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Multi-channel Software Defined Radio Experimental Evaluation and Analysis

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***Abstract* -- Multi-channel software-defined radios (SDRs) can be utilised as inexpensive prototyping platforms for transceiver arrays. The application for multi-channel prototyping is discussed and measured results of coherent channels for both receiver and transmitter experiments are presented. It is concluded that SDR is an affordable solution to rapid prototyping and educational applications.**

***Keywords* -- Multichannel SDR, transceiver arrays, rapid prototyping.**

I. INTRODUCTION

Software-defined radio (SDR) is a rapidly growing technology that allows an inexpensive and simple digital interface to the electromagnetic spectrum [1]. An SDR is a radio system in which some of the traditional hardware components are implemented in software, thus the platform can be reconfigured for a number of different applications [2]. Although SDR is not a new concept, it is only made possible with recent technological hardware advances [3].

The applications of SDR range from communications [4], [5] to research platforms [6], [7]. An SDR can be configured to be a cellular base station [8], [9]; for Wi-Fi networking [10], [11]; audio broadcasting and receiving [12]; radar [13], [14]; passive radar [15] [16] [17]; Global Navigation Satellite System (GNSS) receiver [18] [19] [20]; channel simulator [21]; channel characterisation [22]; radio-frequency identification (RFID) [23], or spectral monitoring and cognitive radio [24]. Open source software packages for these mentioned applications are available.

II. SDR ARCHITECTURE

SDR technology is simple to configure, reconfigurable and relatively cheap; hence it is the ideal tool for rapid prototyping of systems for research and educational purposes [25], [26].

As multiple channels are possible, antenna-array applications are easily implemented. Traditionally antenna arrays require a lot of hardware configuration, however SDRs provide a simple, inexpensive solution. Smart antenna system design is also possible with SDR and has been proposed [27].

SDR platforms are thus ideal for beam forming [28] and phase interferometry based direction finding. Multiple-input, multiple-output (MIMO) communications and sensor systems are also achievable with SDRs. The re-configurability of SDRs allows a single transceiver to take up multiple roles within an environment, so effective system reuse is achieved. This quick reconfiguration allows SDRs to quickly change their frequency band of interest [29], so spectral monitoring over a greater band can be performed through scanning. Applications such as white-space monitoring and cognitive radio are therefore possible with SDRs.

There are different SDR architectures, however only universal software radio peripheral (USRP) system architectures are considered in this discussion as they are commercially available and inexpensive.

A USRP transfers data to and from a host device (usually a computer), and is one of the most popular SDR architectures. The USRP is the radio-frequency (RF) frontend of the system and the radio is thus configured on the host.

Fig. 1 shows the architecture of USRP based SDR.

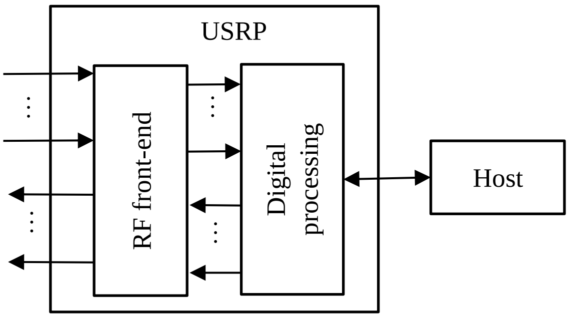

Fig. 1. USRP architecture.

A. *RF front-end*

The RF front-end is the only section of the signal processing that is implemented in hardware. Both receiver (Rx) and transmitter (Tx) channels are discussed in this section. A USRP may have any number of Rx and Tx channels depending on the manufacturer and model. Fig. 2 shows a typical RF front-end architecture of a USRP.

USRPs typically have a low noise amplifier (LNA) with programmable gain to control an Rx channel. Similarly the Tx channel has a programmable amplifier (A) at the last stage

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to ensure that the transmitted signal has the required output power.

A variable frequency oscillator (VFO) and mixer are used to convert the signals to and from baseband. The VFO is controlled by the host device and can thus be tuned to the frequency band of interest for the application.

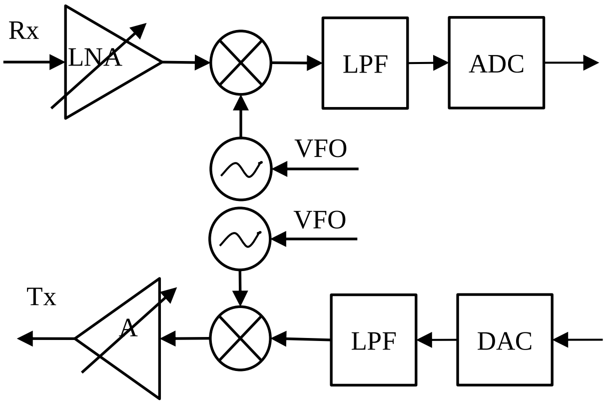

Fig. 2. Block diagram of a USRP architecture.

Analogue baseband low pass filters (LPF) are further implemented to reduce aliasing for the Rx channel before it is passed to the analogue to digital converter (ADC). Similarly smoothing baseband LPFs are implemented after the digital to analogue converter (DAC).

Some hardware issues that do occur are oscillator leak through, spurious signals and aliasing. The dynamic ranges of Rx channels are typically not very high, and the Tx channels have a limited output power range. The dynamic range is a function of the ADC and in increased by 6 dB per ADC bit.

Additional hardware components or stages may be present with different USRPs, for example a band pass filter between the LNA and mixer.

B. *Data processing and porting*

Field programmable gate arrays (FPGA), digital signal processors (DSP), micro controllers or a combination of these are used for the on-board data processing and interfacing on the USRP.

The ADCs and DACs on the USRP are typically set to a fixed hardware sample rate to reduce hardware complexity. The sample rate that the host can specify is decimated/ interpolated from the fixed hardware sample rate. The Rx data samples are decimated through a digital down converter (DDC) chain to match the sample rate required by the host. If the RF front-end of the USRP only has a single ADC per channel, i.e. real sampling, the DDC implements real to complex data conversion, often with a Hilbert transform. The Tx data samples are interpolated through a digital up converter (DUC) chain to match the hardware and host sample rates.

The DDC and DUC are implemented on either an FPGA or DSP to allow fast data processing. Most USRPs implement these stages in firmware and can thus be modified; the user can therefore add additional processing like digital filtering. The hardware sample rate is typically an integer multiple of maximum sample rate that the host can specify; this is done for noise suppression and increased receiver sensitivity through the DDC and DUC. Fig. 3 shows a block diagram of the signal processing on the USRP.

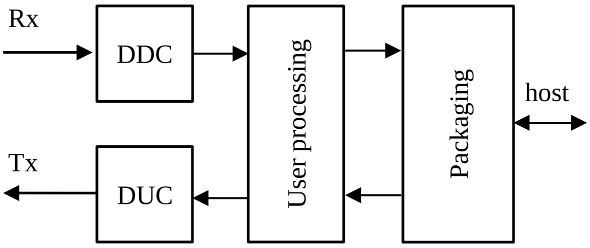

Fig. 3. Architecture of the digital data processing and interface packaging of the data samples on the USRP.

The Rx samples after the DDC and the Tx samples before the DUC are subsequently packed and sent to/from the host device. The connection between the USRP and the host is usually the data-rate limitation of the system. USRPs have a number of different interface options to the host device; the most popular are Universal Serial Bus (USB) 2 and 3, Ethernet and Peripheral Component Interconnect Express (PCI-E). The interface link between the USRP and the host may cause data samples to be lost, hence it is often advised not to set the SDR to utilise the maximum sample rate.

C. *Clock and Multichannel Synchronisation*

There are many different methods of clocking USRPs. All USRPs have an internal local oscillator (LO) that serves as an internal clock source, but usually also includes an option to take an external clock as well. The clock is used to derive the sample rate clock and the VFO for mixing. The internal clock has a typical stability to a few parts per million (ppm); therefore using the independent free running LOs in different USRPs would not allow for synchronous operation. Clock stability is crucial; hence using a very stable external clock yields the best performance.

Some USRPs use on-board Global Positioning System (GPS) disciplined oscillators (GPSDO) for stabile clocking; however an additional outside antenna is required. The GPSDO has a clock stability of a few parts per billion (ppb) and thus is it considerably more stable than the internal clock. The external clock of a USRP is often designed to be 10 MHz, as it can be derived from the signals of GPS satellites and is also widely used in laboratory equipment.

Using external clock distribution, it is therefore possible to synchronise the sample rate and mixing clocks of multiple USRPs. Multichannel transceiver devices can thus be created.

A pulse per second (PPS) signal is used to synchronise the batch samples of USRPs. A PPS signal can also be derived from GPSDO using GPS satellites. The stability of the PPS is important as it aligns the data samples between the different channels.

Phase-matched cables to connect from the external clock distributor are crucial for both the PPS and clock synchronisation, as different delays will create phase offsets of the signals between different USRPs. However, the relatively low frequencies used have long wavelengths, so extremely precise matching of cable lengths is not required.

With the correct hardware configuration multiple USRPs can be synchronised. It is therefore possible to create multiple coherent channels. However, the DDC chain uses a co-ordinate rotation digital computer (CORDIC) which has a random start-up position on power up of the USRP. The CORDIC therefore creates a random phase each time the channels of the USRPs are initialised, but remains constant throughout operation. This phase offset cannot be corrected in hardware; however some software processing techniques can be used to determine the start-up phase and correct it accordingly. This phase offset may have severe consequences for beam-forming applications. USRP phase-stability experiments have been performed to show that channels can be set up to be phase coherent [30].

D. Interface and software packages

Many different software packages are available to interface with USRPs. The most popular package is the Universal Hardware Driver (UHD) as supplied by Ettus Research [31]. The UHD allows interface to the USRP from a host Personal Computer (PC). The UHD is used by many software packages like MATLAB and National Instruments (NI) LabVIEW [32] to interface to the USRP. GNU Radio [33], an open source program that interfaces to the UHD and is used by many applications [34].

OpenBTS (creates a second generation cellular base station on a USRP) [35], and GNSS-SDR (GNSS data processing receiver) [36] are popular examples of open source GNU Radio based applications. The vast number of software packages that is available makes it difficult to list all applications of SDR.

III. EXPERIMENTAL SETUP

The multi-channel Rx and Tx systems are implemented and evaluated separately to prove the phase coherency in isolation. If both can be proven, a combined system development should be possible.

A. Receiver channels

To validate the phase coherency of a set of Rx channels from combined USRPs, a controlled 100 MHz sinusoidal signal is transmitted to all of the Rx channels. The phase differences of the channels are measured.

For the Rx experimental setup, Ettus Research N210 USRPs with Wide Band Transceiver (WBX) daughter-boards are used. A single channel of each N210 USRP is set to be an Rx channel, due to the limitation of the WBX. The N210 USRPs have the option to use a MIMO cable for synchronisation; however it only allows the synchronisation of two USRPs (maximum of four Rx channels, depending on which daughterboard is used). External synchronisation is thus used to prove that larger Rx arrays can be built.

Both USRPs are connected through an Ethernet switch to a host PC. The host PC has a 6- bit operating system, with an Intel Core i7-272-QM Central Processing Unit (CPU), 8 GB Random Access Memory (RAM), an on-board Graphics Processing Unit (GPU) and a 1 Gb/s Ethernet port.

The measurement software is written in GNU Radio. The measured data are both displayed in real-time and written to a hard-drive on the host PC. Methods to calibrate the phase offsets between the channels are also considered and incorporated into the GNU Radio program.

B. Transmitter channels

Frequency diverse array (FDA) research has received significant attention recently [37]. By transmitting at slightly offset center frequencies on each of the channels, a distinct range and angle pattern can be obtained. Note that the range pattern is time dependent and can thus be measured at a fixed point with the only difference being range attenuation.

To show the value of SDR as a research tool and to test the multi-channel transmission, an FDA implementation is done as an experiment.

For this experiment, two Ettus Research B210 USRPs are used, each with two Tx channels. One Rx channel is used to record the resulting signal. These USRPs are connected to a host PC by USB. An external clock source is used for synchronisation. Phase offsets are corrected by manual calibration of the devices through a graphical user interface (GUI) developed in GNU Radio.

IV. RESULTS

A. Receiver channels

Fig. 4 shows the phase difference between two channels of a two USRP system with a synchronised clock, however the PPS trigger is not synchronised. The synchronised clock shows that the phase difference is piecewise constant, so there is no oscillator drift between the two USRPs. The unsynchronised PPS trigger causes the jump discontinuities in the phase difference. The phase discontinuities deteriorate the multi-channel signal quality, and should therefore be reduced. The need for synchronising the channels is thus emphasised in Fig. 4.

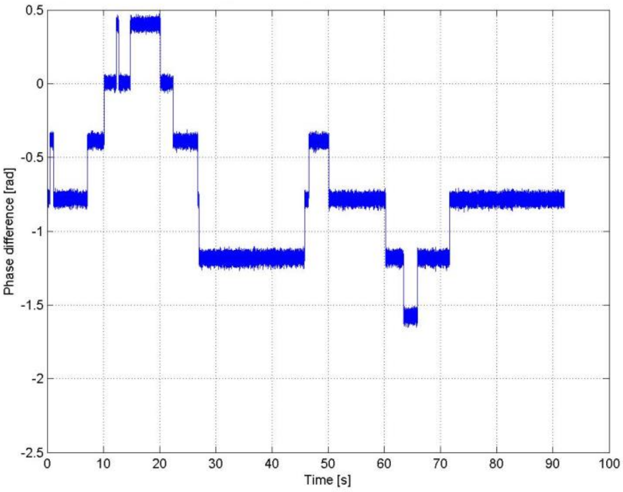

Fig. 4. Two channel Rx system composed of two Ettus Research N210 USRPs, with externally synchronised clock, without synchronised PPS at a sample rate of 2 MS/s.

Phase instability, such as the measured discontinuities, deteriorates control of the channels; as an example it can severely limit the beam-forming capability of an antenna array.

Dropped samples or packet loss between the USRPs and the host of any one of the two USRPs is the main cause for the two USRPs to lose phase synchronisation. Switching of the Ethernet interface between the USRPs and the host has a similar effect.

Fig. 5 shows the phase comparison between two channels of a two N210 USRP system. Fig. 6 shows the same data set as Fig. 5, however it focuses on the phase calibration stage.

Note that after 46 secconds the random phase offset of the CORDIC is estimated and adjusted; hence the phase difference between the two channels is calibrated out. The phase offset in the figure is reduced after the calibration is performed.

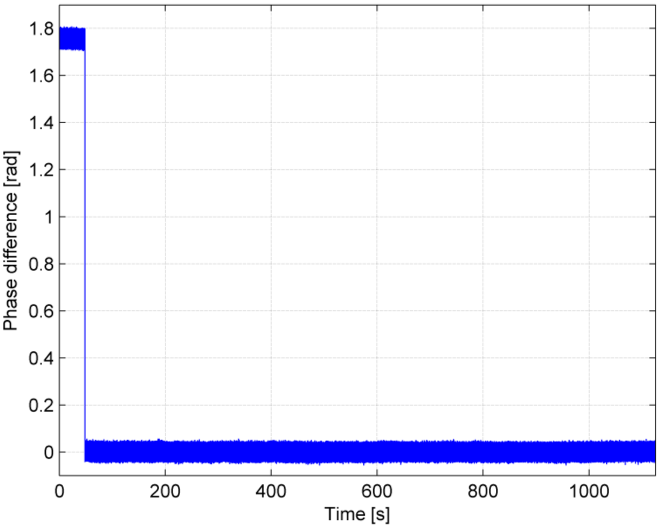

Fig. 5. Four channel Rx system composed of two Ettus Research N210 USRPs, with an externally synchronised clock, PPS and software phase calibration at a sample rate of 3.125 MS/s.

After the phase calibration, the phase difference between the channels is constant, therefore both clock and PPS syncronisation are achieved. This proves that there is no phase drift occuring between the two USRPs. It must however be noted that in this case some samples were dropped, however the phase is unchanged as the samples were realligned at the host, i.e. the host truncated the unaffected channels to match the dropped samples.

Fig. 7 shows the phase difference after the calibration has taken place. Note that the phase difference has a sinusoidal form with a period of 90 ms. This is due to the fact that the test signal has some spurious tones: a sinusoidal phase difference can be caused by a two tone signal. This was the largest unwanted result observed.

The standard deviation of the phase difference between the two USRPs is measured to be 0.0128 radians (0.734 degrees). This shows that the phase stability between the two USRPs is very low (less than one degree). If a better, spurious tone free signal source is used, the sinusoidal rippling observed in Fig. 7 will be reduced, and the standard deviation will be less.

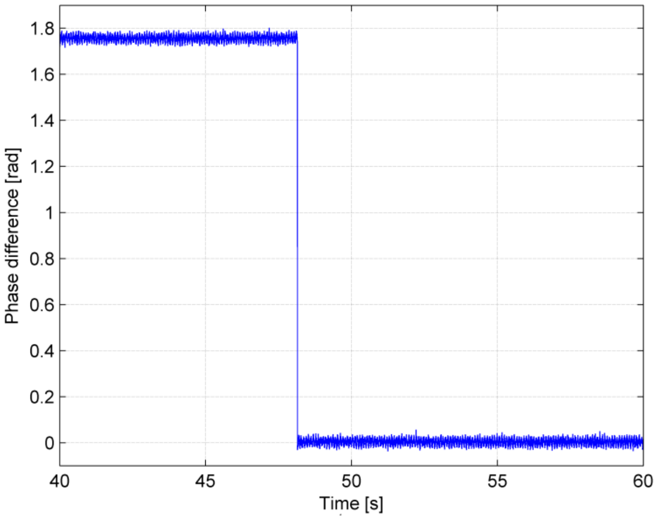

Fig. 6. Four channel Rx system composed of two Ettus Research N210 USRPs, with an externally synchronised clock, PPS and software phase calibration at a sample rate of 3.125 MS/s; with emphasis on the phase calibration.

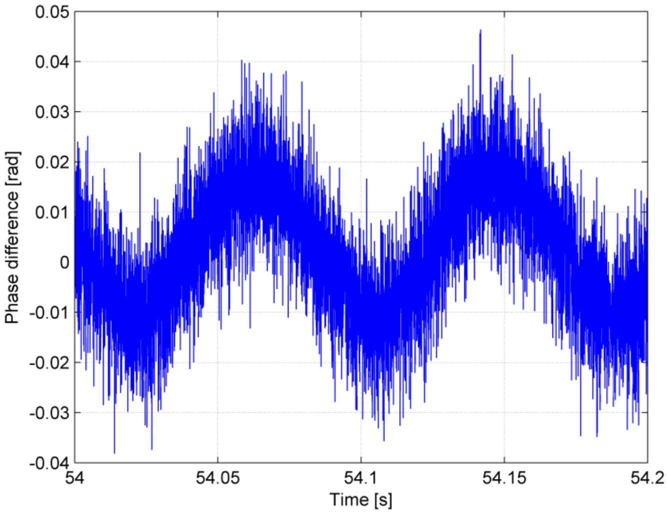

Fig. 7. Four channel Rx system composed of two Ettus Research N210 USRPs, with an externally synchronised clock, PPS and software phase calibration at a sample rate of 3.125 MS/s; after the channels have been calibrated.

B. *Transmitter channels*

Fig. 8 shows both the theoretical result of a four channel FDA transmission and the signal recorded when the FDA is implemented using the B210 USRPs. The theoretical result was calculated using the FDA pattern equation [37] in the Scientific Python Development Environment (Spyder). The theoretical representation is shown in (1) to (3).

$$p(f,t,R_0,\theta) = \frac{\exp\left[\mathrm{j}\left(\phi_c + \pi(N-1)\frac{d\sin(\theta)}{\lambda_0}\right)\right]}{R_0} \times$$

$$\frac{\sin\left[\pi N\left(\Delta f t - \frac{\Delta f R_0}{c} - \frac{d\sin(\theta)}{\lambda_0}\right)\right]}{\sin\left[\pi\left(\Delta f t - \frac{\Delta f R_0}{c} - \frac{d\sin(\theta)}{\lambda_0}\right)\right]} \qquad (1)$$

$$\phi_c = -2\pi f_c \left(t - \frac{R_0}{c}\right) \tag{2}$$

$$f_c = f_0 + \frac{N-1}{2}\Delta f \tag{3}$$

where $p(f, t, R_0, \theta)$ is the resulting pattern, dependent on the frequency, time, distance and angle. Table 1 explains the different symbols used in the equation.

TABLE 1 SYMBOL DEFINITIONS.

Symbol	Definition	Value Used
N	No. of antennas	4
f_n	Frequency of n^{th} channel.	$f_0 = 1$ GHz
Δf	Difference in frequency between successive channels.	300 Hz
c	Speed of light.	3×10^8 m/s
λ_n	Wavelength at f_n.	c/f_n
d	Antenna spacing.	$\lambda_{N-1}/2$

The measured results compare well with the theoretical results, although the nulls of the calculated results are much more pronounced and the lobes of the actual implementation are slightly unbalanced. This is mainly due a minor phase offset still present after manual calibration and measurement noise.

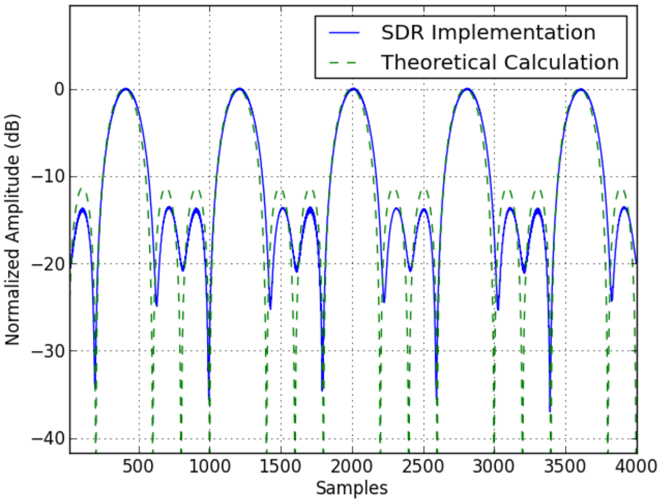

Fig. 8. Four-channel FDA theoretical and actual result.

V. DISCUSSION

A. *Receiver channels*

With the correct hardware and software synchronisation, multiple USRPs can be configured to have coherent channels. However software calibration is required to compensate for random start-up phase offsets.

The calibration process poses a problem as it requires calibration at every start up, adding additional hardware (test signal) and software (calibration) requirements to an operational multi-channel system.

Packet loss was observed, however with the correct configuration all channels received equal packet loss, so the relative phase difference is unaffected. The packet loss is due to the interface between the USRPs and the host, the buffers of the host and the processing capabilities and scheduling of the host. Increasing the host's performance (e.g. using a solid state hard-drive for data storage or adding a dedicated GPU for the display update of results) and reducing the sample rate from the USRPs can reduce the packet loss.

Inadequate isolation between channels on a single USRP may create interference for Rx channels. Characterisation and improvement of a USRP's performance may be required; e.g. adding hardware filters before a signal is passed to the USRP or placing a USRP in an electromagnetically sealed enclosure.

B. *Transmitter channels*

The random start-up phase offsets once again pose the problem of calibration since the system has to be recalibrated at every start-up. Automatic software calibration may be implemented in future experiments, and should yield improved results.

This experiment serves to prove that actual multi-channel transmission systems can be implemented, quickly and cost-effectively using an SDR. The ease of implementing of such a system, using the available open source software, is remarkable. If the required hardware is available, such a system is easily scalable as long as the same external clock and PPS signal are used. The software implementation of the system is also scalable, and can be easily adapted for larger transmitter arrays.

C. *General*

In both the Rx and Tx, it is shown that, phase-coherent systems can be developed simply and inexpensively with a multi-channel SDR system. However the issue of recalibrating the system at every start-up, results in practical end-user implementation issues.

VI. CONCLUSION

It is shown that a multichannel transceiver system can be created by combining multiple USRPs. However some precautions need to be implemented to ensure channel coherency and reliability.

SDRs were used in the configuration of two different experiments to prove that multi-channel systems can be developed, with minimal additional RF-component requirements. The experiments did not require much time for setup, hence it is shown that SDR is an effective rapid-prototyping platform for a range of applications. SDR is thus considered a valuable tool for research and training ona a range of RF systems.

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