A HIGH PERFORMANCE RF TRANSCEIVER IMPLEMENTATION

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ABSTRACT

One key goal of software-defined radio (SDR) is to provide the possibility of operating in a wide range of frequency bands with a single device. At the same time, real-world communication systems require a high degree of amplification and filtering to achieve acceptable performance. Realizing these two goals creates an inherent challenge, as both high frequency selectivity and wide bandwidth tunability are generally difficult to achieve concurrently in a high performance system. This paper details the development of a high performance radio frequency (RF) transceiver daughtercard designed to be used in conjunction with the Ettus Research Universal Software Radio Peripheral (USRP). Motivation for the development of the board grew out of application research in the areas of public safety communications and dynamic spectrum access, both of which require high sensitivity.

1. INTRODUCTION

Motivation for the design and implementation of a new radio frequency (RF) front-end, which will be referred to as the UND 144 transceiver board, grew out of a number of software-defined radio (SDR) research projects underway by the Radioware group [1] at Notre Dame. To support these projects, it was decided to design an RF transceiver board compatible with GNU Radio [2] and the Ettus Universal Software Radio Peripheral (USRP) [3] that would sacrifice some of the flexibility of existing RF solutions in order to provide higher quality performance. This improvement in performance is primarily accomplished through the use of a different local oscillator (LO) architecture and the extensive use of filtering.

SDR [4] promises flexible and even intelligent communication devices. Its most basic goal is to perform as much communication signal processing in software to maximize flexibility and minimize development cost and time. Potential for improved flexibility and simpler development has lead SDR to be widely adopted in research pursuits for which the limited scope of the typical project often makes traditional hardware development impractical. A pure software radio, in which signals are digitized at the antenna and processed completely in software, is at the current time unrealizable due to hardware limitations. As such, there are a number of design tradeoffs that must be made which affect the ultimate performance of any SDR. One such hardware limitation is the result of the limited sampling rates of current analog-to-digital converters (A/Ds), which necessitate the use of RF front-ends in order to operate in a large number of frequency bands of interest. Additionally, the limited dynamic range of A/Ds also means a high degree of filtering is required so that out of band signals do not dominate the signal of interest. Designing an RF front-end that allows both wide tunability and high frequency selectivity to eliminate out of band noise is extremely difficult. Filters, amplifiers, and oscillators must have good performance and be tunable over the entire frequency range of interest, which is not presently possible. Similar issues arise on the transmitter side of SDRs where the problem is to suppress spurious signals generated in the conversion to analog RF from digital baseband.

One of the most widely used SDR platforms within the research community is the combination of the Ettus USRP as a digital front-end and GNU Radio as a baseband processing environment on a general purpose processor. The USRP has a base motherboard that converts signals between an intermediate frequency (IF) and baseband and between the analog and digital domains. There are a number of swappable daughterboards that can be used in conjunction with the USRP motherboard to translate signals between RF and IF. Transceiver daughterboards for the USRP provide frequency flexibility primarily by two means. First, there are various daughterboards designed to transceive on frequencies ranging from 400 MHz up to 5 GHz, each board typically having an operating bandwidth range on the order of a few hundred MHz. The RFX and XCVR [3] daughterboard series are such boards, allowing different bands to be utilized by swapping out boards. Recently, a wideband transceiver board, the WBX daughterboard [3], has been released that allows operation from 50 MHz to 2.2 GHz. Second, the daughterboards usually provide limited filtering in order to allow operation over their entire specified bandwidth. The design philosophy behind these RF front-ends is to provide as much flexibility as possible while retaining acceptable performance.

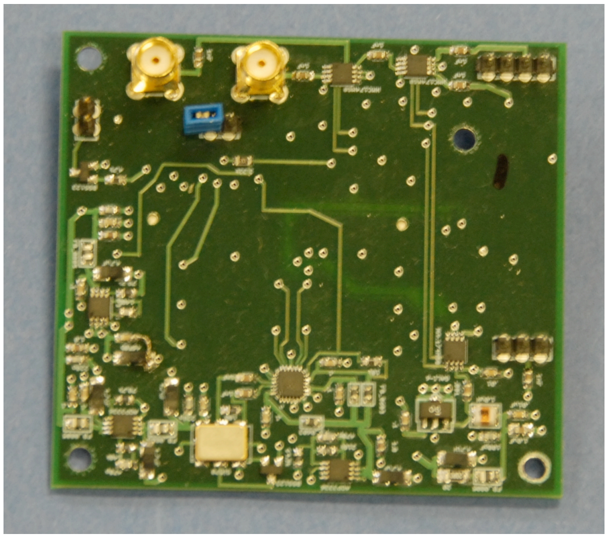

Figure 1: UND 144 transmitter

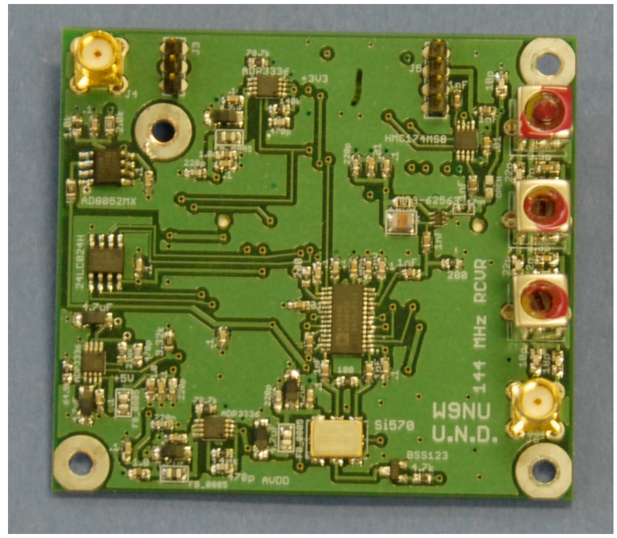

Figure 2: UND 144 receiver

The UND 144 transceiver was designed with extensive onboard filtering and a high quality LO, reducing its overall tunability but ensuring good RF performance. This design decision was made to support a number of applications, one of which being the use of SDR for public safety communications to improve interoperability and to make more efficient use of assigned spectrum. For this project, fieldable hardware is required for a number of reasons, including accurate measurements of spectrum occupancy both with high frequency precision and without degradation due to out of band interference, as well as reception of transmissions at real-world signal strengths. Additionally, to transmit with larger power levels, the output spectrum of the transmitter needs to be accurately centered in the desired band and not produce large spurious out of band harmonics and noise. As amateur radio communication formats and frequency bands are quite similar to those used for public safety communications, the boards are also appropriate for use by the amateur radio community. Spectrum occupancy studies are also planned in various other frequency bands in order to support theoretical research efforts focused on dynamic spectrum access (DSA) [5].

Section 2 of this paper highlights the key design decisions made in construction of the UND 144 transceiver board and discusses similarities and differences with existing daughterboards. Section 3 provides the results of preliminary tests performed on the board as well as a number of existing daughterboards for the USRP as points of comparison. Finally, Section 4 concludes the paper.

2. TRANSCEIVER DESIGN

The transceiver consists of two boards, a transmitter and receiver board, depicted in Figures 1 and 2, respectively, that can operate independently of one another or in unison. The 144 MHz (2 m) operating band was selected to be the standard configuration for the board as it has a number of beneficial qualities. First, it is an amateur radio band, allowing the transceiver to be used directly for implementation and experimental work without additional hardware. Second, the tunability of the selected LO allows the boards to operate at frequencies ranging from approximately 50-500 MHz. This covers a number of other amateur radio bands (50 MHz, 220 MHz, 432 MHz) as well as many common public safety bands (at various frequencies from 50-450 MHz).

Additionally, 144 MHz is a common IF used by amateur UHF and microwave transverters, allowing the transceiver board to be paired with various transverters to operate in an even wider range of frequency bands. Such a pairing is described later in this section. The USRP motherboard provides differential in-phase and quadrature (IQ) signals to transmit daughterboards and is provided similar signals by receive daughterboards. Thus, when used without an external transverter the board has a superheterodyne structure where the RF frequency is selectable between 50-500 MHz. The presence of an external transverter results in an additional IF frequency, 144 MHz, and thus a two stage superheterodyne structure.

2.1 Transmitter Design

Figures 3 and 4 depict simplified block diagrams of the Ettus WBX and UND 144 transmitters, respectively. There are a number of key similarities and differences that warrant discussion. First, both designs use quadrature modulators that produce their in-phase and quadrature signals for

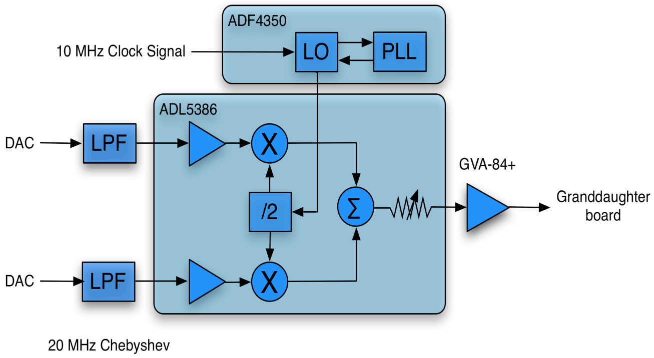

Figure 3: WBX transmitter block diagram

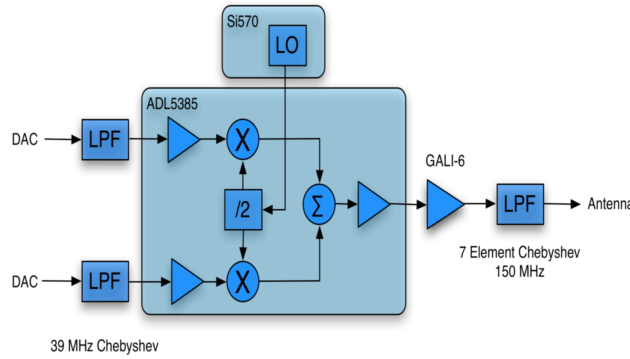

Figure 4: UND 144 transmitter block diagram

mixing through the use of divide-by-two phase splitters. Such devices require the LO input signal be at twice the frequency of the desired frequency translation but produce reference signals that are more accurately in quadrature with one another as compared with polyphase splitters, as are used in the older RFX / FLEX board series. Keeping the reference signals in quadrature reduces IQ-imbalance and provides a higher fidelity reproduction of the input signal at RF. The UND 144 transmitter board uses the ADL5385 quadrature modulator [6], capable of producing signals ranging from 50 MHz to 2.2 GHz, but the input LO of the UND 144 transmitter limits operation to 500 MHz.

The LO is crucial to ensuring that the front-end provides highly calibrated frequency translation of the desired signal that does not drift significantly with time or temperature. For this purpose, the Silicon Labs Si570 digitally controlled oscillator [7] was chosen to produce the LO in the UND transceiver board. This low jitter oscillator is programmable through an I2C interface over a wide range of frequencies, giving an operating range from 50-500 MHz. The low jitter results in improved frequency stability and reduced phase noise; measurements of the former are provided in the next section. The WBX transceiver board uses the ADL4350, a digital VCO, coupled with a phase-locked loop (PLL) to produce its LO. This design provides an LO with similar stability to that given by the Si570 with a slight increase in phase noise due to feedback from the PLL. A key characteristic of the Si570 is sub-Hertz tunability of the oscillator, meaning highly precise frequency calibration can be performed on the RF front-end.

The third key factor in the performance of the designed UND 144 daughtercard is the extensive use of filtering to eliminate out of band interference and noise. Both the WBX board and the UND board have 20 MHz Chebyshev low-pass filters (LPF) on the in-phase and quadrature signals from the USRP to eliminate unwanted spectral components resulting from the digital to analog conversion process. Additionally, the UND transmitter includes a 150 MHz LPF on the output of the quadrature modulator to attenuate harmonics and spurious signals resulting from the mixer. This filter gives a cleaner output spectrum, which will result in tolerable levels of interference to adjacent bands, an important aspect if the device is to be used in high power communications. The major drawback to using the additional onboard LPF is that it limits the frequency bands in which the card can be used, but it can be bypassed using either an external filter or simple jumper to operate in a different band. The WBX board will have stronger spurious signals in its output, but it should be noted that it is designed so that it can be used in conjunction with a grand-daughterboard, that is, another component board on which additional filtering can be performed.

The UND transmitter is capable of providing up to 18 dBm of output power through the GALI-6 monolithic amplifier [8] that follows the output of the quadrature modulator. Additional power can be supplied through external means. An SMA connector and switch on the transmitter board allows the transmitter and receiver to share the same antenna.

2.2 Receiver Design

The design decisions of the UND 144 receiver card in many ways parallel those of the transmitter board. Figures 5 and 6 show block diagrams of the WBX and UND receivers, respectively. On the UND receiver, the RF signal obtained from the antenna is first passed through a highly selective, triple bandpass filter with a passband of 143.5-148.5 MHz before the input to the quadrature demodulator. Use of this bandpass filter (BPF) is selected when the board is operating in the 2 m amateur radio band or in conjunction with a UHF or microwave transverter to cover other frequency bands. Pins are also provided to allow a replaceable filter to be connected when a second frequency band is desired. The onboard BPF ensures noise from adjacent bands does not affect the dynamic range of the ADC. Another important feature of the receiver daughtercard is the inclusion of an MGA-62563 [9] low noise pre-amplifier following the BPF,

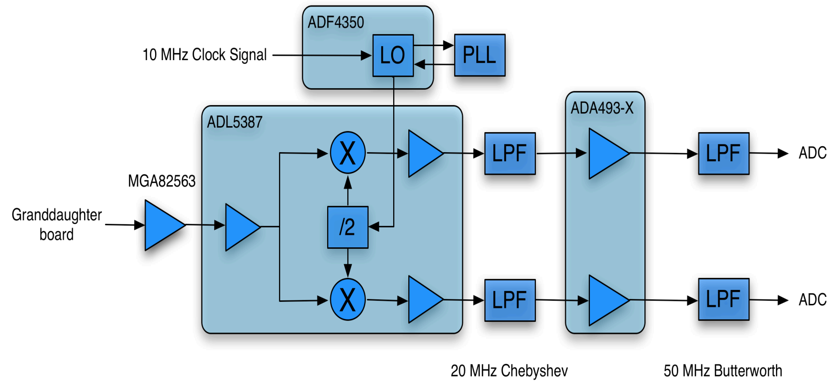

Figure 5: WBX receiver block diagram

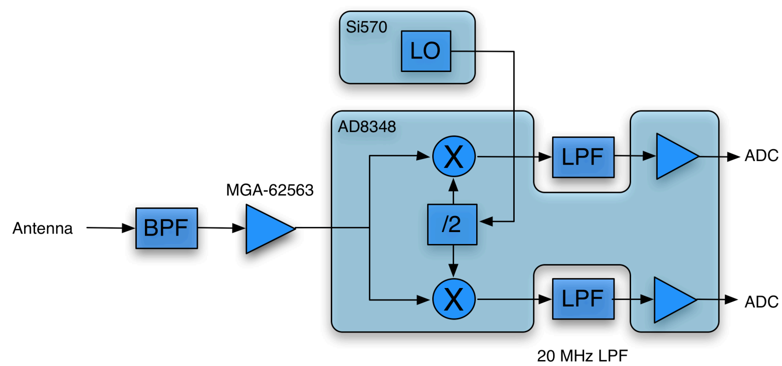

Figure 6: UND 144 receiver block diagram

capable of providing up to 15 dB of gain over the entire range of frequencies.

The signal is then shifted from RF to IF by the AD8348 quadrature demodulator [10] which, again, uses divide-by-two logic to transform an external LO signal to IQ reference signals for the downconversion. The board uses the Si570 to produce an independent LO. LPFs with bandwidths of 20 MHz then filter the signal at IF before it is passed off board to the USRP motherboard for digitization.

2.3 Transverter Configuration

As mentioned earlier, the UND 144 transceiver can operate from 50-500 MHz through use of the external filtering option. If higher frequencies of operation are desired, this can be accomplished through the use of a frequency transverter to convert the signal to 144 MHz as an IF. Such a setup has been realized for experimental purposes. It includes the use of a Kuhne Electronics MKU 23 G2 transverter [11] to convert between 144 MHz and 2.4 GHz. The UND 144 transmitter board has a jumper to enable the addition of a 5 V DC component to the signal to switch the transverter into transmit mode. A mechanical relay on the output of the Kuhne transverter allows for a single antenna to be used for both the transmit and receive chains.

3. PERFORMANCE CHARACTERIZATION

This section details selected operating parameters and performance measurements of the UND 144 transceiver as well as two existing USRP daughterboards as points of comparison. Table 1 compares a number of these parameters and measurements for the UND 144, WBX, and RFX400 boards. As can be seen, the WBX board has a larger operating frequency range than either the RFX or UND boards. This provides a high degree of flexibility, as a large number of center frequencies can be used simply by reprogramming the board in software. The UND board can be tuned over a smaller range of frequencies and requires the addition of an external bandpass filter designed for the operating frequency, or a bypass jumper of the filter stage

Table 1: Daughterboard Comparison

	WBX	FLEX400	UND 144
Freq. Range (MHz)	50-2200	400-500	50-500
Power (mW)	100	100	18
MDS (dBm)	-110.9	-110.8	- 109.5
Tunability	< 1 Hz	300 Hz	< 1 Hz

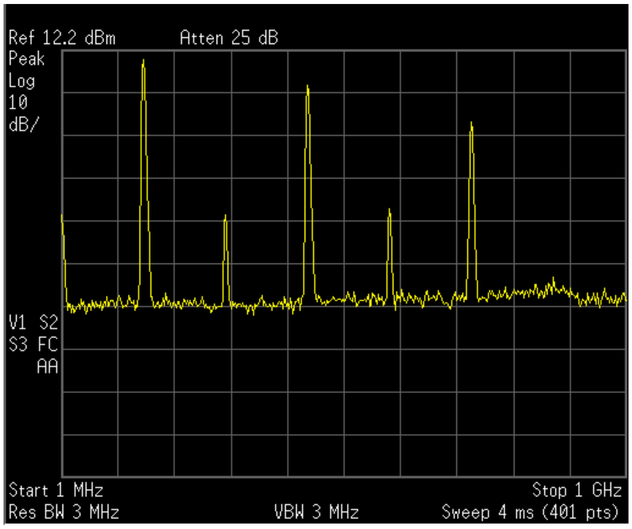

Figure 7: Output spectrum for WBX transmitter

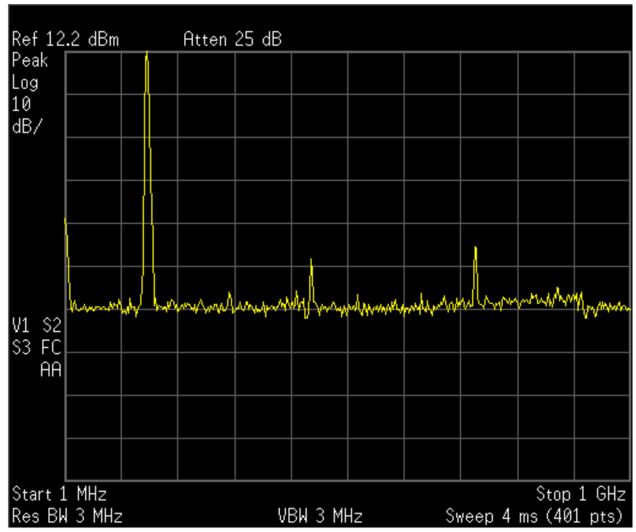

Figure 8: Output spectrum for UND 144 transmitter

which would eliminate the benefits provided by the additional filtering. The RFX series board must be swapped out to operate in a different frequency band.

The output power of the UND board is an order of magnitude less than the WBX and RFX boards, but it is designed to be used with additional amplifiers to reach higher transmit power levels. It also has sub-Hertz tunability for its LO, making very precise frequency calibration possible. This is important for high power transmissions where one must ensure operation within the licensed frequency band, as well as for taking accurate spectrum occupancy measurements.

Minimum discernible signal (MDS) is a quantification of receive sensitivity or the noise floor of a device. Testing of the daughterboards was done following the procedure outlined in the ARRL Test Procedure Manual [12], a widely used document in the amateur radio community. The test is performed by feeding a carrier signal into the device under test (DUT) and having it be converted to an output audio signal comprised of a pure tone. This audio signal is then fed into an audio/distortion meter in order to determine what input power for the carrier signal is required so that the signal and noise powers are equal. This gives a good quantification of the noise floor. Table 1 shows that all three devices have similar MDS values and thus similar receive sensitivities. While MDS is in general a good measure of receiver sensitivity, it does not fully capture the benefits of the additional filtering provided by the UND receiver board. This is because the input signal in the test does not contain out of band noise. A system-level bit-error rate test is discussed later to show the benefits of increased filtering.

Figures 7 and 8 show plots of the output spectrums of the WBX and UND transmitters, respectively, when configured to send a pure tone at a carrier frequency of 145 MHz. Such plots can be used to gauge the spectral purity of the transmitter [12] by comparing the strength of harmonics relative to the fundamental peak. These harmonics will cause interference to out of band users as well as produce extra cross-modulation terms if an additional stage of mixing is used to convert to a higher frequency. The first and largest peak in both plots is the fundamental. The first harmonic on the UND board (290 MHz) is less than -60 dBc (dB relative to the carrier), and the second harmonic (435 MHz) is at -48.2 dBc. For the WBX board, the first and second order harmonics are -36 dBc and -16.2 dBc. Harmonics generated by a transmitter in a communication system are generally not a problem for the intended receiver, as they are far away from the frequency band of the link; however, they cause interference to users of the adjacent frequency spectrum. Regulations by the FCC [13] require the first order harmonic to be at a level of at least -45 dBc to limit interference. The UND transmitter is able to meet this requirement due to its extensive use of filtering on the IF signal. It is thus possible to use the output of the UND transmitter not only for low power laboratory experimentation, but also for higher power, long-range communication typical of public safety and amateur radio formats. It should be noted that use of a custom grand-daughterboard in conjunction with the WBX would allow for the harmonics in Figure 7 to be reduced, but this requires filter design by the user.

The importance of high precision frequency calibration has already been discussed, but another equally important related metric is frequency stability. An oscillator in an RF front-end should not deviate too much from its specified frequency with time or temperature. Otherwise, high

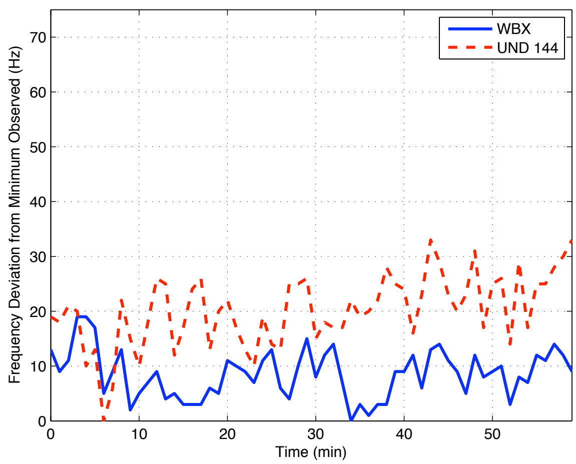

Figure 9: Frequency stability

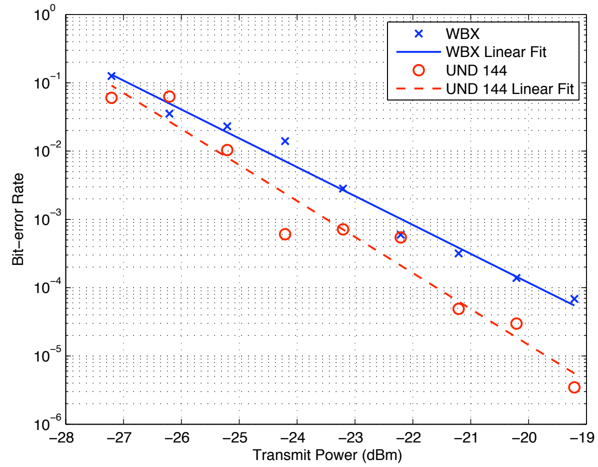

Figure 10: Bit-error rate versus transmit power

frequency calibration would be irrelevant. To measure the frequency stability of the daughterboards under test, they were configured to again transmit a pure carrier wave, fed to a frequency counter. Each board was allowed to warm up for half an hour. The value of the frequency was then recorded every minute for an hour using a one second gate time. Results for the UND and WBX board are shown in Figure 9, which plots the difference of the frequency measured at each time instant with the minimum observed frequency over the entire observation period. Each board has relatively little drift associated with it, no more then a few tens of Hertz. On the UND board this is due to the use of the high performance Si570 crystal oscillator.

Finally, as a measure of system-level performance, bit-error rate (BER) versus transmit power curves were generated using both sets of daughterboards. This test provides a useful measurement of performance for the overall transceivers and allows the benefits of the additional filtering provided by the UND transceiver board to be observed. To obtain the BER curves, the pairs of transceivers were placed in two USRPs a distance 3.2 m apart at table height within an indoor lab environment. The relatively low carrier frequency of 145 MHz used ensures that multipath fading did not play a significant role in affecting the outcome of the experiment. To compare the two transceiver sets directly, the output power of each was adjusted to be exactly 1.2 mW, as measured with a high quality RF power meter. With GNU Radio and the USRP there are two methods of controlling transmit power: in software by adjusting the scale of the digital signal sent to the DAC, and in hardware by adjusting the various gains provided in the analog circuitry, whether it be on the output of the DAC or on the daughterboard itself. The former has the disadvantage of potentially resulting in disparate quantization noise between the two transmitters, so the latter power adjustment method was used.

The output of the transmitting USRP was fed into a variable RF attenuator to simplify taking measurements at various power levels. For software, the standard GNU Radio *benchmark_tx.py* and *benchmark_rx.py* were modified to calculate the number of bit-errors when random data was sent as a packet's payload. The modulation was GMSK with a data rate of 500 kbps. At each power level, 1000 packets of size 1500 bytes were sent. Figure 10 plots the measured BER versus transmit power for each transceiver pair. At most power levels, the UND 144 board has better performance than the WBX board. This is likely the result of the additional filtering provided on the board, allowing for interfering signals and noise to be more thoroughly attenuated. It should be noted that there is a considerable amount of variation in the plots, as they are not the smooth BER curves of theory. Least squares was used to obtain a linear fit for each data set in order to more clearly illustrate the improved performance of the UND 144 transceiver. The variation in measured points is partially the result of nonstationary interference, which no effort was made to characterize. Despite this, the plots shown are representative of what was observed during experimentation and give a rough estimate of the performance of each transceiver pair.

4. CONCLUSION

Though not indicated by its name, software radio is greatly affected by the hardware designs on which it is implemented. RF front-ends have a particularly strong impact on the performance of SDRs, as they affect the operational frequency, bandwidth, and sensitivity of devices. Existing front-ends for the USRP have focused on providing maximum flexibility and performance levels appropriate for laboratory experimentation. This paper has detailed the design of the UND 144 transceiver, which trades some flexibility to provide better performance. Such performance was achieved through the use of additional filtering and high quality oscillators and is observable in both the purer output spectrum of the transmitter and improved BER performance of the overall system. For more information on the design and performance of the UND 144 transceiver board, visit the Radioware website [1].

5. REFERENCES

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