapid design, implementation, and verification of digital communications systems in simulation, while allowing the user to easily test the system with near real time over-the-air transmission. The use of Simulink and MATLAB for communication transceiver development will provide streaming access to the USRP2 without the steep learning curve associated with current workflows. These widely available software packages and the USRP2 will make digital communication system prototyping both affordable yet highly versatile, enabling researchers and industry engineers to conduct studies into new wireless communications and networking architectures including cognitive radio. Furthermore, the interface will allow users to become familiar with tools used in industry while learning communications and networking concepts.

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Chapter 1

Introduction

1.1 Research Motivation

Until recently, many communications systems implemented much of their functionality in dedicated hardware. Dedicated modulators, demodulators detectors and encoders made these systems static and difficult to upgrade. As general purpose processor (GPP) and digital signal processor (DSP) technology improved, a growing number of signal processing steps could be achieved purely in software. While it is common for modern communications systems to include some software, a system is not considered a software-defined radio (SDR) until its baseband operations can be completely defined by software[36]. A SDR moves the transition from the digital to the analog domain close to the radio frequency (RF) front end (antenna, power amplifiers, mixers, oscillators, etc.) while representing the rest of the communications system operations entirely in software. SDR platforms provide communications engineers with an unprecedented amount of flexibility, reducing the amount of time it takes to develop or update communications systems. As a result, an arbitrary number of communications systems can be achieved via a software update. Furthermore, communication system design testing can be performed on known hardware, eliminating the variables associated with testing new software on new hardware. Consequently, SDR

platforms will be able to fundamentally change the way communications systems are used.

One of the applications for this technology is cognitive radio (CR)[35]. Wireless spectrum is a scarce natural resource and the demand for it increases with each new wireless device. The current model of selling sections of spectrum to one user has left much of this precious resource underutilized. CRs sense the environment they are in and adapt to allow secondary users access to spectrum that is already allocated to a primary user without interfering with the primary users. Currently, much of the work conducted by the cognitive radio research community are in the areas of spectrum sensing [35], dynamic spectrum access [29], and agile transmission [37]. However, these research fields are often theoretical in nature. Implementing these new ideas and designs on inexpensive hardware will allow for practical testing. Rapid reconfiguration allows radios to implement multiple standards thus making a single device more versatile.

SDR technology provides communications engineers with an unprecedented amount of versatility. Multiple communications systems can be implemented in software and then loaded on demand. The public-safety community, equipped with SDR devices, can load the same system to their radios as they get onto a scene and have complete communications interoperability between policemen, firemen, EMTs and SWAT team members [28]. Existing systems can be re-implimented to be compatible with systems already deployed. Military communications use the same interoperability to interface systems between Army, Air Force and Navy communications systems. Military radios also employ frequency hopping techniques as a eavesdropping and jamming countermeasure.

Developing and prototyping a conventional hardware radio would be difficult to fit into a single course and be very expensive, but with SDR technology, a basic system can be running in a matter of minutes. Inexpensive hardware and readily available software would make a rapid prototyping platform ideal for communications systems engineering education.

Entire labs can be outfitted with SDR devices and students would be able to build and test fully functional systems during the first lab session.

1.2 Current State-of-the-Art

SDR devices provide the dials and knobs necessary for agile radio transmissions. The first versions of SDR hardware were developed for the military, then research inceptions would develop custom solutions and now commercial options are becoming available. The cost of SDR hardware is driven by features, such as maximum RF bandwidth. The analog to digital converters (ADC) and digital to analog converters (DAC) are a large component of the cost of SDR hardware and are typically the bottleneck dictating the maximum RF bandwidth of the system. Software radios can cost as much as the Lyrtech's SDR Development Platform at $9900. Other research universities have commercially available, such as Rice University's Wireless Open-Access Research Platform (WARP)[14]. This platform is available at an academic price of $6500[6]. In order to keep costs affordable, this thesis focuses on the Universal Software Defined Radio Peripheral (USRP) and USRP2 developed by Ettus Research LLC which possesses a base cost of $750 and $1400[21]. Figure 1.1 plots of the cost of these systems by their maximum RF bandwidth. The ideal system would have the most bandwidth (furthest to the right of the graph) at the least cost (lower on the graph). The figure clearly shows the USRP2 is the best balance of cost and RF bandwidth.

Communications systems for the USRP2 can be developed in one of a few environments. The typical development environment is the GNU Radio (GR) platform [21]. GR is an open source project that uses Python to connect signal processing blocks written in C++ in a custom framework. These blocks being connected form a flow graph, which implements a communications system. Multiple languages and custom solutions makes it difficult for developers new to the platform to get started. GR is strongly tied to the Linux platform,

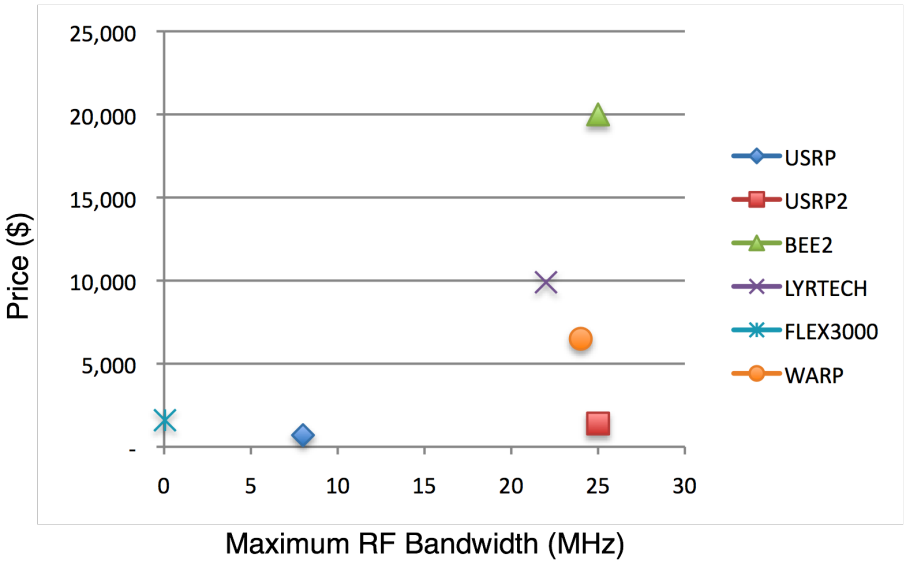


Figure 1.1: RF Front End Comparison

which requires familiarity with this family of operating systems to install the software and start development. GR uses a custom framework to create flow graphs, which the developer has to become familiar with, in addition to Linux, C++ and Python.

Due to the di?culties encountered developing with the GR framework, alternate interfaces to the USRP2 from commercial software were investigated. Other groups have developed interfaces to this hardware, such as the OSSIE pro ject at Virginia Tech [7]. The OSSIE project is largely built upon GR and after a short trial seems to have similar installation and usability issues as GR.

1.3 Thesis Contributions

This thesis provides the following novel contributions:

- An interface in an development environment providing users the ability to leverage existing signal processing libraries to implement modern digital communications sys-

tems. Existing affordable development platforms require the user to learn a new proprietary framework or develop the system from scratch. The interface presented in this thesis will connect low-cost SDR hardware with a development environment that is a common part of communications curriculums and often used in industry for test and verification of communications systems.

- An interface to SDR hardware capable of full reconfigurability by providing full control of the radio front-end to the development environment. Access to each of the dials on the hardware is important to fully realize the reconfigurability of SDRs.

- An interface that is platform agnostic. The current interface to the SDR hardware that is the focus of this thesis is for Linux only. This interface must be compatible across platforms, so after the library supports other operating systems, this interface will get that capability without any further development.

1.4 Thesis Organization

The rest of this thesis is organized as follows: Several SDR platforms that are currently available to the communications systems research and development community are presented in Chapter 2. Chapter 3 consists of the investigation of two alternate interfaces to the USRP hardware. The Simulink interface for the USRP2 is introduced and explained in Chapter 4. Chapter 5 contains conclusions drawn from the project and future work.

Chapter 2

Software Defined Radio Technology

2.1 History of Software Defined Radio

The term software defined radio (SDR) first appeared in Joseph Mitola's 1991 paper "Software Radios: Survey, Critical Evaluation and Future Directions"[27]. Mitola introduces the concept of applying digital signal processing (DSP) on general purpose hardware and using digital to analog converters (DAC) to build digital communications systems. In this paper, Mitola goes on to describe the ideal development environment or computer aided design (CAD) environment[27]:

> Consider the process of designing and developing large scale software radio systems. The transitions from (1) service concept to (2) system definition to (3) simulation and validation to (4) delivery invariably require a mix of radio engineering disciplines. In one vision of the future, an ideal radio CAD environment would facilitate such transitions.

The concepts developed in this paper have laid the foundations for the modern SDR field. Processing power of general purpose hardware is the major technical hurtle to implementing SDR systems. Powerful processors require large amounts of power, making them less ideal for mobile communications systems. Moore's Law predicted the number of transistors that could fit onto a fixed amount of silicon would double every eighteen months [23]. Developments in general purpose processor technology have kept up with the Moore's

Law prediction, resulting in continuing processing capabilities and lower power consumption. Each improvement in silicon wafer technology makes SDR systems more viable. The ability to implement systems capable of rapidly changing communications protocols and dynamically accessing spectrum attracted interest from the United States Military.

2.1.1 SPEAKeasy Military Software Radio

Hazeltine Corporation, now part of BAE Systems Incorporated, was awarded a contract by the Department of Defense to develop a software defined digital communications system. The project, called SPEAKeasy, was divided into two phases. The first phase ran from 1992 to 1996 and involved the creating of a proof-of-concept that software defined radios could fulfill military applications. In 1996, the project went into phase two, implementing existing radios in the SDR framework[24]. A description the the rapid prototyping capabilities of SDR are outlined in Raymond Lackey and Donald Upmal's 1995 paper on the project[24]:

> In the past, a military radio was developed for a 30-year lifetime. It performed a single function, and was optimized for a particular field application. This was primarily caused by the slowly evolving technology and the difficulty of fitting the military users needs into the package space available. Today, commercial applications are driving technology so that the half-life of a component is down to 19 months, that is. the time from product release to the use of its next generation replacement in new designs.

Phase two of the project utilizes SDR's ability to change the communcations systems they implement with an easy change in software. This feature would allow these radios to become compatible with any of the 15 existing military radios re-implimented for this project or quickly become compatible with any radio system used by U.S. Allies. The ability to bridge incompatible communications systems make SDRs ideal for emergency response. As each services responds to a scene, they would be able to download the radio system ideal for the current situation. These capabilities could not be realized without some framework for standardization of SDR technology.

2.1.2 Modular Multifunctional Information Transfer System Task Group

An offshoot of phase one of the SPEAKeasy project was a need to organize a standards committee for the emerging SDR field. The Modular Multifunctional Information Transfer System (MMITS) Task Group held its first meeting March 13th 1996 [1]. Approximately 100 attendees representing the Department of Defense, defense contractors and other commercial companies came together to organize the VMEbus International Trade Association (VITA)[1]. MMITS became the SDR Forum for their twelfth meeting in December of 1998 and still exists today[2]. The forum provides regular meetings for individuals working in the field to get together and discuss current topics.

2.1.3 Joint Tactical Radio Systems

In 1997 the US Military put out a Mission Needs Statement outlining the requirements for a communications system that would be interoperable across all branches of the military [22]. The proposed system would include handheld radios, vehicular (planes, helicopters, cars and trucks) radios, ship based radios and fixed station radios. The project became known as the Join Tactical Radio System [22]. The project has been going over budget since 2005, but Boeing's Cluster 1 program for vehicle-mounted radios has reached $21.6 billion. General Dynamic's Cluster 5 program, consisting of the handheld, manpack and embedded radios has reached $11 billion. These two programs are over budget by $8.9 billion and only represent part of the JTRS program[3]. The project is leveraging SDRs rapid reconfigurability to be compatible with 25 to 30 families of radios currently used by the different branches of the US military. New waveforms are being develop for the project that will ensure secure communications into the future.

Interoperability for this large project comes from the use of the Software Communications Architecture (SCA)[11]. The specification defines the interfaces between hardware

and software. With the interface defined, multiple venders can develop either hardware or software and all of the components would work together. The SDR Forum and the Software Based Communications Domain Task Force are developing on a commercial standard from the SCA[10].

2.1.4 Anywave®Base Station

Vanu®, Inc. developed the Anywave Base station, the first software radio to be certified by the U.S. Federal Communications Commission (FCC)[12]. Cellular base stations were an ideal application for early SDRs. Cell towers are widely distributed, stationary and require frequent updates. Telecommunications providers would have to send a crew to each cellular tower and update the hardware to roll out a new communications standard on the network. SDR technology enables the providers to rollout a new standard by downloading new software to servers located either at the tower, or at a centralized data center. Providers could launch instances of radios as they were needed, instantly responding to the demands of their users. This base station did not include any custom hardware, running entirely on standard servers. Cellular towers do not have the same stringent power requirements that handheld mobile devices must adhere to, working around one of the drawbacks of using general purpose hardware for signal processing. The company was founded in 1998 and is located in Cambridge, Massachusetts. The company was founded by Vanu Bose, an MIT graduate who worked on the SpectrumWare project at the MIT lab for Computer Science as a graduate student[13]. The experience from the SpectumWare project would lay the foundations for Vanu Inc.

2.1.5 IEEE 802.22 - Wireless Regional Area Networks

In 2004 the IEEE identified a need for a wireless standard to provide broadband internet access to remote and rural areas. The 802.22 Working Group was started to develop this

standard[4]. The FCC has reserved large parts of the wireless spectrum for television broadcast. In comparison to unlicensed bands such as the ISM band, spectrum usage in the bands reserved for television broadcasts is very low. An FCC report cites 70% of radio spectrum is underused in different locations at different times[35]. To deal with spectrum congestion this standard will allow unlicensed devices to operate in frequencies designated for television. The television broadcasters and receivers are referred to as the incumbent users or devices. In order to prevent interference with incumbent users, cognitive radios (CRs) will be used. This is the first IEEE wireless standard to use CR, a technology enabled by SDR. Using both radio and software agility, the radios can adapt to changing channel conditions and provide consistent service without interfering with incumbent users.

The standard aims to provide broadband wireless access to remote areas. The services will be of similar speeds to cable and DSL, but will have a much greater range than other wireless standards to reach users who cannot access these technologies. The standard is centered with this use in mind, but will be versatile enough to be used in suburban and urban settings as well (such as college campuses, housing developments etc.) The 802.22 network will "provide services such as data, voice, as well as audio and video traffic with appropriate Quality-of-Sercice (QoS) support." [20] In order to provide QoS support, the network will have to support different classes of traffic, similar to ATM networks.

The frequencies reserved for TV broadcasting were chosen because they are ideal for long range radio communications. That same fact makes them deal for 802.22 networks. "In the US, TV stations operate from channels 2 to 69 in the VHF and UHF portion of the radio spectrum. All these channels are 6 MHz wide, and span from 54-72 MHz, 76 - 88 MHz, 174 - 216 MHz and 470 - 806 MHz." [20] The 6 MHz bandwidth per channel will have important impacts on the standard, since the smallest and most common unoccupied sections of spectrum will fall into 6 MHz units. The Working group is still debating how to

include international standards, which would increase the range of frequencies to 41 to 910 MHz and channel bandwidths of 6, 7 and 8 MHz. The ability to dynamically access these spectral ranges would not be possible without SDR technology.

2.2 Software-Defined Radio Basics

SDRs move the transition between hardware and software as close to the antenna as possible, as shown in Figure 2.1. The figure shows the generic signal processing steps performed by an SDR, from the generation of raw data to the modulation of the signal, and from transmission across the channel to recovering raw data. The vertical dashed line indicates the transition from hardware to software [34] . The data can come from a variety of sources, where it is then compressed and error correction encoding is performed. This compressed and encoded data is then modulated and sent to the RF front end. The RF front ends used for this thesis are the USRP and USRP2. The USRPs are designed to upconvert baseband signals to passband frequencies, then amplifies and sends the signals over the air. The receiving USRP then receives the signal and downconverts the signal from passband to baseband frequencies. This data is sent to a host where timing recovery, synchronization and equalization are performed. The signal can then be demodulated, error checked, and corrected if possible. The data is uncompressed and sent to whatever kind of sink is appropriate. Doing the majority of signal processing in the software domain allows for rapid prototyping and reconfigurability[34] . Costs associated with the software are relatively low, with the software either being offered for free under the GNU Public License (GPL) or being licensed by the research institution for other applications. Analog components located at the RF front end are the primary cost of SDR platforms.

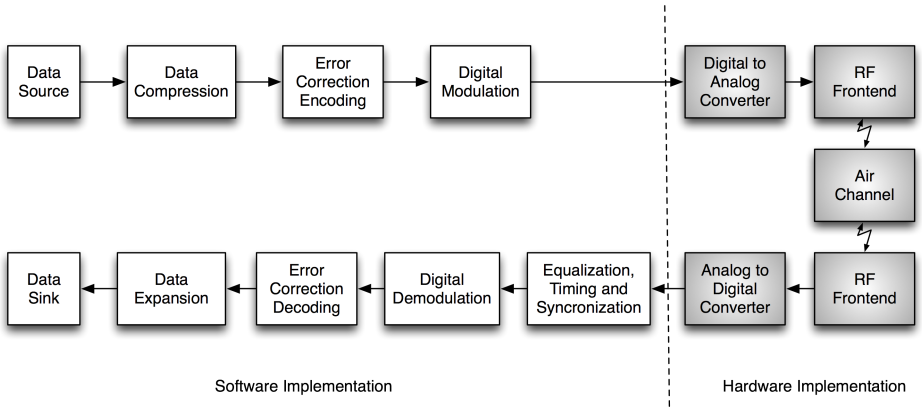


Figure 2.1: Software Defined Radio Block Diagram

2.3 Comparison of Existing Software Defined Radio Platforms

RF front ends used by other research groups were studied to aid in the section of the one used for this project. The University of Kansas developed their own agile radio called the Kansas University Agile Radio(KUAR) [25], requiring a large team of students with a wide variety of technical backgrounds and five years to develop a hardware platform sponsored by the NSF and DARPA. The Centre for Telecommunications Value-Chain Research (CTVR) at the University of Dublin, Trinity College also uses a homemade solution, the Plastic Project [29]. The Center for Wireless Telecommunications (CWT) at Virginia Tech has a homemade solution that includes genetic algorithms to optimize the radio's configuration [29]. The University of California at Berkeley uses the Berkeley Emulation Engine 2 (BEE2) complete with five Xilinx Virtex 2 Pro FPGA units the entire radio is designed in Simulink. The Simulink model is then converted into HDL and combined with the Xilinx System Generator to put the entire radio onto FPGAs [26]. This allows for low latency communications while providing reconfigurability and lots of processing power. Custom solutions require more resources than the average research group can acquire. For a more

accessible hardware solution, the USRP family of products were selected.

Table 2.1 compares some commercially available RF front ends. The table compares the maximum RF bandwidth of each of the systems, indicates where the processing is done and on what, now the device connects to the computer and cost. The processing partition refers to the location of the processing of the baseband signals, either on the device itself, on a host system, or a mix of the two. The processing is done using General Purpose Processors (GPP), commonly the x86 architecture, or using Field Programable Gate Arrays (FPGAs). The cost does not include the cost of the host system or the daughterboards required by each of the systems.

Table 2.1: SDR RF Frontend Comparison Chart

	USRP	USRP2	BEE2	LYRTECH	FLEX 3000	WARP
Year of release	2005	2008	2007	2006	2005	2008
RF bandwidth (MHz)	8	25	25	5, 7, 20 or 22 [1]	0.048	24
Processing partition	Off-board	Mixed	On-board	On-board	Off-board	On-board
Processing architecture	GPP	GPP FPGA	FPGA	GPP FPGA	GPP	FPGA
Connectivity	USB2	GigEthernet	USB Ethernet	Ethernet	Firewire	SATA HSSDC2
No. of antennas or RF paths	4	2	16	2	2	4
Cost	$700.00	$1400.00	$20,000.00 [2]	$9900.00	$1599.00	$6500.00 [3]

[1] Depends on RF module
[2] Estimated by [18], processing only
[3] Academic Price, $9500.00 for commercial users

The USRP and USRP2 were developed by Ettus Research and offer the lowest cost options. These units are connected to a PC, with the majority of the signal processing done on this host system. Using USB to connect the USRP to the host severely limited the maximum bandwidth it can achieve and a smaller FPGA forces all of the signal processing outside of upconversion to the host. The USRP2 has a much higher maximum RF bandwidth and a larger FPGA enables some processing to be done on the device itself.

The BEE2 is the Berkley Emulation Engine 2. This board has 5 Virtex 2 Pro Xilinx FPGAs and all of the signal processing is done on board in the FPGAs. The entire radio is implemented in Simulink, compiled into HDL and downloaded onto the FPGAs [18]. The price, as estimated in a research paper, indicates the cost is around $20,000 [18]. This price is out of the range for many research institutions new to the field of software defined radio, and is too high to deploy these units to an entire lab in a classroom setting.

LYRTECH also has a single unit SDR solution. This board includes a general purpose processor and FPGA on-baord to do all of the signal processing. This system also includes the processing on the board, increasing costs while improving the ability to achieving the full range of sample rates. While less expensive than the BEE2, this board is significantly more expensive than the USRP2 [15].

Flex Radio systems offers a line of SDR hardware for Ham radio applications. These units include the RF front ends, unlike the other units being compared. These front ends are optimized for the Ham radio bands, with a frequency range or 10 kHz to 60 MHz and a maximum RF bandwidth of only 48 kHz [5].

Rice University has developed the Wireless Open-Access Research Platform (WARP). WARP has similar capabilities to other SDR hardware but costs more than the USRP2. A Virtex-4 FPGA allows for significant processing to be done onboard. The Radio Board can be tuned to frequencies in the 2.4 and 5.8 ISM bands[14].

The LYRTECH unit and BEE2 are good options for all-in-one applications, but are significantly more expensive than the USRP family of products. The FLEX 3000 is in the same price range as the USRP products, but are not nearly as versatile, being focused on Ham radio applications and frequencies. The USRP2 products offer the most versatility for the lowest cost.

2.4 The Universal Software-Defined Radio Peripheral Platform

The USRP product family has been developed by Ettus Research LLC [21]. The company started with the USRP and released the USRP2 to a limited number of developers in 2008. The USRP2 officially went on sale in May of 2009.

2.4.1 The Universal Sofwater-Defined Radio Peripheral

The USRP is an inexpensive and versatile SDR platform, consisting of a motherboard with a variety of daughterboards. The motherboard interfaces with a host system using a USB2 interface. Up to 4 channels, consisting of 2 send and 2 receive channels, are multiplexed and demultiplexed using a FPGA located on the motherboard. While 4 channels are possible, the USB2 link is commonly the bottleneck of this system and all 4 channels are not commonly used at the same time. The FPGA also upconverts and downconverts signals to and from an intermediate frequency (IF) stage using a cascaded integrator-comb (CIC) filter. From the FPGA, the signal at IF is sent and received to and from the daughterboards using analog-to-digital converters (ADCs) and digital-to-analog converts (DACs). A block diagram of the motherboard can be found in Figure 2.2.

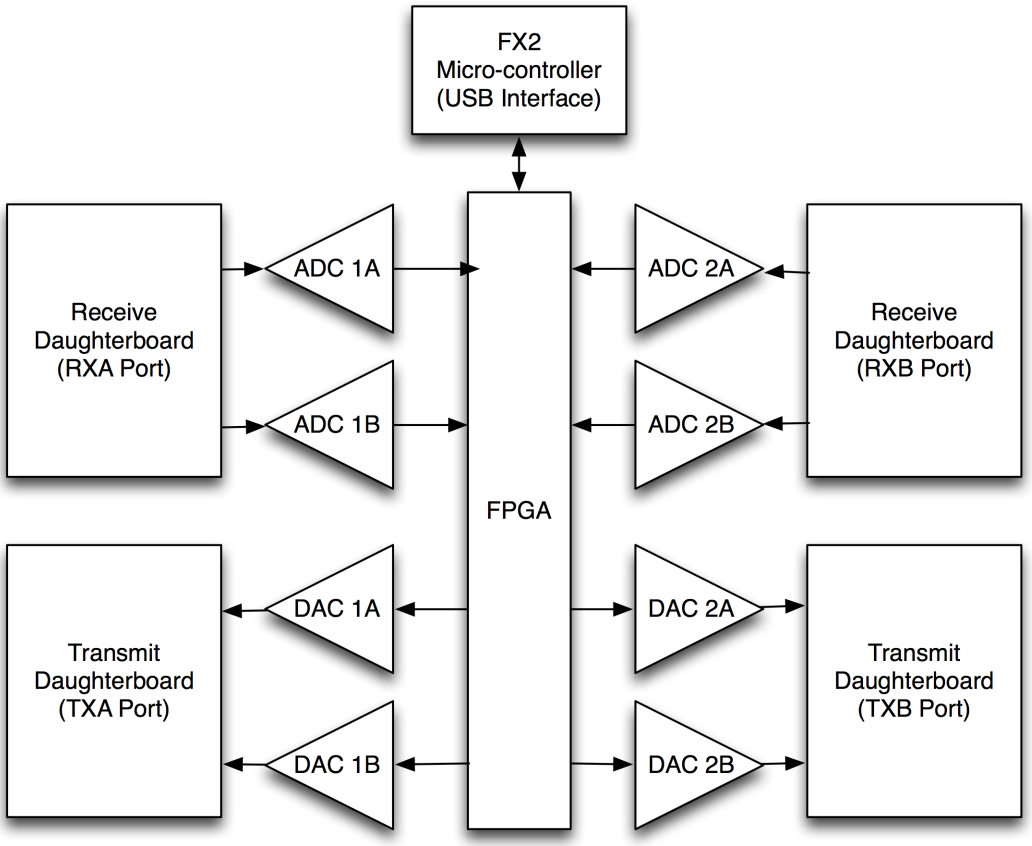


Figure 2.2: USRP Block Diagram

2.4.2 The Universal Software-Defined Radio Peripheral 2

The USRP2 motherboards provide the interpolation and decimation filters on an FPGA and a DAC / ADC outputting an analog signal at an intermediate frequency (IF). To transmit data, a daughterboard containing analog circuitry to up convert this signal to the passband frequency set by the software. The motherboard also has a gigabit Ethernet interface to the host system and a CPLD for loading the FPGA Bitfile from the SD card to the FPGA. Figure 2.3 shows the block diagram of the USRP2 motherboard.

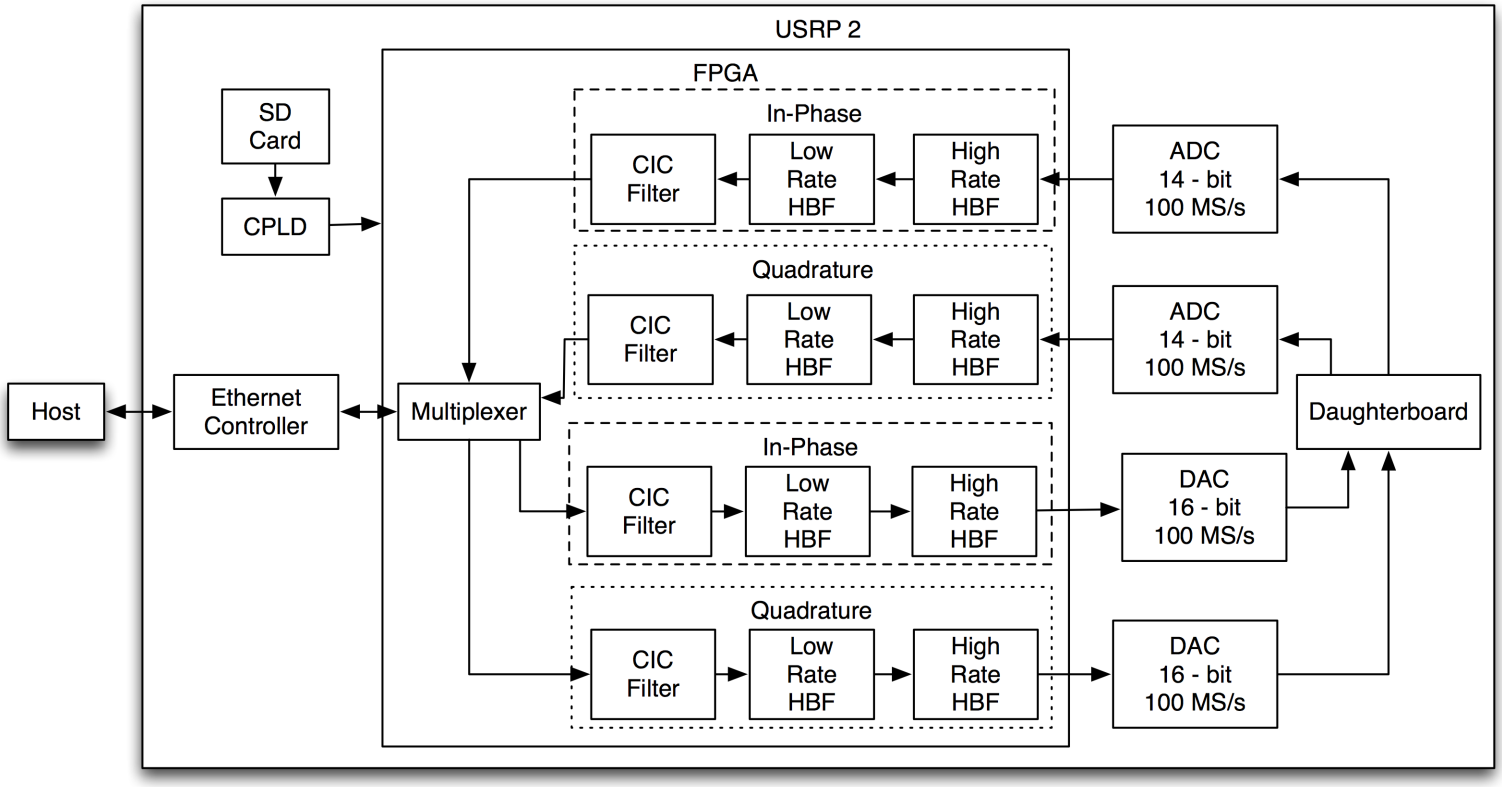


Figure 2.3: Block Diagram Showing Data Paths Through the USRP2

Samples created on the host are sent to the USRP2 over an Ethernet interface. The I and Q data sent over the interface are scaled interleaved 16 bit shorts. A demultiplexer on the FPGA then sends the samples down two different filter chains, one for the in phase and one for the quadrature. There are three interpolation filters in each chain, a low rate half band filter, a cascaded integrating comb filter and a high rate half band filter, as shown in Figure 2.4. At least one of of the half band filters must be enabled, so the minimum interpolation rate is 2. The CIC filter can be set between 1 and 128, and the second HBF also has a factor of 2, so the maximum interpolation rate is 512. This data is then sent to the DAC, which always receives data at 100 mega-samples per second. The data rate between the DAC and the FPGA does not change, so the data rate over the Ethernet interface is dependant on the interpolation rate.

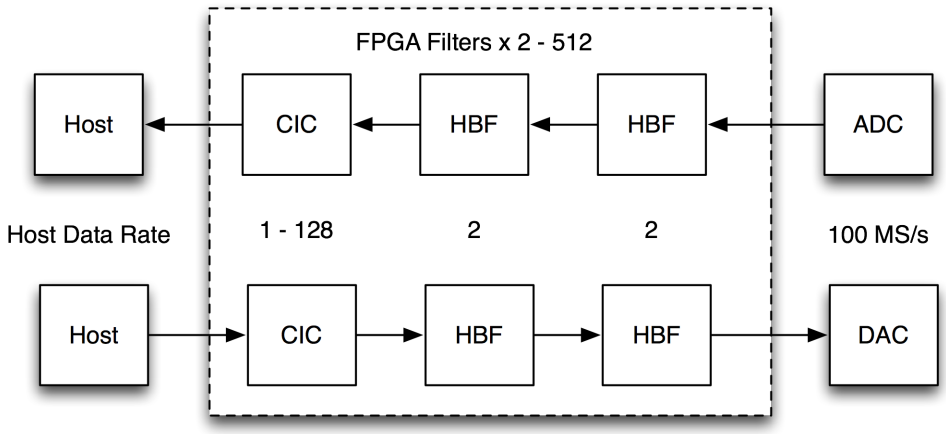


Figure 2.4: USRP2 Filters Block Diagram

A high interpolation rate also means the host has to generate fewer samples. Table 2.2 shows the host sample rate and related maximum RF bandwidth by interpolation / decimation factor. The receive chain is the same, data is sent from the ADC to the FPGA at 100 mega-samples per second, goes through decimation filters and multiplexed to be sent over the Ethernet interface.

$$\text{Host Sample Rate} = \frac{\text{ADC Rate}}{\text{Decimation Rate}} \tag{2.1}$$

$$\text{Maximum Bandwidth} = \frac{\text{Host Sample Rate}}{2} \tag{2.2}$$

Equation (2.1) was used to calculate the host sample times. The ADC rate remained constant and is divided by the decimation rate selected by the user. The Nyquist rate [30] was then used to calculate the maximum RF bandwidth as seen in Equation (2.2).

Table 2.2: USRP2 Data Rate Table

Interpolation Rate or Decimation Rate	Host Sample Rate	Maximum RF Bandwidth
512	195 kS/s	97.6 kHz
256	390 kS/s	195 kHz
128	781 kS/s	390.5 kHz
64	1562.5 kS/s	781 kHz
2	50 MS/s	25 MHz

When the USRP2 is powered on, an onboard CPLD (complex programmable logic device) reads the first megabyte of the attached SD card. This megabyte is the bit file for the FPGA. After the bit file is loaded into the FPGA, the CPLD goes into a pass-through mode so the FPGA can access data on the SD card.

2.4.3 USRP and USRP2 Comparison

Table 2.3 compares the two versions of USRPs. The USRP2 uses a Gigabit Ethernet connection to the computer, alleviating the USB2 bottleneck. The ADCs and DACs are faster with more bits, making them more accurate, and there will be 1 Megabyte of onboard SRAM on the USRP2 if the user wants to write custom FPGA code. The FPGA has been changed to a Spartan 3 and is larger than the Cyclone on the USRP. The USRP2 has only one transmit and one receive channel, simplifying the multiplexing circuitry on the

FPGA and freeing up more resources of the FPGA. The USRP and USRP2 are affordable off-the-shelf hardware solutions, making them ideal solutions for organizations uninterested or unable to develop in-house SDR hardware.

Table 2.3: USRP Comparison Chart

	USRP	USRP Version 2
Daughterboards	2	1
Connection	USB	Gigabit Ethernet
Max RF Bandwidth	8 MHz	25 MHz
FPGA	Cyclone 1, EP1c12	Spartan 3, XC3S2000
Logic Elements	12,060	46,080
ADC	dual 64MHz, 12-bit	dual 100 MHz, 14-bit
DAC	dual 128 MHz, 14-bit	dual 400 MHz, 16-bit
RAM	None	1 Meg SDRAM
Cost	$700.00	$1400.00

While the number of simultaneous daughterboards is reduced with the USRP2, the increase in connection speed with the host greatly increased the maximum RF bandwidth. The larger FPGA enables advanced users to move some of the signal processing steps directly onto the device itself by developing a custom bitfile. The improvements do come and a relatively substantial cost, but compared to other systems the USRP2 is still very affordable.

2.4.4 USRP and USRP2 RF Functionality

The daughterboards are RF front ends that plug into one of four sockets on the motherboard and are each designed to support a wide range of different radio frequency bands. The Basic Tx and Basic Rx boards come individually, while the RFX2400 board comes with the transmit and receive circuitry on a single board as seen in Figure 2.5. Analog components on these boards upconvert, downconvert and amplify the IF signals to the desired RF and broadcasts the signal.

Table 2.4 shows the daughterboards used at WPI. The variety of daughterboards enable

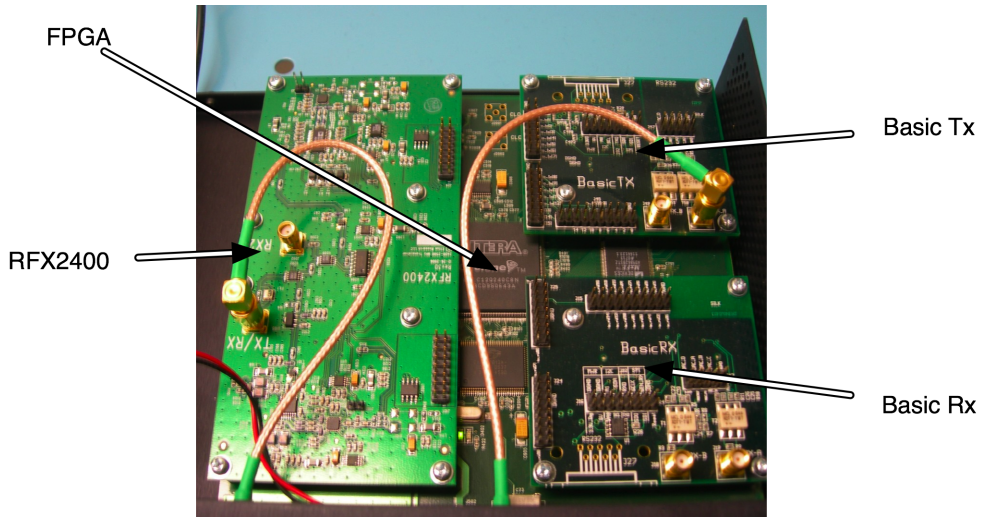


Figure 2.5: USRP Daughterboards

the use of a wide range of frequency ranges. A larger selection of daughterboards are available from Ettus Research [21].

Table 2.4: Daughterboard Comparison

Daughterboard	Frequency Range	Transmit Power
Basic Tx / BasicRx	1 MHz to 250MHz	none
RFX2400	2.3 GHz to 250MHz	50 mW / 17 dBm
XCVR	2.4 GHz to 2.9 GHz	100 mW / 20 dBm
	4.9GHz to 5.9 GHz	
TVRX	50 MHz to 250 MHz	Receive only

The interface for developing daughterboards is open, so research groups can develop custom daughterboards to fulfill specific design requirements. This daughterboard was designed to maximize the range of center frequencies that could be set in software without having to change daughterboards[17].

2.5 Chapter Summary

SDR technology has roots in the military sector but is growing rapidly in the commercial sector as the market requires more spectrum for high bandwidth communications devices. While there are a fair number of Radio front end available for SDR development, the USRP2 offers the best balance of versatility and low cost. The gigabit Ethernet interface with the host system enables a max RF bandwidth of 25 MHz and a wide range of daughterboards can enable transmit center frequencies of up to 5.9 GHz.

Chapter 3

Initial Prototyping Interfaces

The difficulties developing with the GR framework led to a search for alternate ways to interface to the USRP and eventually the USRP2. Two interfaces were developed, the first using the socket interface on the computer to locally connect MATLAB with GR and the second developed a MATLAB function to directly connect to the USRP. These interfaces were investigated for the original USRP, which has slightly different design considerations than the USRP2. While these interfaces were being developed, a research group at the University of Karlsruhe, Germany developed a Simulink interface to the USRP[9].

3.1 Connecting MATLAB to the USRP using Sockets

An alternate approach for interfacing between MATLAB and GR used sockets. MATLAB and GR both have add-ons to enable communication over this computer network interface. A signal processing block was written by Jamie Cooley providing both TCP/IP and UDP sockets for GR [19]. While MATLAB can connect to open sockets, the built-in functions cannot open a socket for another program in order to be connected. Peter Rydester developed a TCP/IP MEX file to provide both host and client functionality to MATLAB [32]. With these two interfaces, data can be easily sent from one software package

to the other.

3.1.1 Overview

Figure 3.1 shows the flow of data generated in MATLAB then sent to a GR flow graph using the sockets interface. This flow graph maintains the connection to the USRP where the data is up-converted and broadcast. The receive chain is simply the reverse.

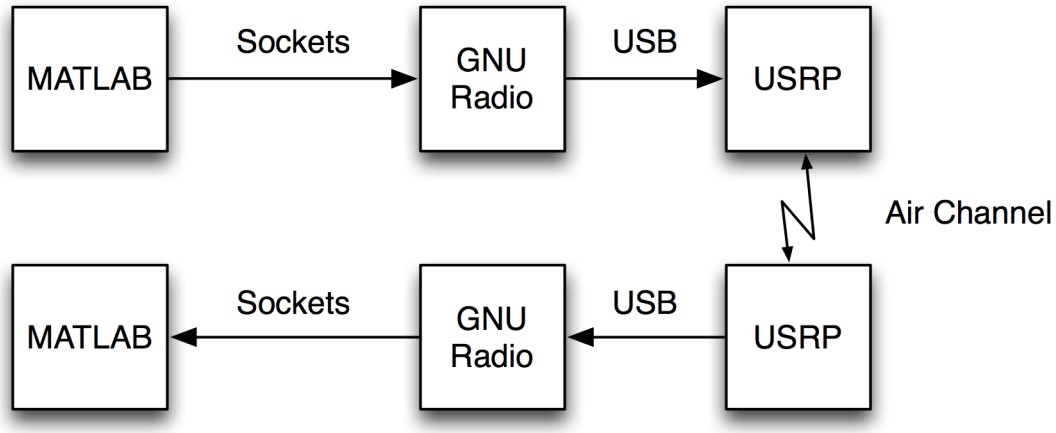


Figure 3.1: MATLAB and GNU Radio Flow Graph

Figure 3.2 shows the simple GR flow graph required to pass data from MATLAB to the USRP. This simple flow graph consists of three blocks, one to maintain the socket interface, another to convert the floating point data necessary for the network connection to the complex data and the third configures the USRP and maintains the connection to it. When run by the user, this flow graph opens a socket on the local host for MATLAB to connect to. I and Q data from the USRP is converted to floating point data and the samples can be sent to the host system.

Appendices A through D have the corresponding code for each of the blocks shown in Figure 3.1. To run the system, the user initiates the GR flow graphs, runs the MATLAB transmitter and then the MATLAB receiver. Configuring the USRP has to be done

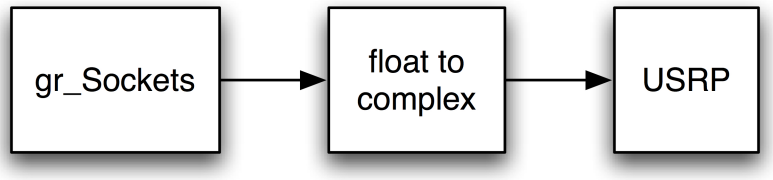


Figure 3.2: GNU Radio Sockets to USRP Flow Graph

when starting the GR flow graphs and the device cannot be reconfigured by the MATLAB transmitter or receiver.

3.1.2 Test Cases

This interfaced was tested using two simple systems to verify the samples being generated in MATLAB are being sent using the USRP hardware. The first test is a simple sine wave and the second a basic digital communication system.

Continuous Sine Wave

While developing this system, a number of minor issues came up. The easiest problem to overlook would be the code that enables, or turns on, the transmitter. The user wouldn't know to include this line and the radio would not error. After enabling transmission on the daughterboard using the command 'subdev.set_enable(True) ', a sine wave created in MATLAB was sent to GR, up converted to 2.4GHz and wirelessly transmitted to the receive side using the system in Figure 3.1.

A sine wave, being sent at 48,000 samples per second, was correctly received and the data collected in MATLAB. The sample rate of 48 kHz was chosen for the audio based testing of the system, 48 kHz being the minimum Nyquist frequency to sample 24 kHz audio samples[30]. To process the signals broadcast on a regular PC, the RF signal must

be down-converted from some center frequency, set by the USRP. The receiver did not realize it was receiving the transmitted data because the USRP was tuned to the wrong center frequency. One of the outputs from GR was misinterpreted as indicating the radio was broadcasting at 2.40401 GHz. A sine wave was being detected here, causing a false belief that the receiver was working. This issue was not discovered until another digital modulation type was implemented and tested.

On-Off Keying

The most basic modulation scheme is *On-Off Keying* [33]. This modulation scheme sends any signal to represent a "1", and nothing to represent a "0". To simplify the design, the transmitter will keep a counter of the number of symbols sent, all odd symbols will be treated as a "1", and even symbols a zero, making it easy to figure out what is expected from the receiver and verify the functionality of the interface. The receiver will receive the data and display it through a MATLAB plot. To aid in tuning the USRP, a GR GUI has been developed with an Fast Fourier Transform (FFT) of the incoming signal. This display will allow fine tuning of the system, and aid in debugging problems.

At first, almost identical code was used from the continuous sine wave transmitter and receiver, just modifying the transmitter to include either a sine wave or zeros. The transmitter was being displayed on a spectrum analyzer, but it could not be decoded. A sockets interface was then added to an existing USRP receiver that provided GUI configuration of the USRP and a FFT of the data being received. The FFT in this GUI enabled tuning of the USRP to verify the signal was received, as seen in Figure 3.3. The receiver was then tested using the DBPSK transmitter introduced earlier. The code for this receiver can be found in Appendix E. With confirmation of a working receiver, the transmitter could then be developed.

The transmitter sends one of two waveforms, either a sine wave of one kilohertz, or zeros,

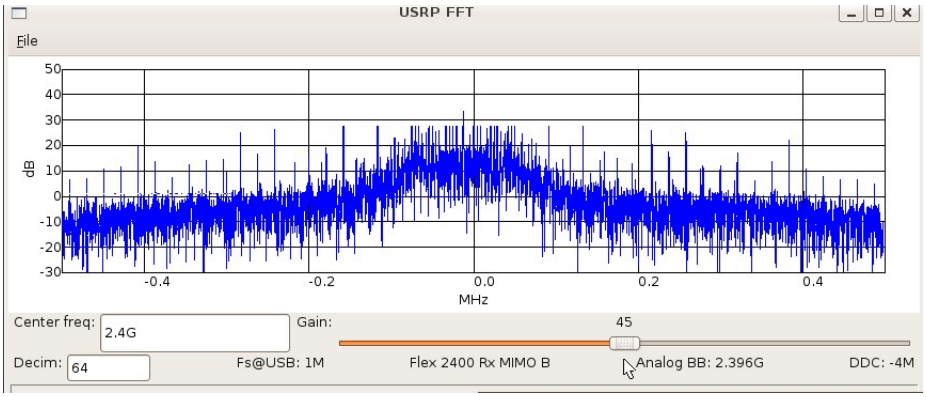


Figure 3.3: FFT of Received Data

thus creating on off keying. The transmitter keeps a counter of the number of packets sent, each packet containing 48,000 samples, or one second of information. Odd packets are treated as 1's and the sine wave is sent, even packets are treated as a zero. This MATLAB code can be found in Appendix F and is very similar to the code used for the sine wave receiver in the previous section. The received data can be seen in Figure 3.4.

The flow graph for the transmitter was also modified. A gain stage was inserted between the socket block and the block that converts floating point data to complex I and Q data. A gain of 100 is applied, so the USRP broadcasts a stronger signal. If too large of a gain is applied the transmission becomes distorted.

3.1.3 Results and Discussion

While this interface is functional, it still involved a flow graph created by GR and running both a GR program and then the MATLAB program. Removing the flow graph framework would allow for more direct debugging, simpler systems and fewer wasted clock cycles. The network layer removes direct control of the USRP from MATLAB, the program doing all of the signal processing. Enabling this control would require a second connection between the two programs to send messages to GNU radio changing the radio's parameters and a more

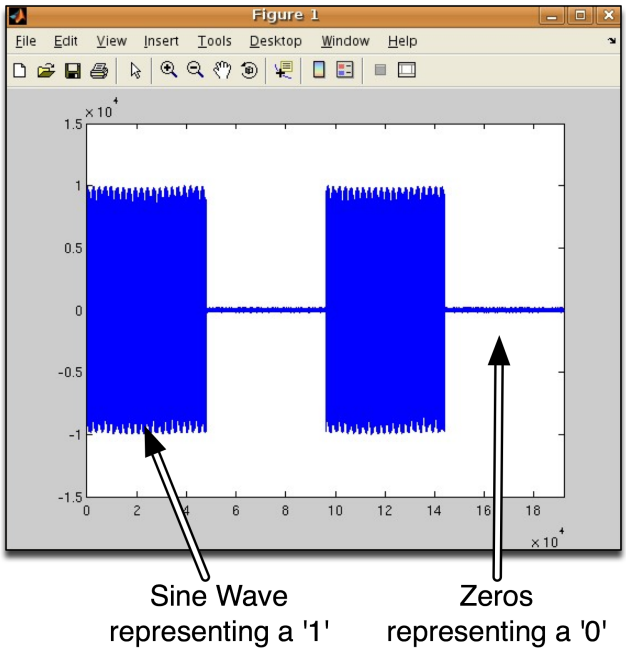


Figure 3.4: Received On-Off Data in MATLAB

complex GR program. This work lead to an interface that directly controlled the USRP hardware without a GR flow graph.

3.2 Direct USRP Interface using a MATLAB MEX Function

Creating a MEX function to configure the USRP would allow direct control of the hardware from MATLAB and remove the majority of the GR code from development. The function would still use the libraries that communicate with the hardware, but would remove the rest of the code, including the use of sockets.

3.2.1 Overview

Removing the flow graph framework and having MATLAB directly control the USRPs would require a direct interface to the GR libraries that control the USRP. The main C++ library to be used is the "usrp_standard" as used by some test programs and a program

called "USRPER." These libraries provide the controls necessary to configure the USRP. These files are written in C++ enabling the creating of a MEX function. The current MEX function can be found in in Appendix G; which can instantiate a USRP object, set it up and send data to the USRP. The M code in Listing 3.1 displays the user interface for the MEX function.

Listing 3.1: User Interface for USRP MEX funtion

```
1    USRP_Tx('setup', CenterFreq, SigPower, InterpolationRate)
2    USRP_Tx('setFrequency', NewFrequency)
3    USRP_Tx('setPower', NewPower)
4    USRP_Tx('setInterpolationRate', NewRate)
5    USRP_Tx('sendData', data)
```

Line 1 of Listing 3.1 sets up a USRP transmitter with a specified center frequency, signal power and interpolation rate. Lines 2 through 4 allow the user to change these parameters of the radio, even after the transmission has been started. Line 5 would be used repeatedly to send data using the configured USRP. The M function remains the same, USRP_Tx, and the first parameter passed to the function specifies the desired command. The remaining parameters depend on the specified command.

MEX functions in MATLAB create objects that are not cleaned up between repeated calls, enabling multiple calls on the same USRP object. The first command initializes the USRP and allows the user to setup the USRP. The following three lines show examples of setting properties individually and are not needed if the values are static and set in the first command. The second to last command prepares the USRP to receive streaming data and the last command actually sends the data to the device.

This interface is not fully implemented, but a switch statement in the MEX function will read the first argument, the command, and act appropriately. Currently the MEX function calls each of these functions during initialization and sends data the MEX function creates to the FPGA. This interface is difficult to test because configuring the daughterboards

without GR has not been accomplished yet.

The C++ code in Listing 3.2 shows the initialization function of the MEX function. Each step of the setup has been broken out into individual funtions. The function calls in this code listing use the default values set in the functions by not passing in any parameters. If the interface was fully implemented, the associated parameters would be passed to these functions. The full code listing of these functions are in Appendix H.

Listing 3.2: MEX Interface Initialization Function

```
1  void mexFunction(
2      int             numOutArgs,     /* number of expected outputs */
3      mxArray         *outputArgs[], /* array of pointers to output arguments */
4      int             numInArgs,      /* number of inputs */
5      const mxArray *inputArgs[]    /* array of pointers to input arguments */
6      )
7       {
8       if (numInArgs < 1||!mxIsChar(inputArgs[0])){
9         mexErrMsgTxt("Invalid mex Input", "First input must be a char array"
10                      "indicating a valid USRP command, see USRP_Tx('help')"
11                      "for list of commands");
12      }
13      mexPrintf("Begin USRP program\n");
14      setupUSRP();
15      setDBFrequency(1000);
16      startUSRP();
17      sendRandDataTest();
18      cleanUSRP();
19      mexPrintf("End USRP programr\n");
20      }
```

When this code is compiled, G++, the GNU C++ complier, successfully finds the libraries required, but the MEX complier returned an "undefined reference" error. This problem was discovered to be a linking error. The makefile was referencing the source code and not the complied C++ library. This issue was addressed, a receiver object was created and received data through a loopback interface. The loopback interface is a configuration for the FPGA on the USRP, where the FPGA simply loops the data it receives to be transmitted back to the host, simulating receiving data. Interfacing to the daughterboards

from this interface has not been implemented, such that no over the air testing could be done with this interface.

The USRP and USRP2 configure daughterboards differently. The USRP requires daughterboard configurations to be read from Python files, where the firmware on the USRP2 holds the configuration. The GR community has not converted the USRP configurations to be compatible with C++ only implementations . In addition to the technical improvements of the USRP2, the way USRP2 handles the daughterboard configuration makes it easier to develop for and firmware updates will enable support for new daughterboards without any further development of the host API's.

3.2.2 Results and Discussion

The release of the USRP2 ended further development of this interface. While a MEX function is a viable option for direct control of the USRP hardware from MATLAB, long term complications from custom daughterboard configurations make the USRP2 a clear choice for easy interface development and long term support. The conversion to the USRP2 also provided an opportunity to change the environment the interface would be developed for, moving from MATLAB to Simulink.

3.3 Chapter Summary

A solution using a sockets interface between MATLAB and GR was easy to implement, but did not provide control of the radio parameters of the USRP. Conversely, a direct MATLAB interface using MEX functions will give the most control over the USRP while keeping as much code as possible in MATLAB, the familiar, easily debuggable software framework. Full implementation of the MEX functions would require the re-implimentation of daughterboard configuration files, which are updated regularly and would require lots of support to maintain.

Hardware improvements of the USRP2 over the USRP make it the clear choice for further development. The transition in hardware also provided an opportunity to change the environment the interface would be used in. MATLAB is its focus on batch processing, ideal for some situation, but not for real time applications. Simulink is a time aware, stream based program, making it better suited for streaming applications such as SDR. The choice of the USRP2 also alleviates the daughterboard configuration issue, simplifying development and enabling the interface to use all the daughterboards supported by the USRP2 firmware.

The research group at the University of Karlsruhe, Germany has released a blockset for the USRP. The blockset provides an interface to the hardware from Simulink models. The masks configure the daughterboards, but do not provide a way to reconfigure the hardware from the model[9].

Chapter 4

Proposed Graphical Interface for Wireless Design and Innovation

4.1 Introduction

Hardware improvements of the USRP2 over the USRP make it the clear choice for future communication systems experimentation and development. The transition in hardware also provides an opportunity to change the environment that the interface would be used in. MATLAB is focused on batch processing, which is ideal for several situations, but not for real time applications. On the other hand, Simulink is a time aware, stream based program, making it better suited for streaming applications such as SDR. Simulink is also the product of choice for code generation of models. Code generation can turn Simulink models into ANSI Portable C or HDL code, providing a better framework for real time processing.

The blocks that were created for this interface are based on C++ S-Functions. S-Functions provide Simulink with a set of functions to call to preform the operations of the block. These S-Functions use a mask to provide the user an interface for configuring the block. Figure 4.1 shows how S-Functions, masks and subsystems are used to create Simulink models. Each block in the model has a mask, the parameters set in the mask are then sent

to the S-Function, which is called during the simulation. S-Functions can be made using a variety of programming languages, but C++ was chosen for this blockset to match the USRP2 library.

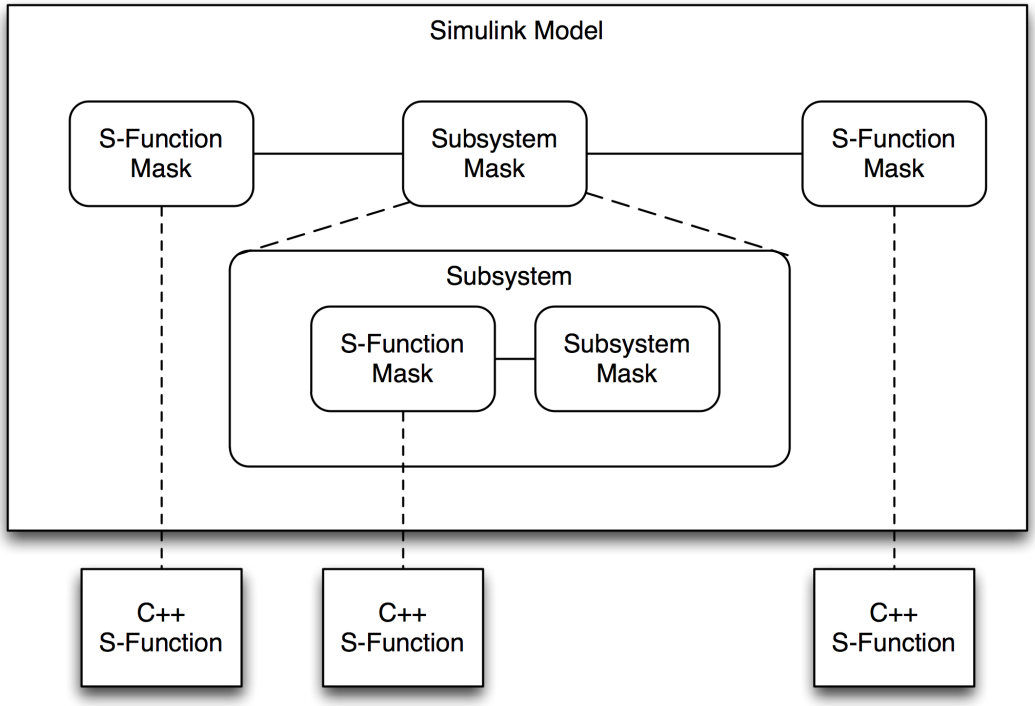


Figure 4.1: Simulink Block: Mask and S-Function Relationship

This project is part of a larger research effort at WPI, as seen in Figure 4.2. This project is focused on creating a blockset to communicate with the USRP2 libraries. By creating a Simulink interface to this hardware, existing signal processing libraries provided by the MathWorks can be leveraged to create communications systems. Other students are working on the proprietary C++ library and Simulink models including higher layers of the TCP/IP model.

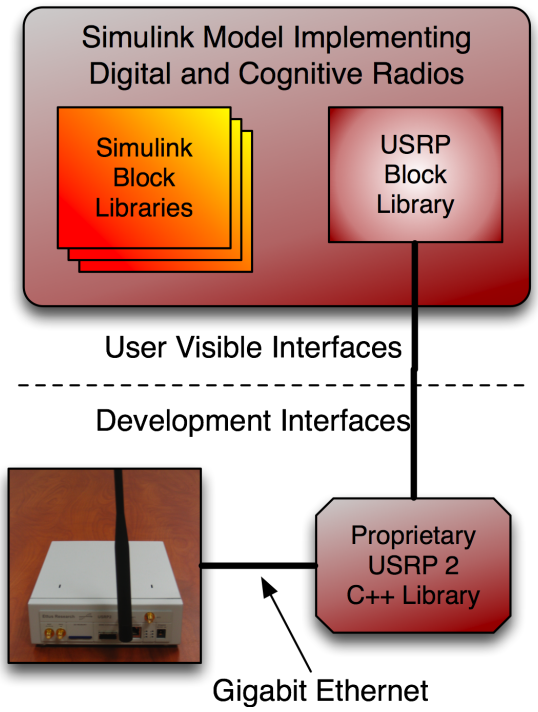


Figure 4.2: How the USRP2 Simulink Library Fits into the Larger Research Project

4.2 User Interface to Control Simulink USRP2 Block

Simulink blocks are published as sets in libraries. The USRP2 Library is in Figure 4.3 with separate transmit and receive blocks. Additional input ports are made available through the mask to enable the model to calculate and adjust the parameters of the radio. Depending on the mask settings, the USRP2s are identified by either the Ethernet interface or the MAC address and this information is displayed on the block.

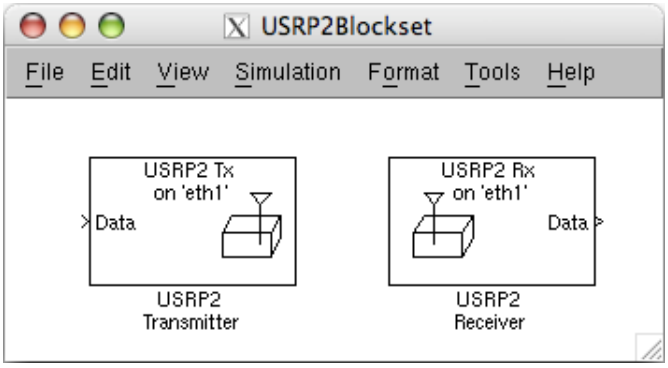


Figure 4.3: USRP2 Simulink Library

4.2.1 USRP2 Transmit Mask

The mask of the transmitter can be seen in Figure 4.4. The mask has some help text and all of the parameters needed to configure the USRP2.

A dedicated gigabit Ethernet interface is commonly used to communicate with the USRP2, so by default the block automatically detects the MAC address of the USRP2 on the specified interface. If more than one USRP2 is on the Ethernet interface, the MAC address can be specified. The exact way to specify the Ethernet interface varies by operating system. Figure 4.5 shows the way to specify the interface on Linux. Figure 4.6 shows how to specify the USRP2 hardware using both the Ethernet Interface and the MAC address.

Connecting more than one USRP2 to an ethernet interface could saturate the Gigabit

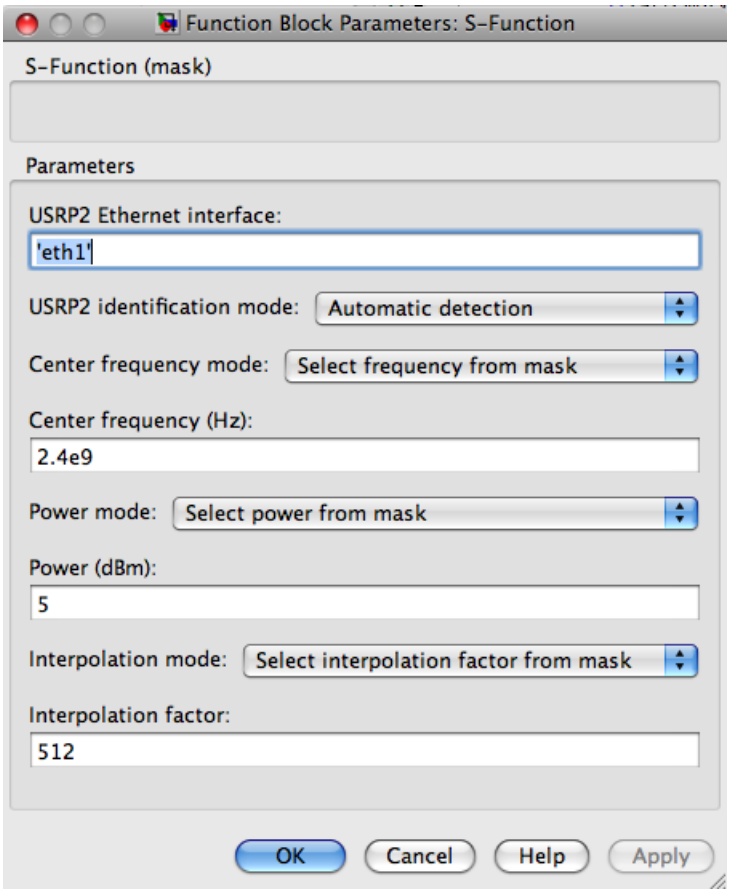


Figure 4.4: USRP2 Transmitter Mask

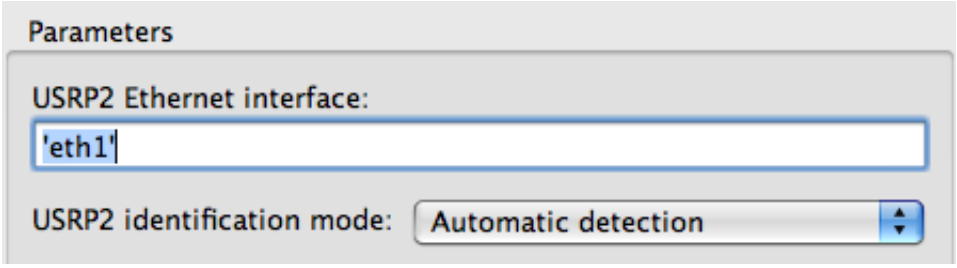


Figure 4.5: USRP2 Identification Parameters Automatic Detection

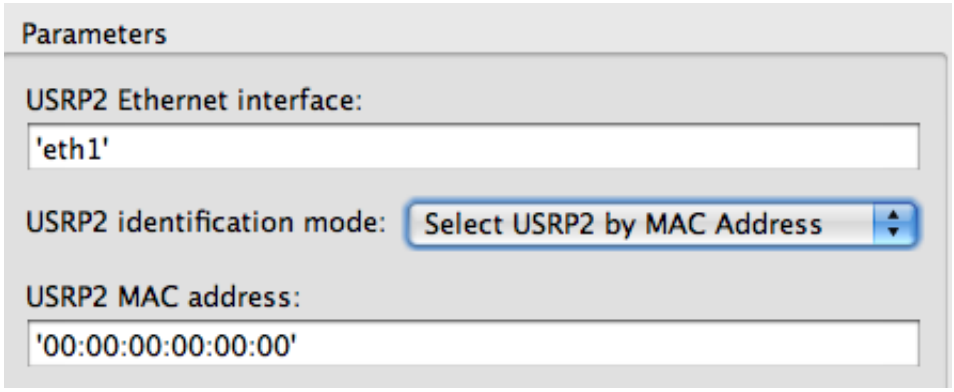


Figure 4.6: USRP2 Identification Parameters Specifying the MAC Address

Ethernet connection if both USRP2 require enough bandwidth. Having more than one USRP2 share a connection could also result in corrupt packets, leading to data loss. The currently library connects to the USRP2 using raw ethernet sockets[16]. These sockets provide error detection, but not error correction, so corrupted packets would not be resent and the packet dropped. Introducing error correction would increase the latency in the system.

The USRP2 has three parameters for the user to control: center frequency, power and interpolation factor. The range for the center frequency and the power are dependant on the attached daughterboard. The Interpolation factor configures filters on the USRP2 as covered in Chapter 2. Figure 4.7 shows the default settings of these parameters.

By default, the parameters of the USRP2 will be statically set in the mask of the block. The blocks will be able to input these parameters from a port, so the parameter can be calculated in the simulation and be changed on the device. Controlling which parameters are visible to the user is done with mask helper functions. The functions are written in M, and the mask helper for the transmitter is in Appendix I and for the receiver is in Appendix J. Figure 4.8 show the mask with the radio parameters hidden.

The interpolation and decimation rates change the sample rate coming from the USRP2

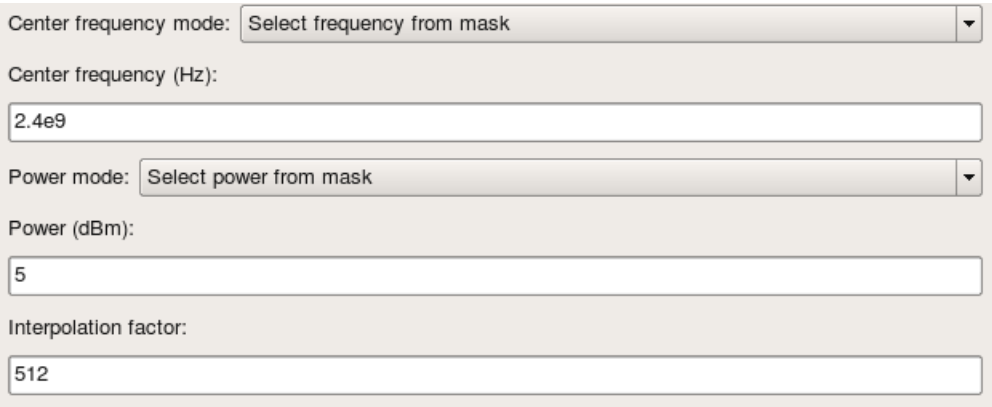


Figure 4.7: USRP2 Radio Parameters set on Mask

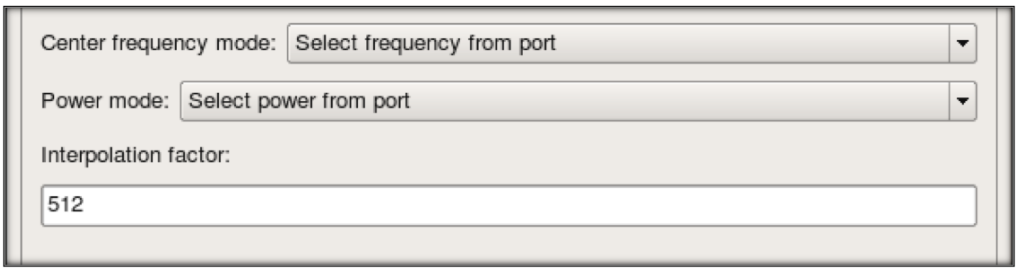


Figure 4.8: USRP2 Radio Parameters set by Port

block in simulink. Simulink currently doesn't support variable rate blocks, so this parameter is no tunable while the model is running.

4.2.2 USRP2 Receive Mask

The majority of the parameters for the receiver are similar to the transmitte. The parameters used to identify the USRP2 are the same, as is the center frequency. The power and interpolation factor in the transmitter has direct parallels in the receiver in the gain and decimation factor parameters.

$$\text{Sample Time} = \frac{1}{\text{Sample Rate}} = \frac{1}{\frac{\text{ADC Rate}}{\text{Decimation Rate}}} = \frac{1}{\frac{100\times10^6}{512}} \tag{4.1}$$

Simulink requires source blocks to specify sample time and frame size. The two settings in Figure 4.9 are for the receiver only. The sample time, or sample step, must use Equation(4.1), this setting reflects the time step between this block being run. The ADC operates at 100 megasamples per second and that sample rate is then downconverted by the decimation factor, the result is the same rate at the host. The sample time is simply 1 over the sample rate. Getting the sample time correct is pivotal to other blocks in the model operating correctly. The frame size sets the number of samples per frame the block outputs.

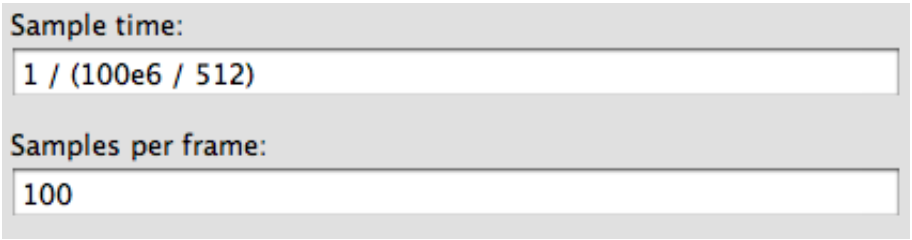


Figure 4.9: USRP2 Receiver Simulation Parameters

4.3 S-Function Development

Simulink calls functions implemented by the S-Function at different parts of the simulation. While the simulation is initializing it calls mdlStart. In this function, a data handler object and FIFO are created and a USRP2 object is instantiated. After the USRP2 object is created, parameters set in the mask are set on the USRP2 hardware while the model is initializing. The data handler object loads data into the FIFO as seen in Figure 4.10. While the simulation is running, Simulink repeatedly calls mdlOutputs, where a frame of data is read from the FIFO, converted to a Simulink data type and sent to the output port to be received in the simulation. When the simulation has finished, the FIFO and data handler are deallocated.

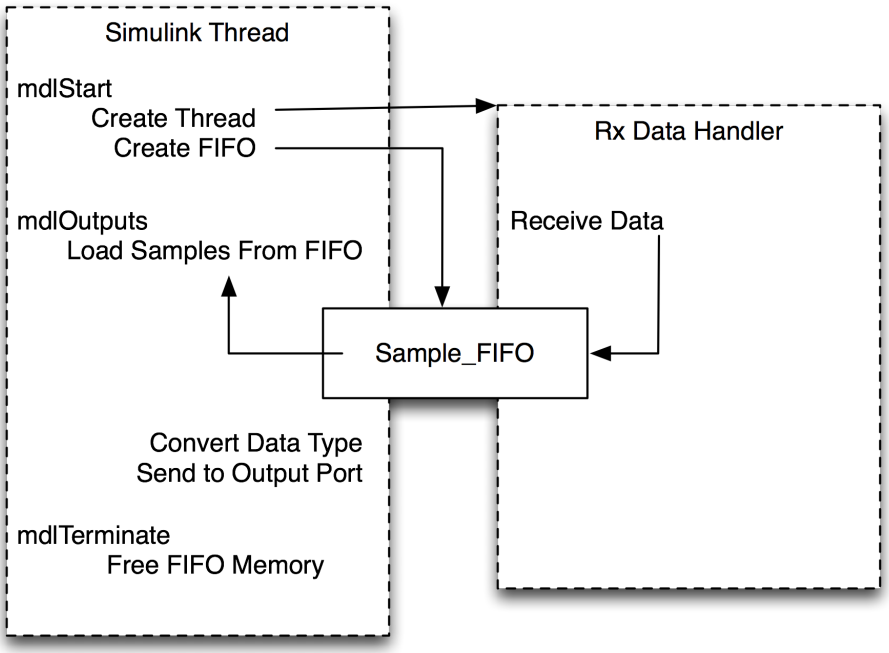


Figure 4.10: USRP2 Receiver Threads

The transmitter is similar, creating a send thread and FIFO during mdlStart as seen in Figure 4.11. In mdlOutputs, the size of the FIFO is checked. If the size is greater than 2

frames of data, the simulation thread is paused to wait for the USRP2 to send waiting data. This ensures there the FIFO will not grow arbitrarily large if the simulation is running faster than the USRP2 can send data. When mdlTerminate is called, the Simulation waits for the remaining data to be sent before deallocating the FIFO and thread.

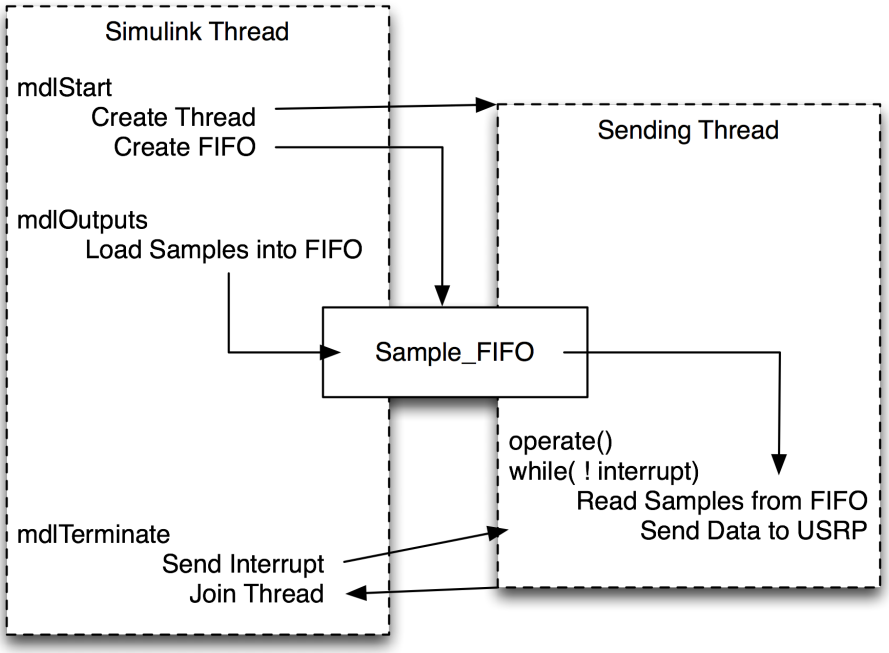


Figure 4.11: USRP2 Transmitter Threads

4.4 Interface Evaluation and Verification

Two sets of models were developed to test this interface. The first set of models is capable of transmitting four different signals and displaying the received spectrum. The second set uses Minimum-Sift Keying (MSK) to transmit arbitrary streams of data.

4.4.1 Multiple Waveform Generation

Sending and receiving a simple sinusoid was ambiguous due to sample time errors and a lack of synchronization and carrier frequency recovery. These errors were corrected and testing was done that did not require synchronization. The transmitter in Figure 4.12 was used to run this testing. The model could send one of four signals over the air.

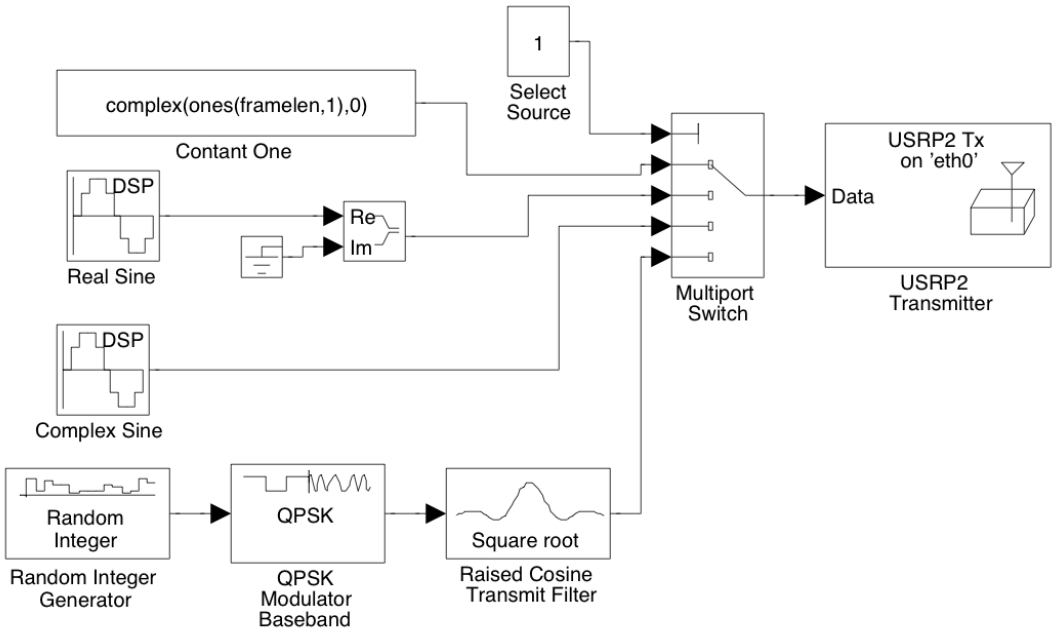


Figure 4.12: Test Transmitter Model

The first signal to be transmitted is a frame of 1000 samples of a complex 1. The data must be complex so the data type is correct for the block, but in this instance the complex component is zero. The second signal generates a frame of 1000 samples of a real sine wave at 30 kHz and adds a zero complex component. The third signal generates 1000 samples of a complex sinusoid. The fourth signal generates frames of random binary data, modulates this data using QPSK and then pulse shapes the impulses using a root raised cosine (RRC) filter.

The model in Figure 4.13 was used to display the data captured using the receive interface. The model simply contains the receive block and a FFT display block. The FFT block uses the sample time to determine the frequency and displays the double-sided FFT of the received signal.

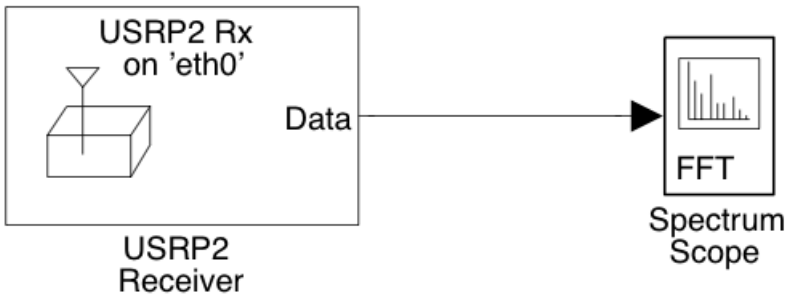


Figure 4.13: FFT Receive Model

Constant complex data would be sent from the transmitter to a receiver. This signal would be sent at 2.45 GHz using the XCVR 2450 boards. By sending a constant, a pulse centered around the carrier frequency would be expected. These testing steps showed the basic functionality of the interface and can be used in the future to ensure a setup is working correctly before attempting to debug more complex systems.

Constant Data

First, constant complex data would be sent from the transmitter to a receiver. By sending a constant, a pulse centered around the carrier frequency would be expected. Figure 4.14(a) shows the output of the spectrum analyzer. Figure 4.14(b) shows the FFT of the data captured by the receiver. The spectrum analyzer shows the transmitter correctly transmitting a pulse centered around the center frequency of 2.45 GHz. The receiver shows a slightly offset pulse centered around the baseband. The offset seen by the receiver is due

to frequency carrier offset in the RF hardware.

Real Sinusoid

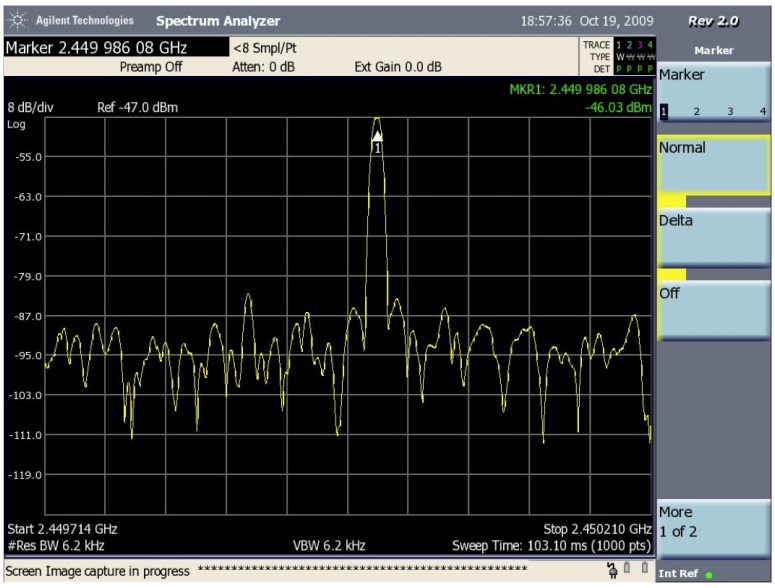
A real sinusoid was transmitted with the same settings on the transmitter and receiver. This 30 kHz sinusoid was generated in Simulink. With a real sinusoid, symmetric peaks are expected at 30 kHz above and below the center frequency. This test confirms a changing in-phase signal is being correctly transmitted. Figure 4.15(a) shows this symmetry at passband and Figure 4.15(b) shows the data captured by the receiver after being downconverted back to baseband. Again, no carrier frequency recovery is done, causing an offset. The harmonic spurs seen by the spectrum analyzer and receiver are created by the direct digital synthesizers on the daughterboards[31].

Complex Sinusoid

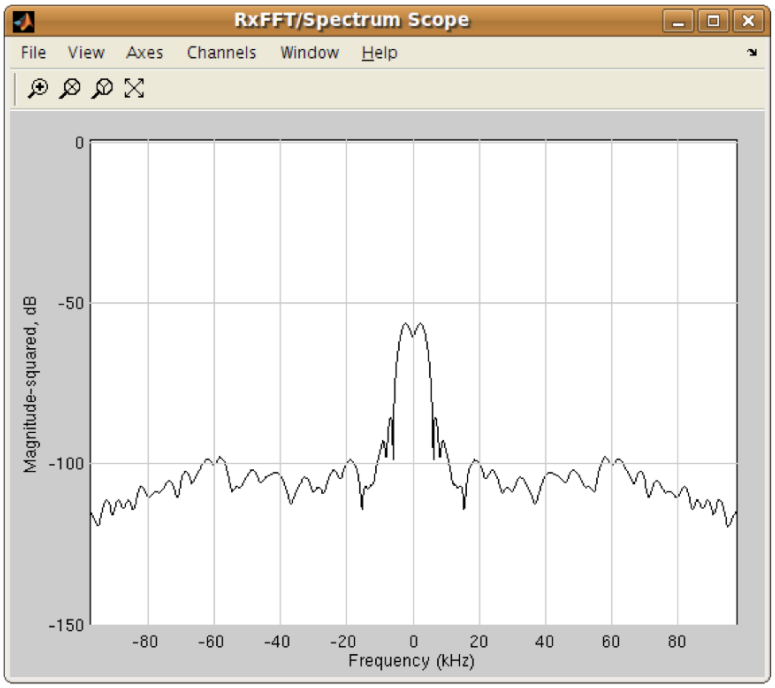
To ensure both the in phase and quadrature components of a varying signal are being handled by the interface correctly, a complex sinusoid was transmitted. The complex sinusoid to be transmitted is also a 30 kHz signal. One pulse is expected at 30 kHz above the center frequency is expected. This pulse can be seen at passband in Figure 4.16(a) and at baseband by the receive block in Figure 4.16(b). As the USRP2 hardware is the same as previous tests, the offset and spurs are still seen.

Random QPSK Pulse Shaped Data

The fourth step in the transmitter creates random binary bits, modulates the data using QPSK and shapes the impulses using a root raised cosine filter. In this test, a wider pulse at the center frequency of the transmitter is expected. Figure 4.17(a) shows this pulse at passband and Figure 4.17(b) shows the correct downconverted signal. The shaped pulse is seen both at the carrier frequency and at baseband, confirming basic digital communication.

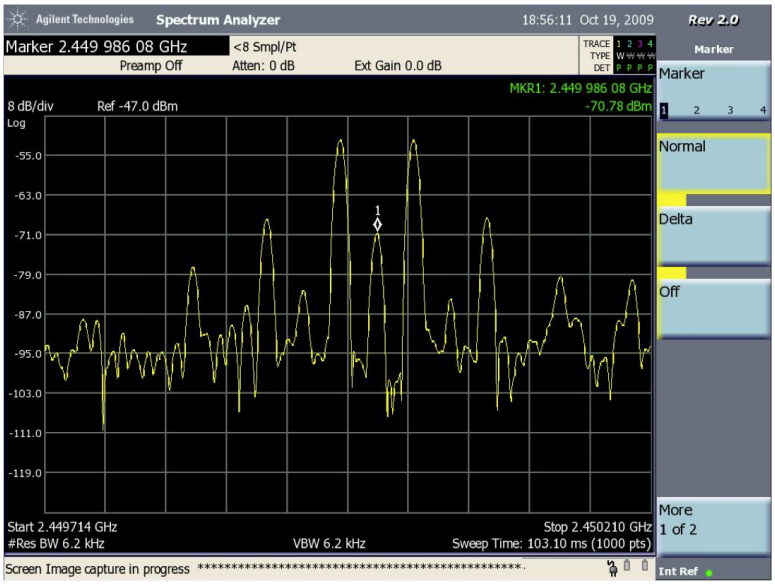


(a) Spectrum Analyzer

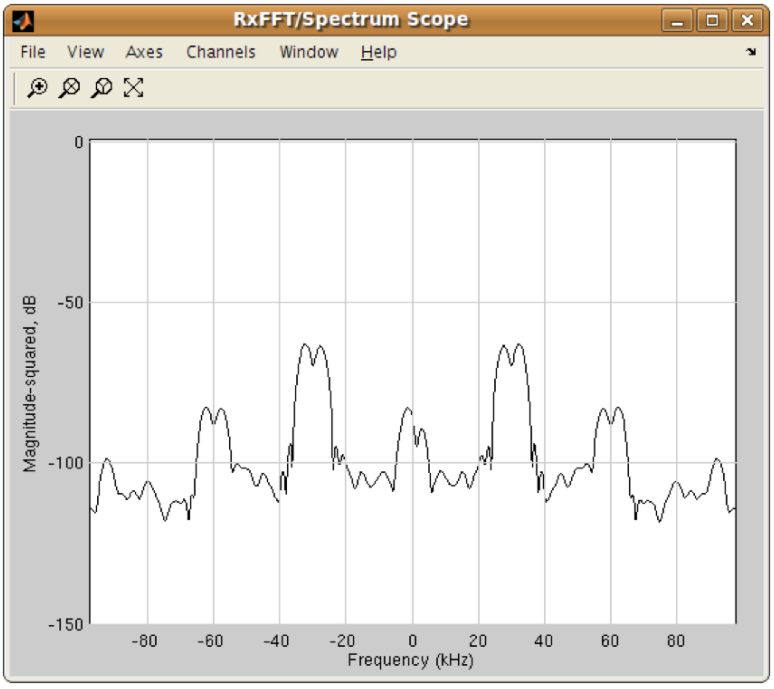


(b) Receiver in Simulink

Figure 4.14: Transmitting a Constant Value

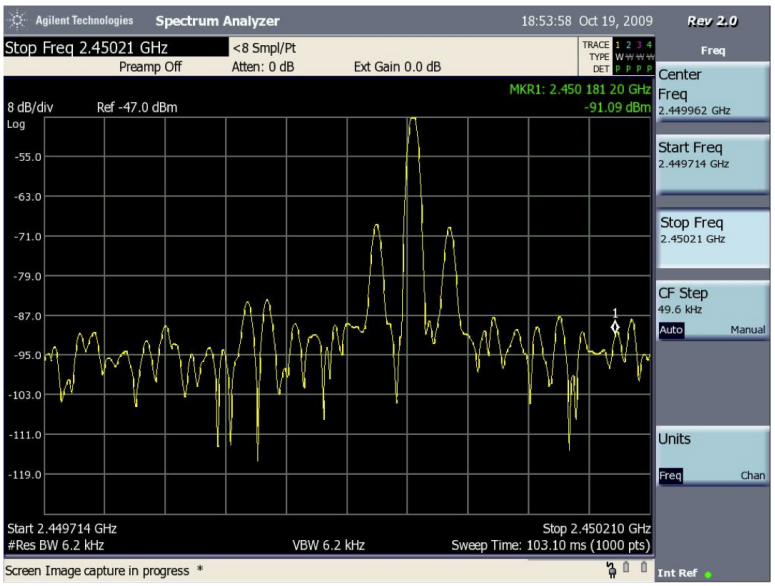


(a) Spectrum Analyzer

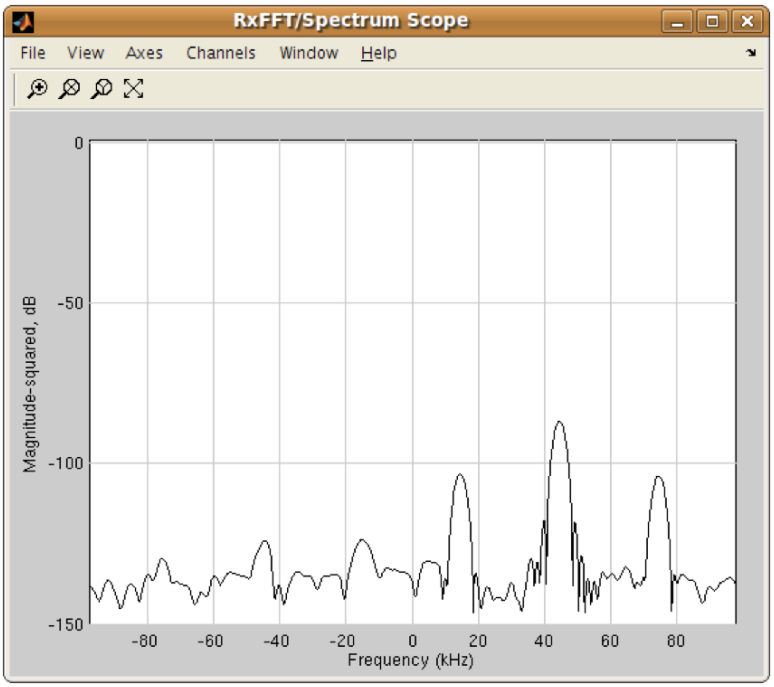


(b) Receiver in Simulink

Figure 4.15: Transmitting a Real Sinusoid



(a) Spectrum Analyzer



(b) Receiver in Simulink

Figure 4.16: Transmitting a Complex Sinusoid

The signal was not decoded further due to the lack of synchronization. As synchronization techniques are developed, more testing of the digital interface can be done.

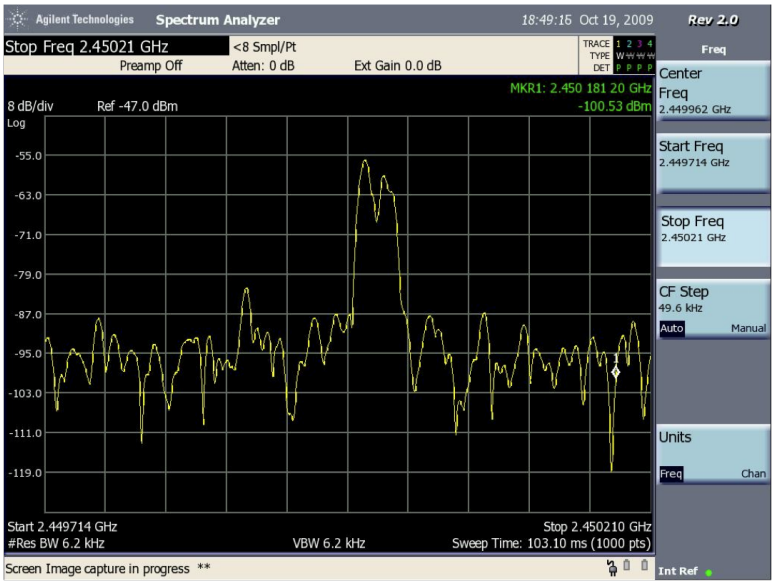
4.4.2 Digital Transmission using Minimum-Shift Keying

Many communications systems use Simulink to simulate theoretical systems and verify the functionality of implemented systems. The ability to convert simulated systems to fully functional broadcasting systems would add live testing capabilities to Simulink with a minimum about of work by designers. To test the ability of this interface to fulfill that role, an existing Simulink example was converted and tested[8]. The original model is the 'MSK Signal Recovery' model is the Communications Blockset.

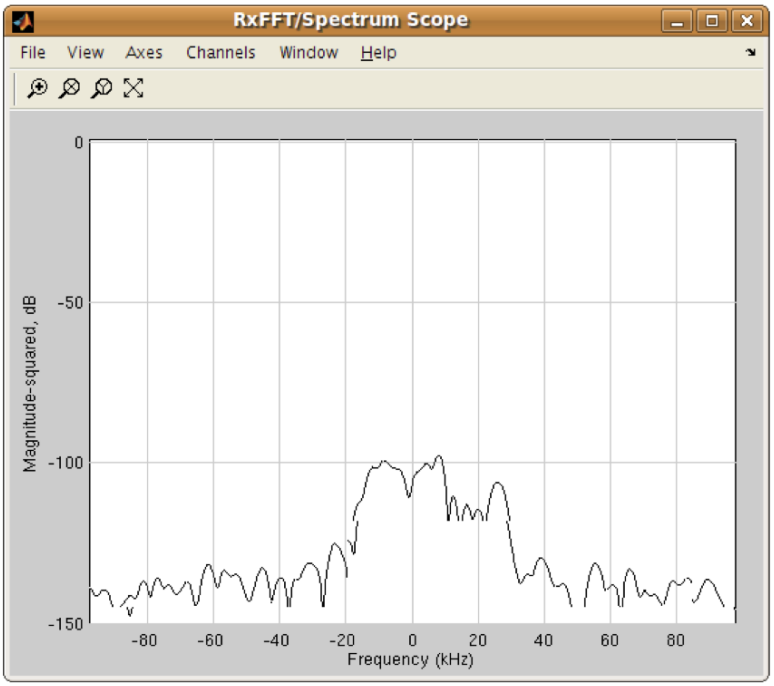
The transmitter, shown in Figure 4.18, was taken from the demo model from Simulink. The USRP2 block replaced the simulated channel and the random binary generator was replaced with a repeating sequence of predefined bits. Using this known sequence would enable simple verification of the received data stream.

Figure 4.19 shows the receiver, based on the demo model in Simulink. Here the transmitter and channel were replaced with the USRP2 receiver block. Each of the synchronization steps could be turned on and off during runtime to show the effects of timing recovery, carrier frequency recovery and phase recovery. More details about the receiver can be found in the MATLAB documentation. The transmitter and receiver were suturing when their gain and power were set too high. These settings were turned down and the constellation correctly formed four distinct clusters.

Initial testing showed an incorrect sequence of bits being received. The problem was in the source block of the transmitter, the sequences of bits were not set to repeat and would transmit constant 0's after the sequence ended. The problem was corrected and the correct pattern of alternating 0's and 1's was seen on the receiver. This demonstrates an existing Simulink model being easily converted to a near real-time broadcasting system.



(a) Spectrum Analyzer



(b) Receiver in Simulink

Figure 4.17: Transmitting a Pulse-shaped QPSK Signal

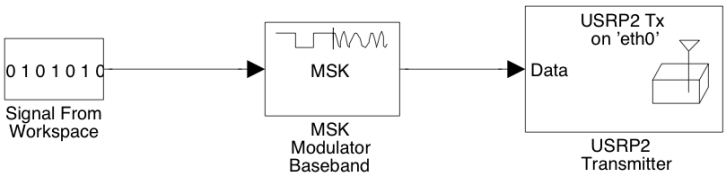


Figure 4.18: MSK Transmitter

4.5 Implementation Pitfalls

The blockset has some control over the sample rate going to and from the USRP2, but the configuration of the USRP2 can cause overflows and underflows. The transmitter block slows down the simulation if the simulation is generating samples faster then the USRP2 can transmit them. If the simulation is generating samples too slowly, the output of the block to the transmitter is zero filled, manifesting as an intermittent transmitter as seen in this figure. Optimizing the simulation, reducing the complexity of the transmitter and increasing the interpolation rate will reduce the intermittency. Simulink has a 3 different optimization modes to makes the simulation run more quickly, and the blocks work with the first optimization mode. Closing data plots and not writing data to workspace also makes the simulation run faster.

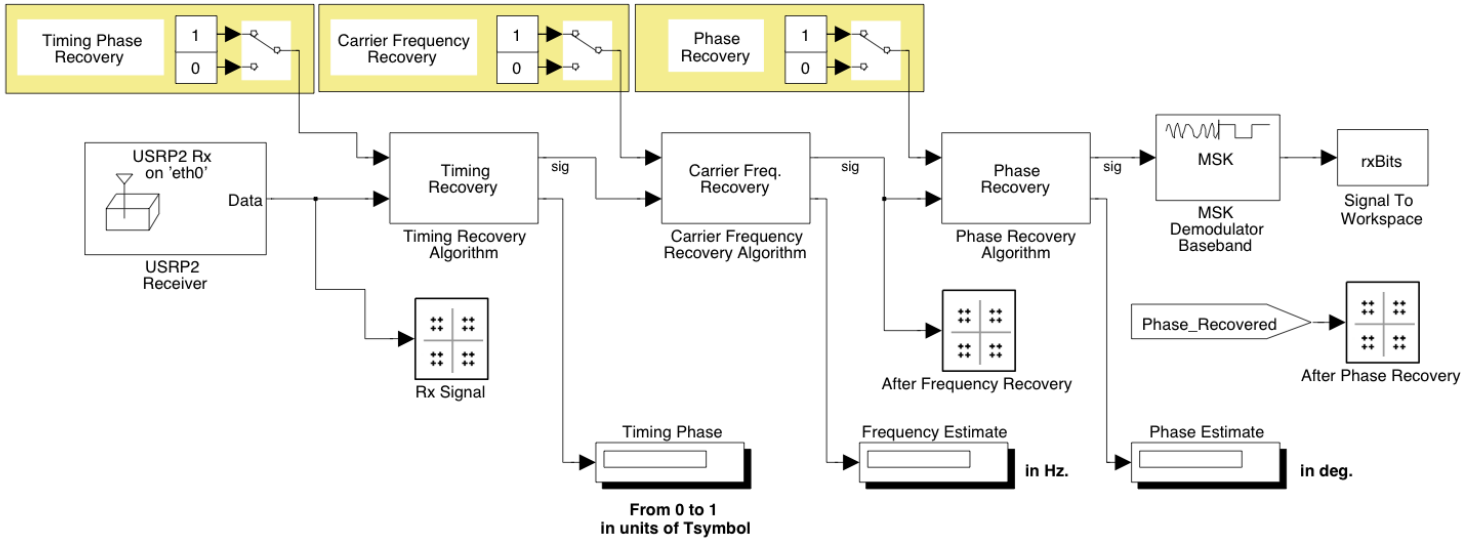


Figure 4.19: MSK Receiver with Synchronization

Similarly, the receiver can pause the simulation to wait for more samples to be received. As samples are received, they are placed in a FIFO buffer to be used by the simulation as is needed. If the data is not placed into this FIFO fast enough, sequence errors of the raw Ethernet frames occur. The library currently writes a S to the Linux command prompt. Adjusting the decimation rate on the USRP2 is the best way to prevent these errors from happening.

4.6 Chapter Summary

The blockset introduced in this thesis fulfills its design goals by providing an interface to the USRP2 hardware that is simple to use and can leverage an existing DSP framework. The user has access to the controls needed to make use of the hardware. Testing showed basic RF functionality with some expected spurs. The MSK demo showed the ease of converting an existing model to a fully functional communications system. This interface will make SDR development more accessible to new users and make development easier for both student and industry professionals.

Chapter 5

Conclusion

5.1 Overview

This thesis explored a variety of RF front ends for radio development and a variety of ways to interface to the hardware. The USRP2 balances versatility with low cost and provides an strong prototyping platform. Analog and digital radios were developed using the GR framework. Difficulties with GR were made evident in this process, with its steep learning cure and underdeveloped documentation. Alternative interfaces were then investigated, including the use of sockets and MEX functions. A complex control channel prevented further development of of the sockets interface, and complications with the USRP library stalled the MEX function. The release of the USRP2 offered the opportunity to start a new interface in the time aware, stream based Simulink.

The interfaced developed for Simulink provides the fundamental configuration of the USRP2 needed for rapid prototyping of SDRs. The user interface has been designed to provide the user with as much control of the USRP2 as possible, while being clean and clear. Novice users should not have a hard time trying out simple radios and be able to get started relatively quickly. Testing of the interface proved it can transmit signals generated in Simulink and receive data from over the air transmission.

Future users will have to focus on balancing the processing power of the host system with the complexities of the communications system. Complex transmitters will result in an intermittent signal and complex receivers will have to buffer data and diminish the realtime aspects of these systems.

The interface developed leverages the commercially supported blocks of Simulink, a software package common engineering curriculums. By using commonly used software to develop the radios, most users will be able to build on past Simulink experience and have less to learn when being introduced to SDR. The blockset includes controls for the core USRP2 functionality and nothing in the S-Function is platform specific enabling advanced functionality and laying the groundwork for future cross-platform support. This interface has met its design goals and will enable future development of radios in the Simulink environment.

5.2 Future Work

There are a number of areas that require more development.

- A proprietary USRP2 communications library will be an important part of this project going forward. To make installation easier, this proprietary library will enable cross platform support and eliminate the need to install the GR framework. The custom library will throw errors inline with other Simulink errors and aid the user in resolving the problems at hand. The current library also causes some of the bugs in the system now, and will have to be addressed with the re-implimentation of this library. This library will also have to provide access to the MIMO capability of the USRP2.

- Block optimizations will continue the effort towards more complex real-time capabilities. The current block buffers memory and changes data types a sample at a time, making these operations work by the frame will make the block run faster. The blocks

currently do not support the Rapid Accelerator mode in Simulink. Support will enable code generation and ensure this interface will run as quickly as other solutions.

- The USRP2 has MIMO capabilities that the current interface does not support. Including access to the remaining MIMO configuration function will provide the user will the full capabilities the USRP2 has to offer.

- Implementing a full network stack will make developing more realistic communications systems easier. Cross layer optimization techniques will also be able to be tested based on these robust models.

- The interface currently targets low data rate designs. Profiling the capability of Simulink against different host hardware configurations would provide a guide to users as to how complex their communications system can be on the hardware they have. This profiling could include testing at video data rates and implementing identical systems in GR for a side by side comparison.

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Appendix A

Sine Wave Generator

```
1  function SinewaveServer(ip, port)
2  % sineServer - generates a sine wave and sends it to the connected host
3  %
4  % Syntax:
5  %     sinewaveServer
6  %   or
7  %     sinewaveServer (ip address, port number)
8  %
9  %   Version: 2002-02-01 for the tcpiptoolbox 2.x API
10 %
11 if(nargin==0),
12      ip='127.0.0.1';
13      port='5000';
14 end
15
16
17 %determines length of sine wave data, should be done in full peroids
```

```
18 samplesPerSecond=48000;
19 numberOfSeconds=1;
20 time=(0:1/samplesPerSecond:numberOfSeconds);
21 frequency=1000;
22 sineWave=single(sin(2*pi*frequency*time));
23 sineCounter=0;
24
25 try,
26   while 1,
27     con=pnet('tcpconnect',ip,port);
28     if con==-1, error 'Bad url or server down.....'; end
29     disp(['Connected to: ' ip]);
30     if(1),
31       try,
32         while 1,
33             pnet(con,'write', sineWave, 'intel');
34             sineCounter= sineCounter+1;
35             disp(sprintf('%d SineWave Sent to host:%s port:%s\n',sineCounter,ip,port))
36             pause(numberOfSeconds)
37         end
38       end
39       pnet(con,'close');
40       drawnow;
41     end
42   end
43 end
44
45 end
```

Appendix B

Socket to USRP Interface

```
1  #!/usr/bin/env python
2  #
3  # Copyright 2005 Free Software Foundation, Inc.
4  #
5  # This file is part of GNU Radio
6  #
7  # GNU Radio is free software; you can redistribute it and/or modify
8  # it under the terms of the GNU General Public License as published by
9  # the Free Software Foundation; either version 2, or (at your option)
10 # any later version.
11 #
12 # GNU Radio is distributed in the hope that it will be useful,
13 # but WITHOUT ANY WARRANTY; without even the implied warranty of
14 # MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE.  See the
15 # GNU General Public License for more details.
16 #
17 # You should have received a copy of the GNU General Public License
```

```
18 # along with GNU Radio; see the file COPYING.  If not, write to
19 # the Free Software Foundation, Inc., 59 Temple Place - Suite 330,
20 # Boston, MA 02111-1307, USA.
21 #
22
23 from gnuradio import gr
24 from gnuradio import audio
25 from gnuradio import blks
26 from gnuradio.eng_option import eng_option
27 from optparse import OptionParser
28
29 from gr_socket import *
30
31 #for USRP
32 from gnuradio import usrp
33 from gnuradio import eng_notation
34
35 #if no daughter board is selected, pick one
36 def pick_subdevice(u):
37     """
38     The user didn't specify a subdevice on the command line.
39     If there's a daughterboard on A, select A.
40     If there's a daughterboard on B, select B.
41     Otherwise, select A.
42     """
43     #dbid is daugher board ID
44     if u.db[0][0].dbid() >= 0:       # dbid is < 0 if there's no d'board or a problem
45         return (0, 0)
46     if u.db[1][0].dbid() >= 0:
47         return (1, 0)
48     return (0, 0)
49
50 #set TX frequency
```

```
51  def set_freq(USRP, subdev, target_freq):
52          """
53          Set the center frequency we're interested in.
54
55          @param target_freq: frequency in Hz
56          @rypte: bool
57
58          Tuning is a two step process.  First we ask the front-end to
59          tune as close to the desired frequency as it can.  Then we use
60          the result of that operation and our target_frequency to
61          determine the value for the digital up converter.
62          """
63          #r = USRP.tune(tx_subdev_spec._which, tx_subdev_spec, target_freq)
64          r = USRP.tune(subdev._which, subdev, target_freq)
65          if r:
66              print "r.baseband_freq =", eng_notation.num_to_str(r.baseband_freq)
67              print "r.dxc_freq      =", eng_notation.num_to_str(r.dxc_freq)
68              print "r.residual_freq =", eng_notation.num_to_str(r.residual_freq)
69              print "r.inverted      =", r.inverted
70              return True
71
72          return False
73
74
75  #
76  # return a gr.flow_graph
77  #
78  def build_graph (options):
79      fg = gr.flow_graph ()
80      audio_rate=48000
81
82      # create socket client
83      (src, fd, conn) = make_socket_source(options.port,
```

```
84                                          gr.sizeof_float)
85
86      #use a sine source for testing
87      #src=gr.sig_source_f(48000,
88                           #gr.GR_SIN_WAVE,
89                           #1000,
90                           #1)
91
92
93      # sound card as final sink
94      audio_sink = audio.sink (int (audio_rate))
95
96      # now wire it all together
97      fg.connect (src, audio_sink)
98
99      #USRP as final sink
100     #setup conversion from float to complex
101     float_To_Complex=gr.float_to_complex()
102
103     #create USRP
104     #Usage usrp.sink _x(which=0, interp_rate=128, nchan=1, mux=0x98,
105                 #fusb_block_size=0, fusb_nblocks=0,
106                 #fpga_filename="", firmware_filename="")
107
108     USRP = usrp.sink_c(interp_rate=256)
109
110     #figure out which subdevice (side) to use
111     tx_subdev_spec=options.tx_subdev_spec
112     if tx_subdev_spec is None:
113         tx_subdev_spec = pick_subdevice(USRP)
114     subdev = usrp.selected_subdev(USRP, tx_subdev_spec)
115     print subdev
116
```

```
117     #set the mux from the USRP
118     #might be unnessary
119     #USRP.set_mux(usrp.determine_tx_mux_value(USRP, subdev))
120     m = usrp.determine_tx_mux_value(USRP, tx_subdev_spec)
121     #print "mux = %#04x" % (m,)
122     USRP.set_mux(m)
123
124     if options.gain is None:
125         subdev.set_gain(subdev.gain_range()[1])     # set max Tx gain
126     else:
127         subdev.set_gain(options.gain)     # set max Tx gain
128
129
130     # Set center frequency of USRP
131     #eng_float tx_freq='100M'
132     ok = set_freq(USRP, subdev, options.freq)
133     print ok
134     ok = set_freq(USRP, subdev, options.freq)
135     if not ok:
136         print "Failed to set Tx frequency to %s" % (eng_notation.num_to_str(options.freq))
137         raise ValueError
138
139
140     subdev.set_enable(True)
141
142     #connect USRP
143     fg.connect(src,float_To_Complex, USRP)
144
145     return (fg,fd,conn)
146     #return fg
147
148 def main ():
149     usage = "usage: %prog [options]"
```

```
150     parser = OptionParser(option_class=eng_option, usage=usage)
151     parser.add_option ("-d", "--dummy", action="store_true", default=False,
152                        help="when set true, uses a sine wave as a source instead of setting up the socket")
153     parser.add_option ("-T", "--tx-subdev-spec", type="subdev", default=(0, 0),
154                        help="select USRP Tx side A or B")
155     parser.add_option("-p", "--port", type="int",
156                       help="spectify the port to accept connections from",default=5000)
157     parser.add_option("-f", "--freq", type="eng_float", default='2.4G',
158                       help="set frequency to FREQ", metavar="FREQ")
159     parser.add_option ("-g", "--gain", type="eng_float", default=None,
160                        help="set output gain to GAIN [default=%default]")
161     (options, args) = parser.parse_args()
162
163     (fg,fd,conn) = build_graph (options)
164     #fg = build_graph (options)
165
166     fg.start ()         # fork thread(s) and return
167     raw_input ('Press Enter to quit: ')
168     fg.stop ()
169
170 if __name__ == '__main__':
171     main ()
```

Appendix C

USRP to Socket Interface

```
1  #!/usr/bin/env python
2  #
3  # Copyright 2004,2005,2007 Free Software Foundation, Inc.
4  #
5  # This file is part of GNU Radio
6  #
7  # GNU Radio is free software; you can redistribute it and/or modify
8  # it under the terms of the GNU General Public License as published by
9  # the Free Software Foundation; either version 3, or (at your option)
10 # any later version.
11 #
12 # GNU Radio is distributed in the hope that it will be useful,
13 # but WITHOUT ANY WARRANTY; without even the implied warranty of
14 # MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE.  See the
15 # GNU General Public License for more details.
16 #
17 # You should have received a copy of the GNU General Public License
```

```
18 # along with GNU Radio; see the file COPYING.  If not, write to
19 # the Free Software Foundation, Inc., 51 Franklin Street,
20 # Boston, MA 02110-1301, USA.
21 #
22
23 #3/31/08
24 #this file currently reads from a file, and sends that floating point data
25 #to both the sound card and a socket at a specified address and port
26 #for this file to make a connection, the receive socket must already be running
27
28
29 from gnuradio import gr
30 from gnuradio import audio
31 from gnuradio.eng_option import eng_option
32 from optparse import OptionParser
33
34 #imported from local folder
35 from gr_socket import *
36
37 #for USRP
38 from gnuradio import usrp
39 from gnuradio import eng_notation
40
41
42 class my_top_block(gr.top_block):
43     def __init__(self):
44         gr.top_block.__init__(self)
45
46         parser = OptionParser(option_class=eng_option)
47         parser.add_option("-F", "--filename", type="string", default="computer.dat",
48                           help="read input from FILE")
49         parser.add_option("-r", "--sample-rate", type="eng_float", default=48000,
50                           help="set sample rate to RATE (48000)")
```

```
51          parser.add_option("-o", "--repeat", action="store_true", default=True)
52          parser.add_option("-O", "--audio-output", type="string", default="",
53                            help="pcm output device name.  E.g., hw:0,0 or /dev/dsp")
54          parser.add_option("-i", "--address", type="string",
55                            help="specify the ip address to connect to",default="localhost")
56          parser.add_option("-p", "--port", type="int",
57                            help="specify the port to connect to",default=5000)
58          #USRP options
59          parser.add_option("-w", "--which", type="int", default=0,
60                            help="select which USRP (0, 1, ...) default is %default",
61                            metavar="NUM")
62          parser.add_option("-R", "--rx-subdev-spec", type="subdev", default='B',
63                            help="select USRP Rx side A or B (default=first one with a daughterboard)")
64          parser.add_option("-A", "--antenna", default=None,
65                            help="select Rx Antenna (only on RFX-series boards)")
66          parser.add_option("-d", "--decim", type="int", default=128,
67                            help="set fgpa decimation rate to DECIM [default=%default]")
68          parser.add_option("-f", "--freq", type="eng_float", default='2.40401G',
69                            help="set frequency to FREQ", metavar="FREQ")
70
71          (options, args) = parser.parse_args()
72
73          if len(args) != 0:
74              parser.print_help()
75              raise SystemExit, 1
76
77          #loads the audio sample rate
78          sample_rate = int(options.sample_rate)
79
80          #sets up reading from a file, expecting floating point values
81          #fileSrc = gr.file_source (gr.sizeof_float, options.filename, options.repeat)
82          #fileSrc=gr.sig_source_f(48000,gr.GR_SIN_WAVE, 1000, 1)
83
```

```
84          #setup a USRP as the soruce of the data
85          USRP = usrp.source_c(which=options.which,
86                               #fpga_filename="RBF1Tx1Rx.rbf",
87                               decim_rate=options.decim)
88          if options.rx_subdev_spec is None:
89              options.rx_subdev_spec = pick_subdevice(USRP)
90          USRP.set_mux(usrp.determine_rx_mux_value(USRP, options.rx_subdev_spec))
91
92          # determine the daughterboard subdevice we're using
93          subdev = usrp.selected_subdev(USRP, options.rx_subdev_spec)
94
95          #set USRP center Frequency
96          ok = self.set_freq(USRP, subdev, options.freq)
97
98          print "Using RX d'board %s"     % (subdev.side_and_name(),)
99          #print "bitrate:          %sb/s" % (eng_notation.num_to_str(self._bitrate))
100         #print "samples/symbol:   %3d"   % (self._samples_per_symbol)
101         #print "decim:            %3d"   % (subdev._decim)
102         #print "Rx Frequency:     %s"    % (self.myform['freq'])
103
104
105         #input_rate = self.u.adc_freq() / self.u.decim_rate()
106
107
108         #sets up the sound card as the sink (and loads the sample rate)
109         #dst = audio.sink (sample_rate, options.audio_output)
110
111         #connects the flow graph
112         #self.connect(fileSrc, dst)
113
114         # create socket server
115         global fileDescriptor
116         (socketSink, fileDescriptor) = make_socket_sink(options.address,
```

```
117                                                     options.port,
118                                                     gr.sizeof_float)
119                                                     #gr.sizeof_gr_complex)
120
121         #connect the scoket client
122         #self.connect(fileSrc,socketSink)
123         converter=gr.complex_to_float()
124         self.connect(USRP,converter,socketSink)
125
126     def pick_subdevice(u):
127         """
128         The user didn't specify a subdevice on the command line.
129         If there's a daughterboard on A, select A.
130         If there's a daughterboard on B, select B.
131         Otherwise, select A.
132         """
133         if u.db[0][0].dbid() >= 0:       # dbid is < 0 if there's no d'board or a problem
134             return (0, 0)
135         if u.db[1][0].dbid() >= 0:
136             return (1, 0)
137         return (0, 0)
138
139     def set_freq(self, USRP, subdev, target_freq):
140         """
141         Set the center frequency we're interested in.
142
143         @param target_freq: frequency in Hz
144         @rypte: bool
145
146         Tuning is a two step process.  First we ask the front-end to
147         tune as close to the desired frequency as it can.  Then we use
148         the result of that operation and our target_frequency to
149         determine the value for the digital down converter.
```

```
150         """
151         r = USRP.tune(0, subdev, target_freq)
152 
153         if r:
154             #self.myform['freq'].set_value(target_freq)     # update displayed value
155             #if self.show_debug_info:
156             #    self.myform['baseband'].set_value(r.baseband_freq)
157             #    self.myform['ddc'].set_value(r.dxc_freq)
158             return True
159 
160         return False
161 
162 
163 if __name__ == '__main__':
164     try:
165         my_top_block().run()
166     except KeyboardInterrupt:
167         pass
```

Appendix D

MATLAB Sockets Receiver

```
1  function allData=dataReceiver(port)
2  % sineServer - generates a sine wave and sends it to the connected host
3  %
4  % Syntax:
5  %    dataReceiver
6  %  or
7  %    dataReceiver port
8  %
9  %  Version: 2002-02-01 for the tcpiptoolbox 2.x API
10 %
11 if(nargin==0),     port=5000; end
12 if(ischar(port)), port=str2num(port); end
13 sock=pnet('tcpsocket',port);
14 if(sock==-1), error('Specified TCP port is not possible to use now.'); end
15 pnet(sock,'setreadtimeout',1);
16 connected=0;
17 counter=0;
```

```
18  dataSize=1000;
19
20  try,
21    disp(sprintf(['Get a webpage with your browser at adress: http://localhost:%d\n' ...
22                  'Or use proper hostname from an other computer.\n'],port));
23    while (connected==0),
24      con=pnet(sock,'tcplisten');
25      if( con~=-1 ),
26        try,
27          [ip,port]=pnet(con,'gethost');
28          disp(sprintf('Connection from host:%d.%d.%d.%d port:%d\n',ip,port));
29          connected=1;
30             %while (pnet(con,'status')),
31             while (1),
32                  %data=pnet(con,'read' [,size] [,datatype] [,swapping] [,'view'] [,'noblock'])
33                  %i get data in, but i have no idea what type it is.  It
34                  %should be audio data, between -1 and 1, but i am getting
35                  %all sorts of values.  a single in matlab is supposed to be
36                  %equalivant to floating point (on 32 bit systems though)
37                  %and there are options for the swaping of bytes
38
39                  %this now seems to work with the 'intel' swapping
40                  %data=[data pnet(con,'read' ,100, 'single', 'intel')];
41                  data=pnet(con,'read' ,dataSize, 'single', 'intel');
42                  counter=counter+1;
43
44                  %this guy works, stop changing him
45                  allData(counter*dataSize:((counter+1)*dataSize-1))=data;
46
47                  %myPlay(data);
48                  %sleep(1)
49
50             end
```

```
51          end
52          pnet(con,'close');
53          drawnow;
54          return
55        end
56      end
57  end
58  pnet(sock,'close');
59  end
60
61  function myPlay(data)
62  audio = double(data);
63  sound(audio,48000);
64  end
```

Appendix E

USRP Sockets Interface with FFT

```
1  #!/usr/bin/env python
2  #
3  # Copyright 2004,2005,2007 Free Software Foundation, Inc.
4  #
5  # This file is part of GNU Radio
6  #
7  # GNU Radio is free software; you can redistribute it and/or modify
8  # it under the terms of the GNU General Public License as published by
9  # the Free Software Foundation; either version 3, or (at your option)
10 # any later version.
11 #
12 # GNU Radio is distributed in the hope that it will be useful,
13 # but WITHOUT ANY WARRANTY; without even the implied warranty of
14 # MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE.  See the
15 # GNU General Public License for more details.
16 #
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```

```
18 # along with GNU Radio; see the file COPYING.  If not, write to
19 # the Free Software Foundation, Inc., 51 Franklin Street,
20 # Boston, MA 02110-1301, USA.
21 #
22
23 from gnuradio import gr, gru
24 from gnuradio import usrp
25 from gnuradio import eng_notation
26 from gnuradio.eng_option import eng_option
27 from gnuradio.wxgui import stdgui2, fftsink2, waterfallsink2, scopesink2, form, slider
28 from optparse import OptionParser
29 import wx
30 import sys
31
32 #imported from local folder
33 from gr_socket import *
34
35
36 def pick_subdevice(u):
37     """
38     The user didn't specify a subdevice on the command line.
39     If there's a daughterboard on A, select A.
40     If there's a daughterboard on B, select B.
41     Otherwise, select A.
42     """
43     if u.db[0][0].dbid() >= 0:       # dbid is < 0 if there's no d'board or a problem
44         return (0, 0)
45     if u.db[1][0].dbid() >= 0:
46         return (1, 0)
47     return (0, 0)
48
49
50 class app_top_block(stdgui2.std_top_block):
```

```
51      def __init__(self, frame, panel, vbox, argv):
52          stdgui2.std_top_block.__init__(self, frame, panel, vbox, argv)
53
54          self.frame = frame
55          self.panel = panel
56
57          parser = OptionParser(option_class=eng_option)
58          parser.add_option("-w", "--which", type="int", default=0,
59                            help="select which USRP (0, 1, ...) default is %default",
60                            metavar="NUM")
61          parser.add_option("-R", "--rx-subdev-spec", type="subdev", default='B',
62                            help="select USRP Rx side A or B (default=first one with a daughterboard)")
63          parser.add_option("-A", "--antenna", default=None,
64                            help="select Rx Antenna (only on RFX-series boards)")
65          parser.add_option("-d", "--decim", type="int", default=64,
66                            help="set fgpa decimation rate to DECIM [default=%default]")
67          parser.add_option("-f", "--freq", type="eng_float", default='2.4G',
68                            help="set frequency to FREQ", metavar="FREQ")
69          parser.add_option("-g", "--gain", type="eng_float", default=None,
70                            help="set gain in dB (default is midpoint)")
71          parser.add_option("-W", "--waterfall", action="store_true", default=False,
72                            help="Enable waterfall display")
73          parser.add_option("-8", "--width-8", action="store_true", default=False,
74                            help="Enable 8-bit samples across USB")
75          parser.add_option("-S", "--oscilloscope", action="store_true", default=False,
76                            help="Enable oscilloscope display")
77          #sockets options
78          parser.add_option("-i", "--address", type="string",
79                            help="spectify the ip address to connect to",default="localhost")
80          parser.add_option("-p", "--port", type="int",
81                            help="spectify the port to connect to",default=5000)
82
83          (options, args) = parser.parse_args()
```

```
84          if len(args) != 0:
85              parser.print_help()
86              sys.exit(1)
87
88          self.show_debug_info = True
89
90          # build the graph
91
92          self.u = usrp.source_c(which=options.which, decim_rate=options.decim)
93          if options.rx_subdev_spec is None:
94              options.rx_subdev_spec = pick_subdevice(self.u)
95          self.u.set_mux(usrp.determine_rx_mux_value(self.u, options.rx_subdev_spec))
96
97          if options.width_8:
98              width = 8
99              shift = 8
100             format = self.u.make_format(width, shift)
101             print "format =", hex(format)
102             r = self.u.set_format(format)
103             print "set_format =", r
104
105         # determine the daughterboard subdevice we're using
106         self.subdev = usrp.selected_subdev(self.u, options.rx_subdev_spec)
107
108         input_rate = self.u.adc_freq() / self.u.decim_rate()
109
110         if options.waterfall:
111             self.scope = \
112               waterfallsink2.waterfall_sink_c (panel, fft_size=1024, sample_rate=input_rate)
113         elif options.oscilloscope:
114             self.scope = scopesink2.scope_sink_c(panel, sample_rate=input_rate)
115         else:
116             self.scope = fftsink2.fft_sink_c (panel, fft_size=8192, sample_rate=input_rate)
```

```
117
118         self.connect(self.u, self.scope)
119
120         #also send data to sockets
121         #convert complex data to float
122         converter=gr.complex_to_float()
123
124         # create socket server
125         global fileDescriptor
126         (socketSink, fileDescriptor) = make_socket_sink(options.address,
127                                                         options.port,
128                                                         gr.sizeof_float)
129
130         self.connect(self.u, converter, socketSink)
131
132         self._build_gui(vbox)
133
134         # set initial values
135
136         if options.gain is None:
137             # if no gain was specified, use the mid-point in dB
138             g = self.subdev.gain_range()
139             options.gain = float(g[0]+g[1])/2
140
141         if options.freq is None:
142             # if no freq was specified, use the mid-point
143             r = self.subdev.freq_range()
144             options.freq = float(r[0]+r[1])/2
145
146         self.set_gain(options.gain)
147
148         if options.antenna is not None:
149             print "Selecting antenna %s" % (options.antenna,)
```

```
150             self.subdev.select_rx_antenna(options.antenna)
151
152         if self.show_debug_info:
153             self.myform['decim'].set_value(self.u.decim_rate())
154             self.myform['fs@usb'].set_value(self.u.adc_freq() / self.u.decim_rate())
155             self.myform['dbname'].set_value(self.subdev.name())
156             self.myform['baseband'].set_value(0)
157             self.myform['ddc'].set_value(0)
158
159         if not(self.set_freq(options.freq)):
160             self._set_status_msg("Failed to set initial frequency")
161
162     def _set_status_msg(self, msg):
163         self.frame.GetStatusBar().SetStatusText(msg, 0)
164
165     def _build_gui(self, vbox):
166
167         def _form_set_freq(kv):
168             return self.set_freq(kv['freq'])
169
170         vbox.Add(self.scope.win, 10, wx.EXPAND)
171
172         # add control area at the bottom
173         self.myform = myform = form.form()
174         hbox = wx.BoxSizer(wx.HORIZONTAL)
175         hbox.Add((5,0), 0, 0)
176         myform['freq'] = form.float_field(
177             parent=self.panel, sizer=hbox, label="Center freq", weight=1,
178             callback=myform.check_input_and_call(_form_set_freq, self._set_status_msg))
179
180         hbox.Add((5,0), 0, 0)
181         g = self.subdev.gain_range()
182         myform['gain'] = form.slider_field(parent=self.panel, sizer=hbox, label="Gain",
```

```
183                                             weight=3,
184                                             min=int(g[0]), max=int(g[1]),
185                                             callback=self.set_gain)
186
187         hbox.Add((5,0), 0, 0)
188         vbox.Add(hbox, 0, wx.EXPAND)
189
190         self._build_subpanel(vbox)
191
192     def _build_subpanel(self, vbox_arg):
193         # build a secondary information panel (sometimes hidden)
194
195         # FIXME figure out how to have this be a subpanel that is always
196         # created, but has its visibility controlled by foo.Show(True/False)
197
198         def _form_set_decim(kv):
199             return self.set_decim(kv['decim'])
200
201         if not(self.show_debug_info):
202             return
203
204         panel = self.panel
205         vbox = vbox_arg
206         myform = self.myform
207
208         #panel = wx.Panel(self.panel, -1)
209         #vbox = wx.BoxSizer(wx.VERTICAL)
210
211         hbox = wx.BoxSizer(wx.HORIZONTAL)
212         hbox.Add((5,0), 0)
213
214         myform['decim'] = form.int_field(
215             parent=panel, sizer=hbox, label="Decim",
```

```
216             callback=myform.check_input_and_call(_form_set_decim, self._set_status_msg))
217
218         hbox.Add((5,0), 1)
219         myform['fs@usb'] = form.static_float_field(
220             parent=panel, sizer=hbox, label="Fs@USB")
221
222         hbox.Add((5,0), 1)
223         myform['dbname'] = form.static_text_field(
224             parent=panel, sizer=hbox)
225
226         hbox.Add((5,0), 1)
227         myform['baseband'] = form.static_float_field(
228             parent=panel, sizer=hbox, label="Analog BB")
229
230         hbox.Add((5,0), 1)
231         myform['ddc'] = form.static_float_field(
232             parent=panel, sizer=hbox, label="DDC")
233
234         hbox.Add((5,0), 0)
235         vbox.Add(hbox, 0, wx.EXPAND)
236
237
238     def set_freq(self, target_freq):
239         """
240         Set the center frequency we're interested in.
241
242         @param target_freq: frequency in Hz
243         @rypte: bool
244
245         Tuning is a two step process.  First we ask the front-end to
246         tune as close to the desired frequency as it can.  Then we use
247         the result of that operation and our target_frequency to
248         determine the value for the digital down converter.
```

```
249             """
250             r = self.u.tune(0, self.subdev, target_freq)
251
252             if r:
253                 self.myform['freq'].set_value(target_freq)     # update displayed value
254                 if self.show_debug_info:
255                     self.myform['baseband'].set_value(r.baseband_freq)
256                     self.myform['ddc'].set_value(r.dxc_freq)
257                 return True
258
259             return False
260
261         def set_gain(self, gain):
262             self.myform['gain'].set_value(gain)     # update displayed value
263             self.subdev.set_gain(gain)
264
265         def set_decim(self, decim):
266             ok = self.u.set_decim_rate(decim)
267             if not ok:
268                 print "set_decim failed"
269             input_rate = self.u.adc_freq() / self.u.decim_rate()
270             self.scope.set_sample_rate(input_rate)
271             if self.show_debug_info:  # update displayed values
272                 self.myform['decim'].set_value(self.u.decim_rate())
273                 self.myform['fs@usb'].set_value(self.u.adc_freq() / self.u.decim_rate())
274             return ok
275
276     def main ():
277         app = stdgui2.stdapp(app_top_block, "USRP FFT", nstatus=1)
278         app.MainLoop()
279
280     if __name__ == '__main__':
281         main ()
```

Appendix F

MATLAB On-Off Keying Server

```
1  function OnOffServer(ip, port)
2  % sineServer - generates a sine wave and sends it to the connected host
3  %
4  % Syntax:
5  %     sinewaveServer
6  %   or
7  %     sinewaveServer (ip address, port number)
8  %
9  %   Version: 2002-02-01 for the tcpiptoolbox 2.x API
10 %
11 if(nargin==0),
12      ip='127.0.0.1';
13      port='5000';
14 end
15
16
17 %determines length of sine wave data, should be done in full peroids
```

```
18 samplesPerSecond=48000;
19 numberOfSeconds=1;
20 time=(0:1/samplesPerSecond:numberOfSeconds);
21 frequency=1000;
22 sineWave=single(sin(2*pi*frequency*time));
23 off=single(zeros(size(time)));
24 %off=single(cos(2*pi*frequency*time));
25 sineCounter=0;
26
27 plot([sineWave off sineWave off])
28
29 try,
30   while 1,
31     con=pnet('tcpconnect',ip,port);
32     if con==-1, error 'Bad url or server down.....'; end
33     disp(['Connected to: ' ip]);
34     if(1),
35       try,
36         while 1,
37             if mod(sineCounter,2)
38                 pnet(con,'write', sineWave, 'intel');
39                 disp(sprintf('%d SineWave Sent to host:%s port:%s\n',sineCounter,ip,port))
40             else
41                 pnet(con,'write', off, 'intel');
42                 disp(sprintf('%d Off Sent to host:%s port:%s\n',sineCounter,ip,port))
43             end
44
45             sineCounter= sineCounter+1;
46
47             %pause(numberOfSeconds-0.2)
48         end
49       catch
50           'Send Sine Wave Error'
```

```
51          end
52          pnet(con,'close');
53          drawnow;
54        end
55    end
56  catch
57        'TCP/IP Error'
58  end
59
60  end
```

Appendix G

MEX Interface to USRP Rx Daughterboard

```
1  /*********************************************************/
2  /*
3  these notes are from Peter Rydester tcp/IP toolbox
4  i left it here for notes on syntax using mex
5
6    Notes for Unix implementation
7    Compile this with:
8
9    mex -O pnet.c
10         the o is for optomize
11
12   Notes for Windows implementation
13
14   When using LCC, compile this with:
15   mex -O pnet.c {MATLAB_INSTALL_DIR}\sys\lcc\lib\wsock32.lib -DWIN32
16
17   When using Visual C++, compile this with:
```

```
18    mex -O pnet.c ws2_32.lib -DWIN32
19  */
20
21  /******* GENERAL DEFINES *********/
22  #ifdef HAVE_CONFIG_H
23  #include "config.h"
24  #endif
25
26  #include <stdio.h>
27  #include <stdlib.h>
28  #include <string.h>
29  #include <unistd.h>
30  #include <usb.h>                        /* needed for usb functions */
31  #include <getopt.h>
32  #include <assert.h>
33  #include <math.h>
34
35  #include "time_stuff.h"
36  #include "usrp_standard.h"
37  //#include "usrp_standard.cc"
38  #include "usrp_bytesex.h"
39  #include <usrp_basic.h>
40  #include "fpga_regs_common.h"
41  #include "fpga_regs_standard.h"
42
43  #ifdef HAVE_SCHED_H
44  #include <sched.h>
45  #endif
46
47  char *prog_name;
48
49  /* Include header file for matlab mex file functionality */
50  #include "mex.h"
```

```
51
52 /*Make the USRP a global variable, maybe put into an array like the sockets program did with connections*/
53 static bool test_input  (usrp_standard_rx *urx, int max_bytes, FILE *fp);
54
55
56 static void
57 set_progname (char *path)
58 {
59   char *p = strrchr (path, '/');
60   if (p != 0)
61     prog_name = p+1;
62   else
63     prog_name = path;
64 }
65
66 static void
67 die (const char *msg)
68 {
69   fprintf (stderr, "die: %s: %s\n", prog_name, msg);
70   exit (1);
71 }
72
73 static bool test_input  (usrp_standard_rx *urx, int max_bytes, FILE *fp)
74 {
75   int              fd = -1;
76   static const int BUFSIZE = urx->block_size();
77   static const int N = BUFSIZE/sizeof (short);
78   short            buf[N];
79   int              nbytes = 0;
80
81   //double         start_wall_time = get_elapsed_time ();
82   //double         start_cpu_time  = get_cpu_usage ();
83
```

```
84  double            start_wall_time = 0;
85  double            start_cpu_time  = 0;
86
87
88  if (fp)
89    fd = fileno (fp);
90
91  bool overrun;
92  int noverruns = 0;
93
94  for (nbytes = 0; max_bytes == 0 || nbytes < max_bytes; nbytes += BUFSIZE){
95
96    unsigned int         ret = urx->read (buf, sizeof (buf), &overrun);
97    if (ret != sizeof (buf)){
98      fprintf (stderr, "test_input: error, ret = %d\n", ret);
99    }
100
101   if (overrun){
102     mexPrintf ("rx_overrun\n");
103     noverruns++;
104   }
105
106   if (fd != -1){
107
108     for (unsigned int i = 0; i < sizeof (buf) / sizeof (short); i++)
109       buf[i] = usrp_to_host_short (buf[i]);
110
111     if (write (fd, buf, sizeof (buf)) == -1){
112       mexPrintf ("write error");
113       fd = -1;
114     }
115   }
116 }
```

```
117
118   //double stop_wall_time = get_elapsed_time ();
119   //double stop_cpu_time  = get_cpu_usage ();
120   double stop_wall_time = 1;
121   double stop_cpu_time  = 1;
122
123   double delta_wall = stop_wall_time - start_wall_time;
124   double delta_cpu  = stop_cpu_time  - start_cpu_time;
125
126   mexPrintf ("xfered %.3g bytes in %.3g seconds.  %.4g bytes/sec.  cpu_time = %.4g\n",
127           (double) max_bytes, delta_wall, max_bytes / delta_wall, delta_cpu);
128   mexPrintf ("noverruns = %d\n", noverruns);
129
130   return true;
131 }
132
133 void initialize(int argc, mxArray **argv)
134 {
135   bool  verbose_p = false;
136   bool  loopback_p = true;
137   bool  counting_p = false;
138   bool  width_8_p = false;
139   int   max_bytes = 128 * (1L << 20);
140   int   ch;
141   char  *output_filename = 0;
142   int   which_board = 0;
143   int   decim = 8;                        // 32 MB/sec
144   double        center_freq = 100000000;
145   int   fusb_block_size = 0;
146   int   fusb_nblocks = 0;
147   bool  realtime_p = false;
148
149
```

```
150   //set_progname (argv[0]);
151
152 #ifdef HAVE_SCHED_SETSCHEDULER
153   if (realtime_p){
154     int policy = SCHED_FIFO;
155     int pri = (sched_get_priority_max (policy) - sched_get_priority_min (policy)) / 2;
156     int pid = 0;  // this process
157
158     struct sched_param param;
159     memset(&param, 0, sizeof(param));
160     param.sched_priority = pri;
161     int result = sched_setscheduler(pid, policy, &param);
162     if (result != 0){
163       perror ("sched_setscheduler: failed to set real time priority");
164     }
165     else
166       printf("SCHED_FIFO enabled with priority = %d\n", pri);
167   }
168 #endif
169
170   FILE *fp = 0;
171
172   if (output_filename){
173     fp = fopen (output_filename, "wb");
174     if (fp == 0)
175       perror (output_filename);
176   }
177
178   int mode = 0;
179   if (loopback_p)
180     mode |= usrp_standard_rx::FPGA_MODE_LOOPBACK;
181   if (counting_p)
182     mode |= usrp_standard_rx::FPGA_MODE_COUNTING;
```

```
183     mexPrintf("Mode: %d\n",mode);
184
185   //usrp_standard_rx usage
186     //int which_board,
187     //unsigned int decim_rate,
188     int nchan = 1;
189     int mux = -1;
190     //int mode = 0,
191     //int fusb_block_size = 0,
192     //int fusb_nblocks = 0,
193     const std::string fpga_filename="";
194     const std::string firmware_filename = "";
195
196
197     //try{
198   /*
199     USRP_Rx = usrp_standard_rx::make(
200                                       which_board,
201                                       decim,
202                                       nchan,
203                                       mux,
204                                       mode,
205                                       fusb_block_size,
206                                       fusb_nblocks,
207                                       fpga_filename,
208                                       firmware_filename);
209   */
210       usrp_standard_rx *urx = usrp_standard_rx::make(which_board,
211                                       decim,
212                                       nchan,
213                                       mux,
214                                       mode,
215                                       fusb_block_size,
```

```
216                                     fusb_nblocks);
217                                     //fpga_filename,
218                                     //firmware_filename);
219     //}
220     //catch(...){
221     //if (urx == 0){
222     //     mexPrintf("USRP_Initialization_Error\n");
223     //}
224
225     //}
226
227   //if (urx == 0)
228   //   die ("usrp_standard_rx::make");
229
230   if (!urx->set_rx_freq(0, center_freq))
231     die ("urx->set_rx_freq");
232
233   if (width_8_p){
234     int width = 8;
235     int shift = 8;
236     bool want_q = true;
237     if (!urx->set_format(usrp_standard_rx::make_format(width, shift, want_q)))
238       die("urx->set_format");
239   }
240
241   urx->start();          // start data xfers
242
243   test_input (urx, max_bytes, fp);
244
245   if (fp)
246     fclose (fp);
247
248   delete urx;
```

```
249
250   //return 0;
251
252   mexPrintf("Hello initialized\n");
253 }
254
255 /*this is my main function, it will do great things one day*/
256 void mexFunction(
257     int             nlhs,           /* number of expected outputs */
258     mxArray         *plhs[],        /* array of pointers to output arguments */
259     int             nrhs,           /* number of inputs */
260     const mxArray *prhs[]           /* array of pointers to input arguments */
261     )
262      {
263      mexPrintf("Hello world\n");
264      initialize(nlhs, plhs);
265      }
```

Appendix H

MEX Interface to USRP Tx

```
1  l/*******************************************************/
2  /*
3  these notes are from Peter Rydes ter tcp/IP toolbox
4  i left it here for notes on syntax using mex
5
6    Notes for Unix implementation
7    Compile this with:
8
9    mex -O pnet.c
10         the o is for optomize
11
12   Notes for Windows implementation
13
14   When using LCC, compile this with:
15   mex -O pnet.c {MATLAB_INSTALL_DIR}\sys\lcc\lib\wsock32.lib -DWIN32
16
17   When using Visual C++, compile this with:
```

```
18    mex -O pnet.c ws2_32.lib -DWIN32
19  */
20
21  /******* GENERAL DEFINES *********/
22  #ifdef HAVE_CONFIG_H
23  #include "config.h"
24  #endif
25
26
27  #include <stdio.h>
28  #include <stdlib.h>
29  #include <string.h>
30  #include <unistd.h>
31  #include <usb.h>                        /* needed for usb functions */
32  #include <getopt.h>
33  #include <assert.h>
34  #include <math.h>
35
36  #include "time_stuff.h"
37  #include "usrp_standard.h"
38  #include "usrp_standard.cc"
39  #include "usrp_bytesex.h"
40  #include <usrp_basic.h>
41  #include "fpga_regs_common.h"
42  #include "fpga_regs_standard.h"
43
44  #ifdef HAVE_SCHED_H
45  #include <sched.h>
46  #endif
47
48  char *prog_name;
49
50  /* Include header file for matlab mex file functionality */
```

```
51 #include "mex.h"
52 #include "matrix.h"
53
54 /*Make the USRP a global variable, maybe put into an array like
55       the sockets program did with connections*/
56 usrp_standard_tx *utx;
57 // count number of calls
58 int numCalls = 0;
59
60 // Debugging - allow for a verbose mode
61 bool verbose = true;
62
63 static bool test_input  (usrp_standard_rx *urx, int max_bytes, FILE *fp);
64 void        display_subscript(const mxArray *array_ptr, mwSize index);
65
66 static void
67 set_progname (char *path)
68 {
69   char *p = strrchr (path, '/');
70   if (p != 0)
71     prog_name = p+1;
72   else
73     prog_name = path;
74 }
75
76 static void
77 die (const char *msg)
78 {
79   fprintf (stderr, "die: %s: %s\n", prog_name, msg);
80   exit (1);
81 }
82
83
```

```
84  static bool
85  test_output (usrp_standard_tx *utx, unsigned long max_bytes, double ampl,
86               bool dc_p, bool counting_p)
87  {
88    static const int BUFSIZE = utx->block_size();
89    static const int N = BUFSIZE/sizeof (short);
90
91    short            buf[N];
92    unsigned long    nbytes = 0;
93    int              counter = 0;
94
95    static const int    PERIOD = 65;              // any value is valid
96    static const int    PATLEN = 2 * PERIOD;
97    short               pattern[PATLEN];
98
99    for (int i = 0; i < PERIOD; i++){
100     if (dc_p){
101       pattern[2*i+0] = host_to_usrp_short ((short) ampl);
102       pattern[2*i+1] = host_to_usrp_short ((short) 0);
103     }
104     else {
105       pattern[2*i+0] = host_to_usrp_short
106         ((short) (ampl * cos (2*M_PI * i / PERIOD)));
107       pattern[2*i+1] = host_to_usrp_short
108         ((short) (ampl * sin (2*M_PI * i / PERIOD)));
109     }
110   }
111
112   double           start_wall_time = 0;
113   double           start_cpu_time  = 0;
114
115   bool  underrun;
116   int   nunderruns = 0;
```

```
117   int    pi = 0;
118
119   for (nbytes = 0; max_bytes == 0 || nbytes < max_bytes; nbytes += BUFSIZE){
120
121     if (counting_p){
122       for (int i = 0; i < N; i++)
123         buf[i] = host_to_usrp_short (counter++ & 0xffff);
124     }
125     else {
126       for (int i = 0; i < N; i++){
127         buf[i] = pattern[pi];
128         pi++;
129         if (pi >= PATLEN)
130           pi = 0;
131       }
132     }
133
134     int ret = utx->write (buf, sizeof (buf), &underrun);
135     if ((unsigned) ret != sizeof (buf)){
136       mexPrintf ("test_output: error, ret = %d\n", ret);
137     }
138
139     if (underrun){
140       nunderruns++;
141       mexPrintf ("tx_underrun\n");
142       //printf ("tx_underrun %9d %6d\n", nbytes, nbytes/BUFSIZE);
143     }
144   }
145
146   utx->wait_for_completion ();
147
148   double stop_wall_time = 1;
149   double stop_cpu_time  = 1;
```

```
150
151   double delta_wall = stop_wall_time - start_wall_time;
152   double delta_cpu  = stop_cpu_time  - start_cpu_time;
153
154   mexPrintf ("xfered %.3g bytes in %.3g seconds.   %.4g bytes/sec.   cpu time = %.3g\n",
155           (double) max_bytes, delta_wall, max_bytes / delta_wall, delta_cpu);
156
157   mexPrintf ("%d underruns\n", nunderruns);
158
159   return true;
160 }
161
162
163 static bool test_input  (usrp_standard_rx *urx, unsigned long max_bytes,
164                          FILE *fp)
165 {
166   int              fd = -1;
167   static const int BUFSIZE = urx->block_size();
168   static const int N = BUFSIZE/sizeof (short);
169   short            buf[N];
170   unsigned long    nbytes = 0;
171
172   //double         start_wall_time = get_elapsed_time();
173   //double         start_cpu_time  = get_cpu_usage();
174
175   //used when timing is broken
176   double           start_wall_time = 0;
177   double           start_cpu_time  = 0;
178
179
180   if (fp)
181     fd = fileno (fp);
182
```

```
183   bool overrun;
184   int noverruns = 0;
185
186   for (nbytes = 0; max_bytes == 0 || nbytes < max_bytes; nbytes += BUFSIZE){
187
188     unsigned int         ret = urx->read (buf, sizeof (buf), &overrun);
189     if (ret != sizeof (buf)){
190       mexPrintf ("test_input: error, ret = %d\n", ret);
191     }
192
193     if (overrun){
194       mexPrintf ("rx_overrun\n");
195       noverruns++;
196     }
197
198     if (fd != -1){
199
200       for (unsigned int i = 0; i < sizeof (buf) / sizeof (short); i++)
201         buf[i] = usrp_to_host_short (buf[i]);
202
203       if (write (fd, buf, sizeof (buf)) == -1){
204         mexPrintf ("write error");
205         fd = -1;
206       }
207     }
208   }
209
210   // double stop_wall_time = get_elapsed_time();
211   //double stop_cpu_time  = get_cpu_usage();
212   double stop_wall_time = 1;
213   double stop_cpu_time  = 1;
214
215   double delta_wall = stop_wall_time - start_wall_time;
```

```
216   double delta_cpu  = stop_cpu_time  - start_cpu_time;
217
218   mexPrintf ("xfered %.3g bytes in %.3g seconds.  %.4g bytes/sec.  cpu time = %.4g\n",
219           (double) max_bytes, delta_wall, max_bytes / delta_wall, delta_cpu);
220   mexPrintf ("noverruns = %d\n", noverruns);
221
222   return true;
223 }
224
225
226 void setupUSRP(
227     int daughterBoardSelect = 0,
228     unsigned int interpRate = 16,
229     int numChan = 1,
230     int mux = -1,
231     int fusb_block_size = 0,
232     int fusb_nblocks = 0,
233     const std::string fpga_filename="",
234     const std::string firmware_filename = "",
235     bool  verbose_p  = false, //not used
236     bool  loopback_p = true,
237     bool  counting_p = false,
238     bool  width_8_p  = false  //not used
239
240 ){
241   // setup real time scheduling if requested and possible
242 #ifdef HAVE_SCHED_SETSCHEDULER
243   if (realtime_p){
244     int policy = SCHED_FIFO;
245     int pri = (sched_get_priority_max (policy) - sched_get_priority_min (policy)) / 2;
246     int pid = 0;  // this process
247
248     struct sched_param param;
```

```
249       memset(&param, 0, sizeof(param));
250       param.sched_priority = pri;
251       int result = sched_setscheduler(pid, policy, &param);
252       if (result != 0){
253         perror ("sched_setscheduler: failed to set real time priority\n");
254       }
255       else
256         printf("SCHED_FIFO enabled with priority = %d\n", pri);
257     }
258   #endif
259
260     //determine mode for USRP, may not be needed for Tx
261     int mode = 0;
262     if (loopback_p){
263       mode |= usrp_standard_rx::FPGA_MODE_LOOPBACK;
264       mexPrintf("Using Loopback mode\n");
265     }
266     if (counting_p){
267       mode |= usrp_standard_rx::FPGA_MODE_COUNTING;
268       mexPrintf("Using counting mode\n");
269     }
270
271
272     utx = usrp_standard_tx::make (daughterBoardSelect,
273                                   interpRate,
274                                   numChan,
275                                   mux,
276                                   fusb_block_size,
277                                   fusb_nblocks,
278                                   fpga_filename,
279                                   firmware_filename);
280
281     if (utx == 0){
```

```
282       die ("usrp_standard_tx::make");
283       mexPrintf("USRP_initialization_failed\n");
284     }
285
286     }
287
288 void setDBFrequency( // sets the frequency on the daughterboard, won't_work_until
289 ________________//_code_is_added_to_configure_daughterboard
290 ___int_frequency,
291 ___int_side_=_1){
292
293 __if_(!utx->set_tx_freq_(1,_frequency)){
294 ________mexPrintf("Expected_set_frequency_error\n");
295 ________if("utx->set_tx_freq"==NULL){
296 ________die_("utx->set_tx_freq");
297 ____}
298 __}
299 __//_i_thought_this_was_called_in_the_if_statement....
300 __utx->set_tx_freq(1,100000);
301
302 __mexPrintf("%d\n",utx->nchannels_());
303 __mexPrintf("%d\n",utx->tx_freq(1));
304
305 }
306
307 void_startUSRP(){
308 __utx->start();__________//_start_data_xfers_(lock_the_USRP_for_data_transfers?)
309 __mexPrintf("USRP_started\n");
310 }
311
312 void_sendData(
313 __short_*data){
314
```

```
315  ␣␣mexPrintf("Sending␣data␣to␣USRP\n");
316
317  ␣␣//␣these␣values␣should␣be␣cached,␣but␣recalcuated␣on␣changes
318  ␣␣static␣const␣int␣USRPBufferSize␣=␣utx->block_size();
319  ␣␣static␣const␣int␣maxNumShortsInBuffer␣=␣USRPBufferSize/sizeof␣(short);
320  ␣␣//short␣␣␣␣␣␣␣␣␣␣buffer[maxNumShortsInBuffer];
321  ␣␣short␣␣␣␣␣␣␣␣␣␣␣*buffer;
322  ␣␣//␣cache␣the␣size␣of␣the␣buffer␣with␣respect␣to␣the␣size␣of␣type␣char
323  ␣␣//␣for␣the␣usrp␣write␣function
324  ␣␣static␣const␣int␣bufferSize␣=␣sizeof(buffer);
325  ␣␣static␣const␣int␣dataSize␣=␣sizeof(data);
326
327  ␣␣//␣␣unsigned␣long␣␣␣␣␣␣␣␣nbytes␣=␣0;
328  ␣␣int␣␣␣␣␣␣␣␣␣␣␣␣␣␣counter␣=␣0;
329  ␣␣bool␣␣underrun;
330
331  ␣␣for␣(int␣bufferCntr=␣0;␣bufferCntr␣<␣dataSize;␣bufferCntr++){
332  ␣␣␣␣//␣read␣one␣buffer's worth of data into the buffer                    **FIX ME**
333      buffer = data;
334
335      int ret = utx->write (buffer, bufferSize, &underrun);
336
337      if ((unsigned) ret != sizeof (buffer)){
338        mexPrintf ("test_output:␣error,␣ret␣=␣%d\n", ret);
339      }
340
341      if (underrun){
342        //nunderruns++;
343        mexPrintf ("tx_underrun\n");
344        //printf ("tx_underrun␣%9d␣%6d\n", nbytes, nbytes/BUFSIZE);
345      }
346
347      utx->wait_for_completion ();
```

```
348     }
349     mexPrintf("Data sent to USRP\n");
350   }
351
352   short genRandData(
353     int     PERIOD = 65,            // any value is valid
354     int     PATLEN = 130,  // must be an integer multipal of peroid
355     int     ampl = 1,
356     bool    dc_p = false){
357
358     short pattern[PATLEN];
359
360     for (int i = 0; i < PERIOD; i++){
361       if (dc_p){
362         pattern[2*i+0] = host_to_usrp_short ((short) ampl);
363         pattern[2*i+1] = host_to_usrp_short ((short) 0);
364       }
365       else {
366         pattern[2*i+0] = host_to_usrp_short
367           ((short) (ampl * cos (2*M_PI * i / PERIOD)));
368         pattern[2*i+1] = host_to_usrp_short
369           ((short) (ampl * sin (2*M_PI * i / PERIOD)));
370       }
371     }
372
373     static const int BUFSIZE = utx->block_size();
374     static const int N = BUFSIZE/sizeof (short);
375     short             buffer[N];
376     unsigned long     nbytes = 0;
377     int               counter = 0;
378     int               pi = 0;
379     for (int i = 0; i < N; i++){
380        buffer[i] = pattern[pi];
```

```
381       pi++;
382       if (pi >= PATLEN)
383         pi = 0;
384     }
385     return *buffer;
386
387 }
388
389
390 void cleanUSRP(){
391     delete utx;
392     mexPrintf("USRP cleaned up\n");
393 }
394
395 void sendRandDataTest(
396       unsigned long max_bytes = 40000,
397       double ampl = 1,
398       bool dc_p = false,
399       bool counting_p = false){
400
401     static const int BUFSIZE = utx->block_size();
402     static const int N = BUFSIZE/sizeof(short);
403
404     short            buf[N];
405     unsigned long    nbytes = 0;
406     int              counter = 0;
407
408     static const int    PERIOD = 65;              // any value is valid
409     static const int    PATLEN = 2 * PERIOD;
410     short               pattern[PATLEN];
411
412     for (int i = 0; i < PERIOD; i++){
413       if (dc_p){
```

```
414         pattern[2*i+0] = host_to_usrp_short ((short) ampl);
415         pattern[2*i+1] = host_to_usrp_short ((short) 0);
416       }
417       else {
418         pattern[2*i+0] = host_to_usrp_short
419           ((short) (ampl * cos (2*M_PI * i / PERIOD)));
420         pattern[2*i+1] = host_to_usrp_short
421           ((short) (ampl * sin (2*M_PI * i / PERIOD)));
422       }
423     }
424
425     double            start_wall_time = 0;
426     double            start_cpu_time  = 0;
427
428     bool  underrun;
429     int   nunderruns = 0;
430     int   pi = 0;
431
432     for (nbytes = 0; max_bytes == 0 || nbytes < max_bytes; nbytes += BUFSIZE){
433
434       if (counting_p){
435         for (int i = 0; i < N; i++)
436           buf[i] = host_to_usrp_short (counter++ & 0xffff);
437       }
438       else {
439         for (int i = 0; i < N; i++){
440           buf[i] = pattern[pi];
441           pi++;
442           if (pi >= PATLEN)
443             pi = 0;
444         }
445       }
446
```

```
447       int ret = utx->write (buf, sizeof (buf), &underrun);
448       if ((unsigned) ret != sizeof (buf)){
449         mexPrintf ("test_output: error, ret = %d\n", ret);
450       }
451
452       if (underrun){
453         nunderruns++;
454         mexPrintf ("tx_underrun\n");
455         //printf ("tx_underrun %9d %6d\n", nbytes, nbytes/BUFSIZE);
456       }
457     }
458
459     utx->wait_for_completion ();
460
461     mexPrintf ("xfered %.3g bytes\n",
462             (double) max_bytes);
463
464     mexPrintf ("%d underruns\n", nunderruns);
465
466   }
467
468   void displayStringArray(const mxArray *string_array_ptr){
469     char *buf;
470     mwSize number_of_dimensions, buflen;
471     const mwSize *dims;
472     mwSize d, page, total_number_of_pages, elements_per_page;
473
474     /* Allocate enough memory to hold the converted string. */
475     buflen = mxGetNumberOfElements(string_array_ptr) + 1;
476     mexPrintf("Num elements in command: %d\n", buflen);
477     buf = (char*) mxCalloc(buflen, sizeof(char));
478
479     /* Copy the string data from string_array_ptr and place it into buf. */
```

```
480     if (mxGetString(string_array_ptr, buf, buflen) != 0)
481       mexErrMsgTxt("Could not convert string data.");
482
483     /* Get the shape of the input mxArray. */
484     dims = mxGetDimensions(string_array_ptr);
485     number_of_dimensions = mxGetNumberOfDimensions(string_array_ptr);
486
487     elements_per_page = dims[0] * dims[1];
488     /* total_number_of_pages = dims[2] x dims[3] x ... x dims[N-1] */
489     total_number_of_pages = 1;
490     for (d=2; d<number_of_dimensions; d++) {
491       total_number_of_pages *= dims[d];
492     }
493
494     for (page=0; page < total_number_of_pages; page++) {
495       mwSize row;
496       /* On each page, walk through each row. */
497       for (row=0; row<dims[0]; row++)  {
498         mwSize column;
499         mwSize index = (page * elements_per_page) + row;
500         mexPrintf("\t");
501         display_subscript(string_array_ptr, index);
502         mexPrintf(" ");
503
504         /* Walk along each column in the current row. */
505         for (column=0; column<dims[1]; column++) {
506           mexPrintf("%c",buf[index]);
507           index += dims[0];
508         }
509         mexPrintf("\n");
510       }
511     }
512 }
```

```
513
514 char getCommand(
515   const mxArray *inputPtrToString
516                 ){
517   char *command;
518   mwSize numElements;
519
520   numElements = mxGetNumberOfElements(inputPtrToString) + 1;
521   if (verbose)
522     mexPrintf("Num elements in command: %d\n", numElements);
523   //if number of elements of command is greater than 1, error
524
525   // Allocate enough memory for string
526   command = (char*) mxCalloc(numElements, sizeof(char));
527
528   /* Copy the string data from string_array_ptr and place it into buf. */
529   if (mxGetString(inputPtrToString, command, numElements) != 0)
530     mexErrMsgTxt("Could not convert string data.");
531
532   return *command;
533 }
534
535 /* Display the subscript associated with the given index. */
536 void
537 display_subscript(const mxArray *array_ptr, mwSize index)
538 {
539   mwSize     inner, subindex, total, d, q, number_of_dimensions;
540   mwSize       *subscript;
541   const mwSize *dims;
542
543   number_of_dimensions = mxGetNumberOfDimensions(array_ptr);
544   subscript = (mwSize*) mxCalloc(number_of_dimensions, sizeof(mwSize));
545   dims = mxGetDimensions(array_ptr);
```

```
546
547     mexPrintf("(");
548     subindex = index;
549     for (d = number_of_dimensions-1; ; d--) { /* loop termination is at the end */
550
551       for (total=1, inner=0; inner<d; inner++)
552         total *= dims[inner];
553
554       subscript[d] = subindex / total;
555       subindex = subindex % total;
556       if (d == 0) {
557           break;
558       }
559     }
560
561     for (q=0; q<number_of_dimensions-1; q++) {
562       mexPrintf("%d,", subscript[q] + 1);
563     }
564     mexPrintf("%d)", subscript[number_of_dimensions-1] + 1);
565
566     mxFree(subscript);
567   }
568
569
570   /*this is my main function, it will do great things one day*/
571   void mexFunction(
572       int             numOutArgs,           /* number of expected outputs */
573       mxArray         *outputArgs[],        /* array of pointers to output arguments */
574       int             numInArgs,            /* number of inputs */
575       const mxArray *inputArgs[]            /* array of pointers to input arguments */
576       )
577        {
578        if (numInArgs < 1||!mxIsChar(inputArgs[0])){
```

```
579         mexErrMsgTxt("Invalid mex Input", "First input must be a char array indicating"
580                         "a valid USRP command, see help for list of commands");
581     }
582     numCalls++;
583     mexPrintf("Call number: %d \n", numCalls);
584     short   data;
585     mexPrintf("Begin USRP program\n");
586     mexPrintf("Show Command: ");
587     displayStringArray(inputArgs[0]);
588     //getCharArray(inputArgs[0]);
589     char *commandPtr;
590     char command;
591     commandPtr = (char*) getCommand(inputArgs[0]);
592     //command = &commandPtr;
593     //initialize(numOutArgs, outputArgs);
594     //if (numInArgs > 0){
595     mexPrintf("command: %s\n", *commandPtr);
596     //if(strcmp(command,"Hi mom") == 0)
597     //mexPrintf("Command was Hi mom");
598     //}
599     setupUSRP();
600     setDBFrequency(1000);
601     startUSRP();
602     //data = genRandData();
603     //sendData(&data);
604     sendRandDataTest();
605     cleanUSRP();
606     mexPrintf("End USRP program .... so far\n");
607     }
```

Appendix I

USRP2 Transmitter Mask Helper Function

```
1  function usrp2tx(block, action)
2  %
3
4
5  Vals     = get_param(block, 'maskvalues');
6  Vis      = get_param(block, 'maskvisibilities');
7  En       = get_param(block, 'maskenables');
8
9  % --- Field numbers
10 EthInterface         = 1;
11 IDMode               = 2;
12 MACAddress           = 3;
13 FreqMode             = 4;
14 CenterFrequency          = 5;
15 PowerMode            = 6;
16 Power                = 7;
17 InterpolationMode    = 8;
```

```
18 InterpolationFactor = 9;
19
20
21 % Display the title of the block with some identification of the hardware
22 %   The interface IDs on windows will have to be shortened
23 title = ['text(0.5,␣0.85,␣''USRP2␣Tx\n␣on␣''' ...
24             Vals{EthInterface} ''''', '...
25              '''horizontalAlignment'', ''center'' ); '␣...
26 ␣␣␣␣␣␣␣␣␣␣␣␣'port_label(''input'', 1,''Data''); '];
27
28
29 USRPFigure␣=␣['plot([0.65 0.65 0.9 0.9 0.65],[0.2 0.4 0.4 0.2 0.2], '...
30 ␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣'[0.65 0.7],[0.4 0.55], '...
31 ␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣'[0.9 0.95], [0.4 0.55], '...
32 ␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣'[0.9 0.95], [0.2 0.35], '...
33 ␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣'[0.7 0.95 0.95],[0.55 0.55 0.35],'...
34 ␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣'[0.85 0.85 0.8 0.9 0.85], [0.3 0.65 0.75 0.75 0.65]);'];
35
36 switch(action)
37 ␣␣␣␣case␣'init'
38 ␣␣␣␣␣␣␣␣%feval(mfilename,block,'IDMode');
39 ␣␣␣␣␣␣␣␣%feval(mfilename,block,'CenterFreqMode');
40 ␣␣␣␣␣␣␣␣%feval(mfilename,block,'PowerMode');
41 ␣␣␣␣␣␣␣␣%feval(mfilename,block,'InterpolationFactorMode');
42 ␣␣␣␣␣␣␣␣%[varargout{1:1}]␣=␣feval(mfilename,block,'PortLabeling');
43
44
45 ␣␣␣␣case␣'PortLabeling'
46
47
48
49 ␣␣␣␣case␣'IDMode'
50 ␣␣␣␣␣␣␣␣if(strcmp(Vals{IDMode},'Automatic detection'))
```

```
51  ␣␣␣␣␣␣␣␣␣␣␣␣if(strcmp(Vis{MACAddress},'on'))
52  ␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣En{MACAddress}␣␣␣␣␣␣␣␣␣␣=␣'off';
53  ␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣Vis{MACAddress}␣=␣'off';
54  ␣␣␣␣␣␣␣␣␣␣␣␣end;
55  ␣␣␣␣␣␣␣␣elseif(strcmp(Vis{MACAddress},'off'))
56  ␣␣␣␣␣␣␣␣␣␣␣␣En{MACAddress}␣␣␣␣␣␣=␣'on';
57  ␣␣␣␣␣␣␣␣␣␣␣␣Vis{MACAddress}␣␣␣␣␣=␣'on';
58  ␣␣␣␣␣␣␣␣end
59  ␣␣␣␣␣␣␣␣set_param(block,'MaskVisibilities',Vis,'MaskEnables',En);
60
61  ␣␣␣␣case␣'CenterFreqMode'
62  ␣␣␣␣␣␣␣␣if(strcmp(Vals{FreqMode},'Select frequency from port'))
63  ␣␣␣␣␣␣␣␣␣␣␣␣if(strcmp(Vis{CenterFrequency},'on'))
64  ␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣En{CenterFrequency}␣␣␣␣␣␣␣␣␣␣=␣'off';
65  ␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣Vis{CenterFrequency}␣␣␣␣=␣'off';
66  ␣␣␣␣␣␣␣␣␣␣␣␣end;
67  ␣␣␣␣␣␣␣␣elseif(strcmp(Vis{CenterFrequency},'off'))
68  ␣␣␣␣␣␣␣␣␣␣␣␣En{CenterFrequency}␣=␣'on';
69  ␣␣␣␣␣␣␣␣␣␣␣␣Vis{CenterFrequency}␣␣␣␣␣␣␣␣=␣'on';
70  ␣␣␣␣␣␣␣␣end
71  ␣␣␣␣␣␣␣␣set_param(block,'MaskVisibilities',Vis,'MaskEnables',En);
72
73  ␣␣␣␣case␣'PowerMode'
74  ␣␣␣␣␣␣␣␣if(strcmp(Vals{PowerMode},'Select power from port'))
75  ␣␣␣␣␣␣␣␣␣␣␣␣if(strcmp(Vis{Power},'on'))
76  ␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣En{Power}␣␣␣␣␣␣␣␣␣␣␣␣␣␣=␣'off';
77  ␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣Vis{Power}␣␣␣␣␣␣=␣'off';
78  ␣␣␣␣␣␣␣␣␣␣␣␣end;
79  ␣␣␣␣␣␣␣␣elseif(strcmp(Vis{Power},'off'))
80  ␣␣␣␣␣␣␣␣␣␣␣␣En{Power}␣␣␣=␣'on';
81  ␣␣␣␣␣␣␣␣␣␣␣␣Vis{Power}␣␣=␣'on';
82  ␣␣␣␣␣␣␣␣end
83  ␣␣␣␣␣␣␣␣set_param(block,'MaskVisibilities',Vis,'MaskEnables',En);
```

```
84
85  ____case 'InterpolationFactorMode'
86  ________if(strcmp(Vals{InterpolationMode},...
87  ________________'Select interpolation factor from port'))
88  ____________if(strcmp(Vis{InterpolationFactor},'on'))
89  ________________En{InterpolationFactor}_________='off';
90  ________________Vis{InterpolationFactor}________='off';
91  ____________end;
92  ________elseif(strcmp(Vis{InterpolationFactor},'off'))
93  ____________En{InterpolationFactor}_____='on';
94  ____________Vis{InterpolationFactor}____='on';
95  ________end
96  ________set_param(block,'MaskVisibilities',Vis,'MaskEnables',En);
97
98  display = [title USRPFigure];
99  set_param(block, 'maskdisplay', display);
100
101 end
```

Appendix J

USRP2 Receiver Mask Helper Function

```
1  function usrp2rx(block, action)
2  %
3
4
5  Vals     = get_param(block, 'maskvalues');
6  Vis      = get_param(block, 'maskvisibilities');
7  En       = get_param(block, 'maskenables');
8
9  % --- Field numbers
10 EthInterface         = 1;
11 IDMode               = 2;
12 MACAddress           = 3;
13 FreqMode             = 4;
14 CenterFrequency          = 5;
15 PowerMode            = 6;
16 Power                = 7;
17 InterpolationMode    = 8;
```

```
18 InterpolationFactor = 9;
19
20
21 % Display the title of the block with some identification of the hardware
22 %   The interface IDs on windows will have to be shortened
23 title = ['text(0.5,␣0.85,␣''USRP2␣Rx\n␣on␣''' ...
24             Vals{EthInterface} '''', '...
25              '''horizontalAlignment'', ''center'' ); '␣...
26 ␣␣␣␣␣␣␣␣␣␣␣␣'port_label(''output'', 1,''Data''); '];
27
28
29 USRPFigure␣=␣['plot([0.1 0.1 0.35 0.35 0.1],[0.2 0.4 0.4 0.2 0.2], '...
30 ␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣'[0.35 0.4],[0.4 0.55], '...
31 ␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣'[0.1 0.15], [0.4 0.55], '...
32 ␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣'[0.35 0.4], [0.2 0.35], '...
33 ␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣'[0.15 0.4 0.4],[0.55 0.55 0.35],'...
34 ␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣'[0.2 0.2 0.15 0.25 0.2], [0.3 0.65 0.75 0.75 0.65]);'];
35
36 switch(action)
37 ␣␣␣␣case␣'init'
38 ␣␣␣␣␣␣␣␣feval(mfilename,block,'IDMode');
39 ␣␣␣␣␣␣␣␣feval(mfilename,block,'CenterFreqMode');
40 ␣␣␣␣␣␣␣␣feval(mfilename,block,'PowerMode');
41 ␣␣␣␣␣␣␣␣feval(mfilename,block,'InterpolationFactorMode');
42 ␣␣␣␣␣␣␣␣%[varargout{1:1}]␣=␣feval(mfilename,block,'PortLabeling');
43
44
45 ␣␣␣␣case␣'PortLabeling'
46
47
48
49 ␣␣␣␣case␣'IDMode'
50 ␣␣␣␣␣␣␣␣if(strcmp(Vals{IDMode},'Automatic detection'))
```

```
51  ␣␣␣␣␣␣␣␣␣␣␣␣if(strcmp(Vis{MACAddress},'on'))
52  ␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣En{MACAddress}␣␣␣␣␣␣␣␣␣␣=␣'off';
53  ␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣Vis{MACAddress}␣=␣'off';
54  ␣␣␣␣␣␣␣␣␣␣␣␣end;
55  ␣␣␣␣␣␣␣␣elseif(strcmp(Vis{MACAddress},'off'))
56  ␣␣␣␣␣␣␣␣␣␣␣␣En{MACAddress}␣␣␣␣␣␣=␣'on';
57  ␣␣␣␣␣␣␣␣␣␣␣␣Vis{MACAddress}␣␣␣␣␣=␣'on';
58  ␣␣␣␣␣␣␣␣end
59  ␣␣␣␣␣␣␣␣set_param(block,'MaskVisibilities',Vis,'MaskEnables',En);
60
61  ␣␣␣␣case␣'CenterFreqMode'
62  ␣␣␣␣␣␣␣␣if(strcmp(Vals{FreqMode},'Select frequency from port'))
63  ␣␣␣␣␣␣␣␣␣␣␣␣if(strcmp(Vis{CenterFrequency},'on'))
64  ␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣En{CenterFrequency}␣␣␣␣␣␣␣␣␣␣=␣'off';
65  ␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣Vis{CenterFrequency}␣␣␣␣=␣'off';
66  ␣␣␣␣␣␣␣␣␣␣␣␣end;
67  ␣␣␣␣␣␣␣␣elseif(strcmp(Vis{CenterFrequency},'off'))
68  ␣␣␣␣␣␣␣␣␣␣␣␣En{CenterFrequency}␣=␣'on';
69  ␣␣␣␣␣␣␣␣␣␣␣␣Vis{CenterFrequency}␣␣␣␣␣␣␣␣=␣'on';
70  ␣␣␣␣␣␣␣␣end
71  ␣␣␣␣␣␣␣␣set_param(block,'MaskVisibilities',Vis,'MaskEnables',En);
72
73  ␣␣␣␣case␣'PowerMode'
74  ␣␣␣␣␣␣␣␣if(strcmp(Vals{PowerMode},'Select power from port'))
75  ␣␣␣␣␣␣␣␣␣␣␣␣if(strcmp(Vis{Power},'on'))
76  ␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣En{Power}␣␣␣␣␣␣␣␣␣␣␣␣␣␣=␣'off';
77  ␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣Vis{Power}␣␣␣␣␣␣=␣'off';
78  ␣␣␣␣␣␣␣␣␣␣␣␣end;
79  ␣␣␣␣␣␣␣␣elseif(strcmp(Vis{Power},'off'))
80  ␣␣␣␣␣␣␣␣␣␣␣␣En{Power}␣␣␣=␣'on';
81  ␣␣␣␣␣␣␣␣␣␣␣␣Vis{Power}␣␣=␣'on';
82  ␣␣␣␣␣␣␣␣end
83  ␣␣␣␣␣␣␣␣set_param(block,'MaskVisibilities',Vis,'MaskEnables',En);
```

```
84
85  ____case 'InterpolationFactorMode'
86  ________if(strcmp(Vals{InterpolationMode},...
87  ________________'Select interpolation factor from port'))
88  ____________if(strcmp(Vis{InterpolationFactor},'on'))
89  ________________En{InterpolationFactor}_________='off';
90  ________________Vis{InterpolationFactor}________='off';
91  ____________end;
92  ________elseif(strcmp(Vis{InterpolationFactor},'off'))
93  ____________En{InterpolationFactor}_____='on';
94  ____________Vis{InterpolationFactor}____='on';
95  ________end
96  ________set_param(block,'MaskVisibilities',Vis,'MaskEnables',En);
97
98  display = [title USRPFigure];
99  set_param(block, 'maskdisplay', display);
100
101 end
```