Software Defined Radio Injection-Locking using a GPS signal for multichannel coherent receivers

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Abstract—**This paper explores the potential benefits of combining the use of injection-locking techniques with GPS signals as a common clock source when applied to a low-cost Software Defined Radio (SDR) to improve the accuracy of coherent multiple receivers. Coherent systems impose severe requirements on the frequency stability of the signal source at the receiver. In this work, injection-locked oscillators are used as local clock receivers, which inherently synchronizes the SDR analog digital converter (ADCs) sampling times and keeps the local oscillator locked on to the GPS stimulus periodic signal. This paper illustrates the hardware modifications needed for to the injection locking oscillators of eight RTL-SDR radios and the theory behind it, and experimentally measures the degree of coherency in the frequency, phase and time synchronization to verify the proposed method. The coherency demonstrated in the results prove the feasibility of using beamforming, multiple input multiple output (MIMO) and RF transmitter geo-localization.**

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1. INTRODUCTION

Software defined radios (SDRs) are enabling low cost versatile radio communications from the medium frequency (MF) to millimeter-wave (MMW) [1, 2] range of the electromagnetic spectrum. Since their inception in the early 1990s [3–5], SDRs have become both accessible and widely available for education, research and development, and commercial applications. Current generation low-cost SDRs are tunable from 1 kHz [6] to at least 6 GHz [7], typically provide at least 8 bits [8] analog-to-digital converter (ADC) resolution and up to 16 bits [9]. Quadrature (I/Q) sampling rates from 80 kS/s [10] up to 400 MS/s [11] with low RF noise figure ($\sim$1.5 dB), and USB, ethernet, or other bus connectivity to a wide range of host computer platforms are readily available. Programming can be accomplished using open source applications tools such as GNU radio [12–14]. Demonstrated applications include amateur radio, air traffic monitoring, global navigation satellite service (GNSS) geolocation and timing, radioastronomy, spectrum analysis and monitoring, and MIMO communication systems [15, 16], along with AM and FM radio and digital TV broadcast reception.

While a variety of SDRs are commercially available, the generic RTL-SDR provides the potential for system scalability due to its very low cost (typically $25 USD) and generally competitive electrical performance [13, 17–19].

The RTL-SDR is based on the Rafael R820T Si CMOS tuner and the Realtek RTL2832U analog-to-digital converter and digital demodulator integrated circuits (ICs). The combination of these ICs provides an RF tuning capability from approximately 25 MHz-1750 MHz with receiver noise figure as low as $\sim$3.5 dB. The commercial success of this IC combination has enabled many applications such as Multiple-Input Multiple-Output (MIMO) transceivers, spectrum monitoring nodes, multiple receiver beam forming, and radio direction of arrival (DOA) devices. The development of receivers with many simultaneous RF input channels using this chip set is the result of a moderate processed sample rate of up to 2.4 MS/s and USB connectivity. Software Defined Radio in many instances offers signal processing implemented in software making it easy to debug, to use, or to modify. Open source software for SDRs offers the ability to use both simulations and experiments on the same tool.

The test bed utilizes an open source, GNU Radio software environment, which reduces the cost and complexity of the system development. GNU Radio provides the benefit from an active community, a graphical editor to set transceivers, a graphical output to visualize the signal processing in real-time, and a large variety of supported radio platforms [20]. GNU Radio and the multiple channels receivers packages [21] were used to build a program to capture data in real-time from the coherent and sampling synchronous system proposed. The application sample rate is set to 2 MSps. Matlab is also used for post processing to analyze the spectrum, cross-correlate channels, and plot the signals degree of coherency and their ADCs time sampling synchronization.

In the remainder of this paper, Section 2 describes the hardware modification and wired synchronization of multiple RTL-SDR receivers using a GPS 10 MHz reference signal. Section 3 illustrates the technique to provide a phase synchronous of local oscillators and analog-to-digital converter (ADC) clock signal to ensure a phase coherency of down-conversion and sampling. Section 4 demonstrates the theory of injection locking leading to a received coherent signals. Finally, Sections 5 and 6 present the method of ADCs time synchronization, and the experiment results and analytical.

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2. SDR HARDWARE CONFIGURATION

The RTL-SDR essential functions for this project are provided by the Rafael R820T tuner and Realtek RTL2832U demodulator chips (Figure 1). The R820T is a highly integrated silicon CMOS tuner comprised of a low noise amplifier (LNA), mixer, fractional Phase Locked Loop (PLL), variable gain amplifier (VGA), tracking filter, and low dropout (LDO) voltage regulator. The R820T was originally designed for digital TV audio reception. The integrated components have made this chip a popular solution for SDR receiver front ends. The RTL2832U is a high-performance Digital Video Broadcasting — Terrestrial (DVB-T) Coded Orthogonal Frequency-Division Multiplexing (COFDM) demodulator that supports a USB 2.0 interface (more recent versions support a USB 3.0 interface). In a COFDM transmission system, the information is conveyed using a large number of equally spaced sinusoidal subcarriers, all of which are transmitted simultaneously [22]. Modulation parameters (e.g., code rate and guard interval) are automatically detected and applied in the demodulation process by the chip. The RTL2832U uses a 28.8 MHz clock signal and interfaces with tuners at intermediate frequency (IF, 36.125 MHz), low-IF (4.57 MHz), or zero-IF (baseband) output. The RTL2832U automatic gain control (AGC) function is used to adjust received signal strength to a level suitable for the ADC range. The chip supports two AGC control signals, one for each of the IF and RF gains. The RTL2832U automatically selects use of either IF, or zero-IF sampling to process received signals. For non-zero IF frequencies the digital down conversion (DDC) function converts the sampled IF signal to complex I/Q base band signals for further processing. The processor can be programmed to resample the received signal from a fixed ADC sampling rate to the decoded CODFM or other sampling rate according to the desired signal bandwidth.

3. SIGNAL INJECTION

RTL-SDRs provide a maximum dropout-free I/Q sample data rate of up to $\sim$2.4 MSps with a 28.8 MHz clock signal. The coherent use of sampled data from these or any other SDRs requires phase coherent local oscillator signals for downconversion, phase coherent clocking of each SDR's ADC, and sampling time synchronization between the multiple units. Even when a common clock oscillator is used there is no guarantee that the ADC data streams are sample-time synchronized. The published literature has provided several different techniques used to synchronize RTL-SDR ADC samples. In 2014, Bogdan [23,24] experimented with multiple RTL2832u SDR receivers in order to create a multichannel receiver by using the CDCLVC1310-EVM board from TI that provides ten outputs low jitter clock distribution system with selectable inputs from external clock sources and signal correlations to obtain correction of the sampling time deltas between the signals. When the USB transfer is started for each receiver, there is no way to control the moment of acquisition of the samples relatively to the other receivers [24]. In order to still achieve the sample coherence between receivers, a simple method of calculating the correlation between the channels signals is employed. In 2016, Coherent Receiver's company worked on RTL-SDR V3 to create a multi-channel coherent receiver product based on the RTL-SDR, i.e. two or more RTL-SDR multi-channel that are running from a single clock source [25]. To allow signal samples from two different antennas to be synchronized against time, a clock card was used for the realisation of the entry level receiver. Such an architecture enables the configuration of up to five receiving channels [26]. Their receivers attached a control board which has a buffered 0.1 PPM TCXO (buffered so it can power multiple RTL-SDR's). An 8-bit register is added and I2C connection capabilities which allows for control of future add-on boards. In 2016 Krysik [27] illustrated the time-synchronization of two RTL-SDRs using a cable between crystal oscillators to demonstrate FM broadcast signal reception. In this implementation one of the receiver's crystals was removed such that samples coming from different channels are aligned in time automatically. although coherence was not demonstrated. In 2020, [28] tentatively proposed time and sample rate synchronization of one RTL-SDR using a GPS receiver. The PPS signal is injected into an IF stage of the RTL-SDR and detected by correlation of an expected signal shape and the measured data.

To the above-proposed solutions, it is demonstrated that the hardware modification does not guarantee that multiple RTL-SDRs would actually sample simultaneously. Therefore, based on the targeted application, a software solution, i.e. cross correlation was used to correct the drift. The hardware solution in this project uses a GPS-derived synthesizer signal to injection-lock RTL-SDR oscillators so as to ensure the LO and ADC clock coherence and preclude sampling jitter. The RTL-SDR local oscillator crystals are not removed as in the above studies but rather are phase locked using a small-amplitude ($\sim$600 mVpp from 50Ω source) signal obtained using an eight way splitter (Figure 2). The aim of this system is to minimize phase differences between RTL-SDR clocks.

The GPS signal is used as a frequency standard to correct a separate crystal oscillator on RTL-SDRs as shown in Figure (2). The GPS signal is fed to a highly stable GPS discipline oscillator (GPSDO) BG7TBL 2020-06-10 receiver. The output of the GPSDO is tapped and divided down to generate 10000000 Pulses Per Second and continuously compared with the accurate 1 PPS from the GPS signal. The GPS receiver that allows the PPS signal enables the possibility of a frequency divider to make it suitable to the RTL-SDRs which uses 28.8 MHz oscillators. The 10 MHz signal from the GPSDO is fed to an Agilent 8648B signal generator synthesizer that divides it down to 28.8 MHz. The 28.8 MHz signal goes through a splitter and then leaked on the RTL-SDRs local oscillator pin using a $101pF$ capacitors (Figure 1). Any tripped of the local oscillator leads to a tuning correction signal to the oscillator, which will stay locked to the PPS. This anticipates that such a system will produce an accurate reference with high quality coherent output signals.

The GPS disciplined oscillator BG7TBL 2020-06-10 receiver is used to provide a 10 MHz square wave reference signal to reference the Agilent 8648B signal generator synthesizer. The GPS signal is divided down to a desired frequency and distributed via a splitter to inject the signal and clock the RTL-SDRs. As each RTL-SDR oscillator is in unlock state, the aim of this system is to generate a stable frequency at multiple of an input frequency, recover the signal from a noisy communication channel, and distribute precisely the timed clock pulses to minimally reduce the phase difference between oscillating signals. Ideally, injected signal will be in locked step with a fixed phase difference between them. The lagging time and frequency are expected to be the same across all RTL-SDRs. The idea of using a GPS signal as a frequency standard is to provide an output signal called Pulse Per Second or PPS. A PPS is a 1-Hz square wave signal, which depending on the model has its rising and falling slope synchronized to occur precisely at the moment that the GPS time advances to the next second. Naturally, this only works when the GPS sees enough satellites to work

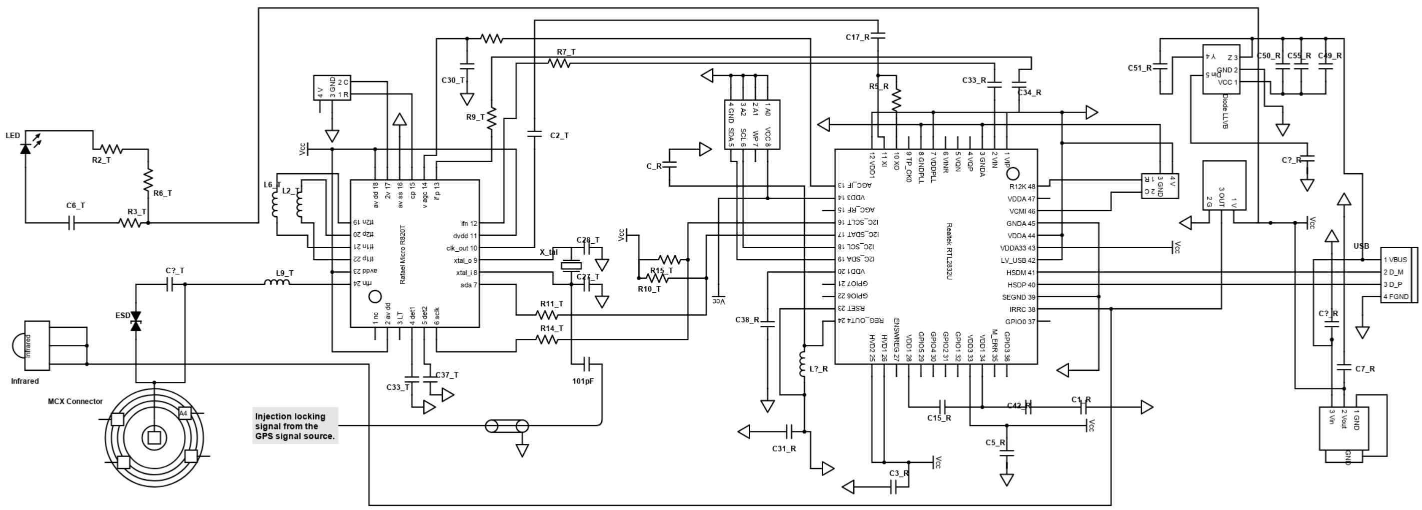

Figure 1. RTL-SDR radio block diagram schematic to illustrate the Rafael R820T tuner and Realtek RTL2832U demodulator with a description focused on components of interest for this study and to primarily illustrate the LO pin used for the injection locked. The proposed schematic is a reverse-engineering of the printed circuit board main components to understand the connectivity and to injection locked the GPS signal source.

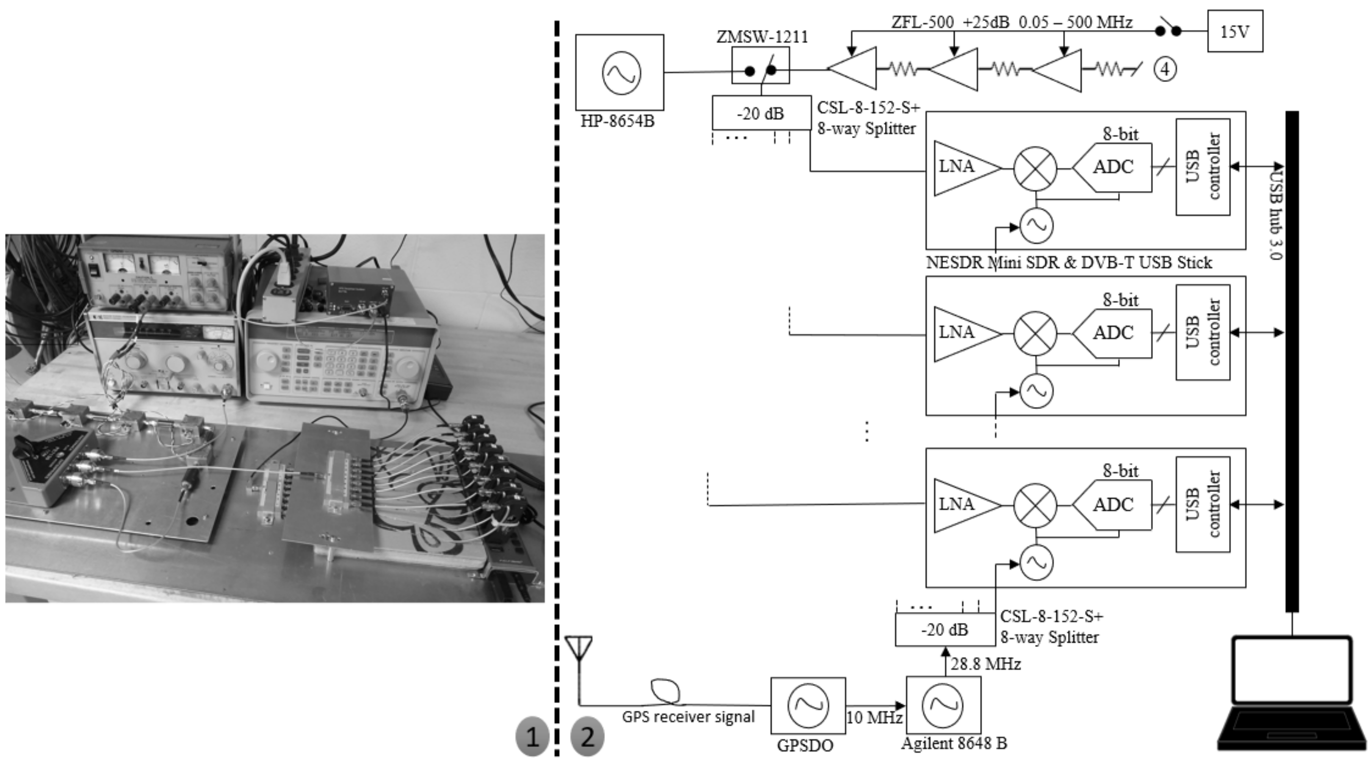

Figure 2. Experiment setup in the laboratory (1-picture and 2-schematic of the design): consists of hardware assembled to build the coherent multi-receivers of eight channels using RTL-SDR radio: synchronization signal is fed from an external source provided by the GPS 1 PPS, GPSDO translates to 10 MHz, and the signal generator divides 10MHz down to 28.8 MHz, which is injected to the LO oscillator. A noise source ZFL-500 is used to calibrate the RTL-SDRs before they tune to the desired frequency.

out its position and the GPS time. Global Positioning System or GPS is a global tool for positioning and navigating, and is also the main system used to distribute high accuracy time and frequency world wide. GPS satellites carry atomic oscillators that are steered from stations [29] to agree with the coordinated universal time scale (UTC) maintained by the United States Naval Observatory (USNO). UTC and the National Institute of Standard and Technology (NIST) time scale are kept in close agreement and seldom differ from each other by more than $20ns$ [30]. The GPS signal is fed to a GPS discipline oscillator (GPSDO) (Figure 2). The basic function of a GPSDO is to receive signals from the GPS satellites and to use the information contained in these signals to control the frequency of a local oscillator. The satellite's signals can be trusted as a reference for two reasons [31] : First, they originate from atomic oscillators, and they must be accurate in order for the GPS to meet its specifications as a positioning and navigation system. Second, the maximum acceptable contribution from the satellites clocks to the positioning uncertainty is generally considered to be about one meter [29]. Since light travels at about 3x10$^8 m/s$, one meter requirement is equivalent to a time error of about $3.3ns$. Thus, in order for the GPS system to meet its specification, the satellite clocks must be stable enough to keep time with uncertainty of less than $3.3ns$ during the period between corrections. This translates to a frequency stability specification near 6x10^{-14} [29]. The goal of the GPSDO design is to transfer the inherent accuracy and stability of the satellite signals generated by the local quartz oscillator.

Injection locked clocking is the physical phenomenon where an oscillator locks on to an external stimulus periodic signal and fundamentally synchronizes with the input when the frequency of the input signal is close enough to the oscillator native frequency or its sub-harmonics [32]. Suppose a signal frequency ω_i is injected into an oscillator (Figure 3), which has a self-oscillation or free running frequency ω_0. When ω_i is quite different from ω_0, the "beats" of the two frequencies are observed [32–34]. As ω_i approaches ω_0, the beats frequency ($|\omega_i - \omega_0|$) decreases. When ω_i enters some neighborhood very close to ω_0, the beats disappear and the oscillator starts to oscillate at ω_i. The frequency range in which injection locking happens is called the locking range ω_L. The oscillator frequency locks to the injected frequency with a phase shift of:

$$\psi = \arcsin\left(\frac{\omega_0 - \omega_i}{\omega_L}\right) \tag{1}$$

Recall that injection locking also happens when ω_i is close to the harmonic or sub-harmonic of ω_0, i.e., $n\omega_0$ or $\frac{1}{n}\omega_0$, with integer n>1. The former case can be used for frequency division, and the latter for frequency multiplication. The locking signal in the oscillator describes the case of synchronization where any transient disturbance vanishes in time and gives way to a steady state in which phase difference between oscillator and external signal is constant [32]. Experimentally, the locking range observed with the RTL-SDR radio, i.e. the generic Nooelec NESDR Mini SDR & DVB-T USB, is between 28.73MHz and 28.89MHz. Typically, the locking range is $\sim$ 10% of the oscillation frequency and the experiment has proven to be true [34].Locking range is an important parameter for many reasons. First, it clearly controls the detuning range over which the oscillator will remain locked. Second, the locking range determines the time constant for the response of the oscillator to an external perturbation. [34].

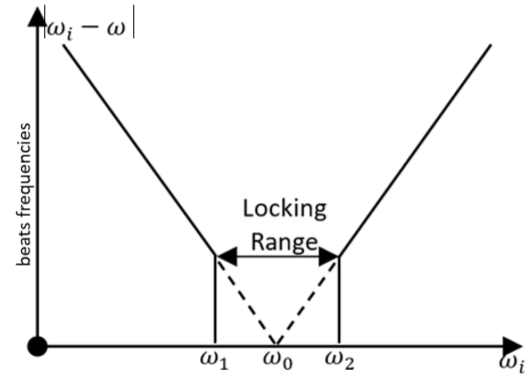

Figure 3. Range of injected signal to the RTL-SDRs receivers: injection locked oscillator based on a driven common clock fed by the GPS signal

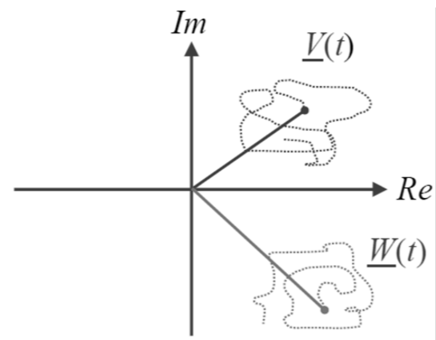

Figure 4. Two signals oscillation coherent measured [35]

4. Coherence of Received Signals

Random Signals

In probability theory, when a random process does not change its statistical properties with time, such as the mean and variance of the process, the stochastic process exhibits stationarity and ergodicity. Consider recording a random power signal at two different time, the expectation of that signal can be computed at two times separated by tau (τ). $\tau = t_1 - t_2$ depends on the time difference.

$$E[v(t_1)v(t_2)] = E[v(t)v(t-\tau)] \tag{2}$$

A process is said to be ergodic if the time average of a process is equal to the ensemble average. The idea is that any collection of random samples from a given process must represent the average statistical properties of the entire process. If that is the case, ergodic power signals are such that an expectation or ensemble average $E[\cdot]$ is identical to a time average $\langle\cdot\rangle$. $\langle\cdot\rangle = E[\cdot]$. Meaning that

$E[v(t)v(t-\tau)] = \langle v(t)v(t-\tau\rangle$ Given the signal $v(t)$, the phasor representation is $\underline{V}$, and the rotating vector is $\underline{V}e^{j\omega t}$. For instance:
Differentiating $v(t)$, we differentiate the rotating vector,

$$\frac{d(\underline{V}e^{j\omega t})}{dt} = j\omega\underline{V}e^{j\omega t}.$$

Therefore, $j\omega\underline{V}$ is the differential vector.

Correlation of Monochromatic Signals

It is the correlation of two signals using the same angular frequency $\omega = 2\pi f_0$.
Lemma:

$$\langle v(t)w(t)\rangle = \langle|\underline{V}|\cos(\omega_0 t + \phi_v)|\underline{W}|\cos(\omega_0 t + \phi_w)\rangle \quad (3)$$

Knowing the product identity of two cosines is $\cos(a)\cos(b) = \frac{1}{2}[\cos(a-b) + \cos(a+b)]$,

$$\begin{aligned}\langle v(t)w(t)\rangle &= \\ &\langle \frac{|\underline{V}||\underline{W}|}{2}[\underbrace{\cos(\phi_v - \phi_w)}_{\text{Time independent}} \\ &+ \underbrace{\cos(2\omega_0 t + \phi_v + \phi_w)}_{because\, \omega_0\, will\, oscillate\, twice, \langle\cdot\rangle \to 0}]\rangle\end{aligned} \quad (4)$$

$$\langle v(t)w(t)\rangle = \frac{1}{2}|\underline{V}||\underline{W}|\cos(\phi_v - \phi_w) \quad (5)$$

$$\langle v(t)w(t)\rangle = \frac{1}{2}\,\mathrm{Re}\{|\underline{V}||\underline{W}|^*\} \quad (6)$$

Quasi-Monochromatic Signals

It consists of allowing the phase to be slowly time variant

$$v(t) = \mathrm{Re}\{\underline{V}(t)e^{j\omega_0 t}\} \quad (7)$$

$$\underline{V}(t) = V_R(t) + jV_I(t) \quad (8)$$

Therefore,

$$\begin{aligned}v(t) &= \mathrm{Re}\{(V_R(t) + jV_I(t))e^{j\omega_0\tau}\} \\ &= \mathrm{Re}\{[V_R(t) + jV_I(t)][cos(\omega_0 t) + jsin(\omega_0 t)]\} \\ &= \mathrm{Re}\{V_R(t)[cos(\omega_0 t) + jsin(\omega_0 t)] \\ &+ jV_I(t)[cos(\omega_0 t) + jsin(\omega_0 t)]\} \\ &= \mathrm{Re}\{V_R(t)cos(\omega_0 t) + jV_R(t)sin(\omega_0 t) \\ &+ jV_I(t)cos(\omega_0 t) + jV_I(t)sin(\omega_0 t)\} \\ &= \mathrm{Re}\{V_R(t)cos(\omega_0 t) + jV_R(t)sin(\omega_0 t) \\ &+ jV_I(t)cos(\omega_0 t) - V_I(t)sin(\omega_0 t)\}\end{aligned}$$

$$v(t) = V_R(t)cos(\omega_0 t) - V_I(t)sin(\omega_0 t) \quad (9)$$

The auto or cross correlation now requires time averaging:

$$R_{vw}(0) = \langle v(t)w(t)\rangle = \frac{1}{2}\,\mathrm{Re}\{\langle\underline{V}(t)\underline{W}^*(t)\rangle\} \quad (10)$$

Theory of coherent signals

Coherence is a statistic that can be used to measure the relation between two signals, which is different from correlation. It is used in the context of nearly monochromatic signals. Figure (4) illustrates two phasors: phasor $\underline{V}(t)$ and phasor $\underline{W}(t)$, which corresponds to the time processes $v(t)$ and $w(t)$. They are also slowly time varying phase. At any point in time, they lie somewhere in the complex plane. The following question can be asked: do these two slowly time phasors move throughout the complex plane in some kind of coordinated fashion? Are they cohered? There is a function that describes that and is called coherency function [35]:

$$\Gamma_{vw}(\tau) = \langle\underline{V}(t)\underline{W}^*(t-\tau)\rangle \quad (11)$$

and can be read as: gamma is a function of two processes v and w, as a function of time lag tau τ, is equal to the expected value of phasor $\underline{V}(t)$ time phasor $\underline{W}(t)$ conjugate time shifted. However, there is a relationship between the cross-correlation function and the coherency [35].

$$R_{vw}(\tau) = \langle v(t)w(t-\tau)\rangle = \frac{1}{2}\,\mathrm{Re}\{\Gamma_{vw}(\tau)e^{j\omega_0\tau}\} \quad (12)$$

where ω_0 is the center frequency that corresponds to these two phasors. Another related concept is the degree of coherence γ_{vw}. It is simply the coherency function normalized by the variances of those phasors $\underline{V}(t)$ and $\underline{W}(t)$ [35]:

$$\gamma_{vw} = \frac{\langle\underline{V}(t)\underline{W}^*(t)\rangle}{\sqrt{\langle|\underline{V}(t)|^2\rangle\langle|\underline{W}(t)|^2\rangle}} \quad (13)$$

γ_{vw} measures how similarly two signals oscillate. When the coherence function is equal to one, it means that two signals are perfectly related.

Coherence of Received Signals with Additive Noise

Let's consider two phasors, phasor $\underline{V}(t)$ and phasor $\underline{W}(t)$,

$$\Gamma_{vw}(\tau) = \langle\underline{V}(t)\underline{W}^*(t-\tau)\rangle \quad (14)$$

Adding random white noise $N_1(t)$ and $N_2(t)$ to each channel will result to the following:

$$\begin{aligned}\Gamma^n_{vw}(\tau) &= \langle[\underline{V}(t) + \underline{N}_1(t)][\underline{W}^*(t-\tau) \\ &+ \underline{N}_2^*(t-\tau)]\rangle \\ &= \langle\underline{V}(t)[\underline{W}^*(t-\tau) + \underline{N}_2^*(t-\tau)] + \underline{N}_1(t)[\underline{W}^*(t-\tau) \\ &+ \underline{N}_2^*(t-\tau)]\rangle \\ &= \langle\underline{V}(t)\underline{W}^*(t-\tau) + \underline{V}(t)\underline{N}_2^*(t-\tau) + \underline{N}_1(t)\underline{W}^*(t-\tau) \\ &+ \underline{N}_1(t)\underline{N}_2^*(t-\tau)\rangle \\ &= \langle\underline{V}(t)\underline{W}^*(t-\tau)\rangle + \langle\underline{V}(t)\underline{N}_2^*(t-\tau)\rangle \\ &+ \langle\underline{N}_1(t)\underline{W}^*(t-\tau)\rangle + \langle\underline{N}_1(t)\underline{N}_2^*(t-\tau)\rangle \\ &= \langle\underline{V}(t)\underline{W}^*(t-\tau)\rangle + \langle\underline{N}_1(t)\underline{N}_2^*(t-\tau)\rangle \\ \Gamma^n_{vw}(\tau) &= \Gamma_{vw}(\tau) + \sigma^2_{n_1 n_2}(\tau)\end{aligned}$$

Or,

$$\Gamma_{vw}(\tau) = \Gamma^n_{vw}(\tau) - \sigma^2_{n_1 n_2}(\tau) \quad (15)$$

For Gaussian distribution, the mean vector often assumed to be zero. Very often, the noise among channels is uncorrelated resulting in a diagonal covariance matrix. As is shown in equation (15), it is impossible to obtain 100 % degree of coherency between two signals because noise from different sources must be removed.

5. ADCs Time Sampling Synchronization

Although fed with the same clock source, RTL-SDRs ADCs do not sample at the same time. The generic RTL-SDR radio synchronization between several ADCs is painful to achieve because the drift is substantial. Even if a common clock

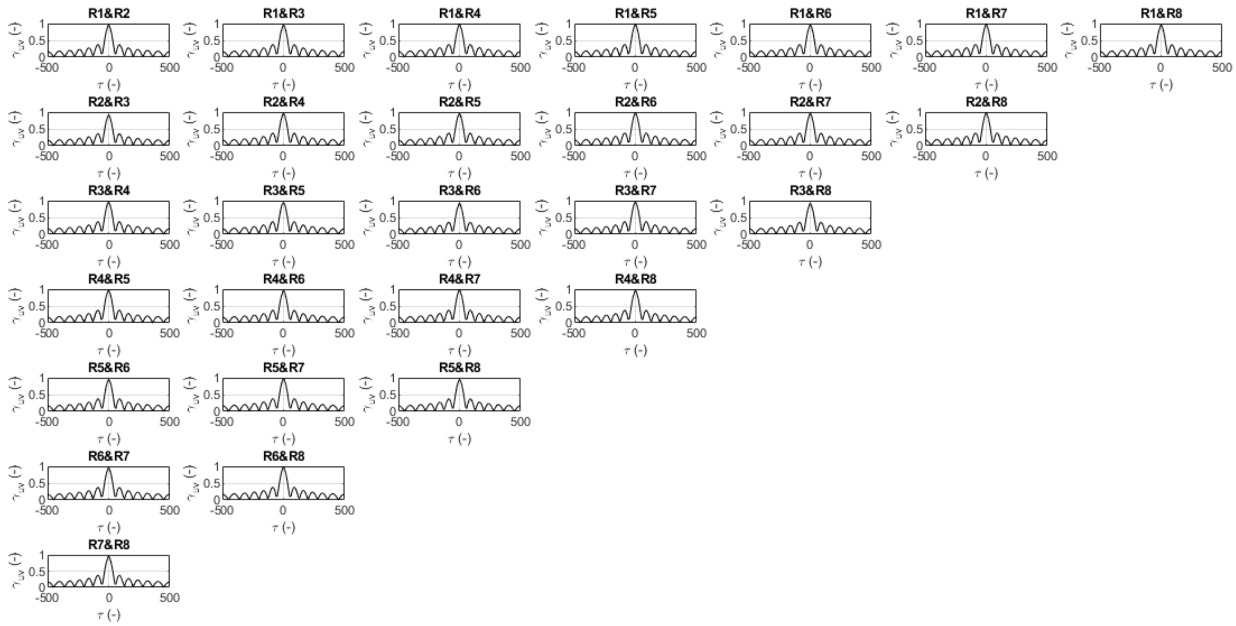

Figure 5. Degree of coherency with eight receivers tuned to some desired frequency (100MHz). R stands for radio Receiver, and X the radio number, X=1,2,...,8

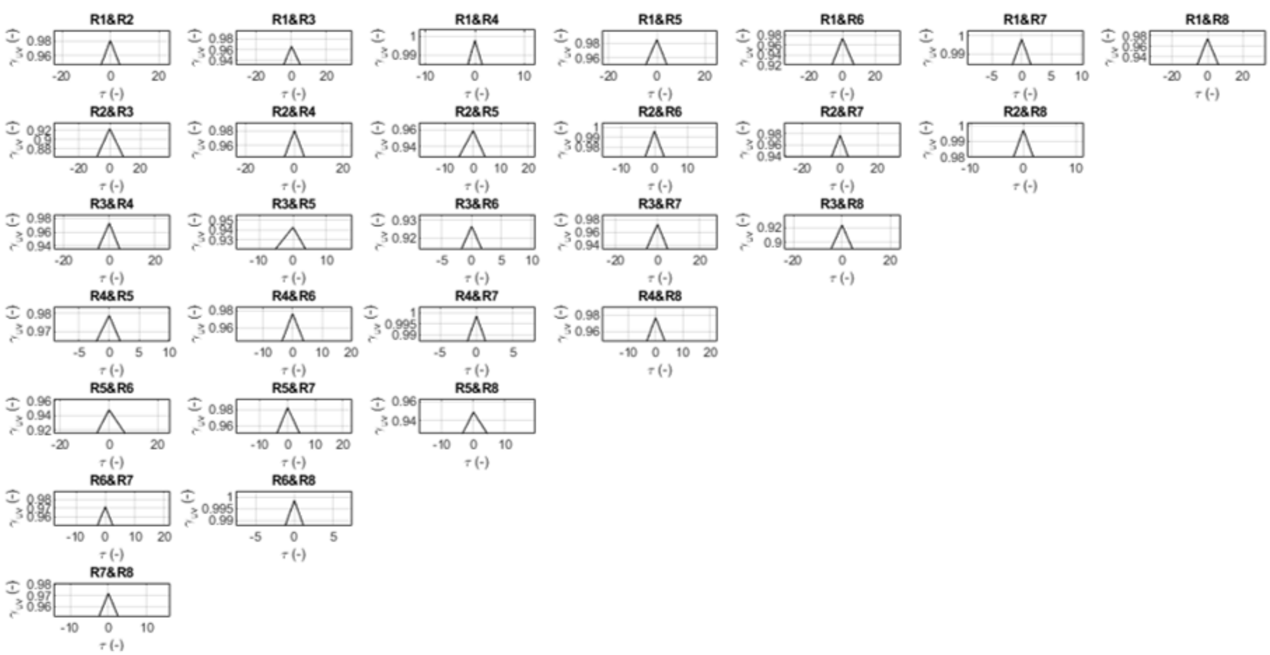

Figure 6. Figure (5) zoom-in to show the coherent degree level

is used, there is no guarantee that the samples' streams are synchronized. Signals coming from the antenna are filtered, amplified, down-converted to a base-band, discretized by the ADC, and samples are transmitted to a computer through a USB hub. Multiple RTL-SDRs receiving simultaneously signals at the same frequency will be perfectly aligned if they are fully synchronized. To handle the time and phase synchronization in this project, a calibration step is required. All RTL-SDRs receivers are tuned to a reference signal provided by the noise source ZFL-500, record a short signals, compute the cross-correlation of the signals with respect to one selected channel (channel one has been chosen). The cross correlation computation produced a peak located at an index that represents how many samples apart the two sets of samples are in order to estimate relative delays of the channels, and correcting the delays so that the channels are time-synchronized. After all SDRs dongles are calibrated and synchronized, all RTL-SDRs are tuned to the desired frequency [21]. The calibration step added to the injection locking processes enables a fixed offset between channel signals as Figures (5) and (7) illustrate. The system is synchronized with a time fixed offset, consistent, and stays there over time. A similar open source technique has been developed by [23].

6. EXPERIMENT RESULTS

The results of the experiment show that the proposed scheme achieves a high degree of coherency and a time synchronization of ADCs with minimal time offset between samplings. With a stable and steady signal source, injection-locked clocking significantly reduces the skew and jitters in the clock distribution networks. Experimentally, the lock range that maximizes the injection is determined to be within the range of 28.73MHz and 28.89MHz.

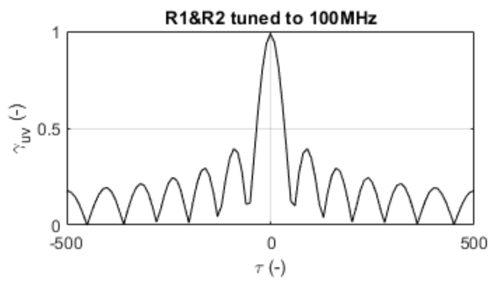

Figure 7. Degree of coherency with two receivers tuned to a given frequency (100MHz)

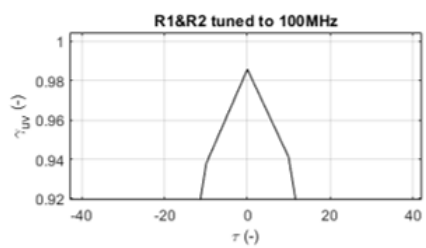

Figure 8. Figure (7) zoom-in to show the coherent degree level

Table (1) summarizes the signals power from the Agilent 8648B to inject-locked the LO, ZFL-500 noise source to calibrate the RTL-SDRs for a sampling synchronous, and the Agilent 8654B for a tunable frequency . If the injection-locked signal is only applied to the RTL-SDRs radios, the result provides a coherent signal received, but no time synchronization is observed. The time synchronization requires a calibration step of RTL-SDR. Applying the two processes show a coherence and time synchronization across all RTL-SDRs. In the Gnu Radio application, a basic RTL-SDR block has been used and the sample rate set to 2 mega samples per second. Running the program for a duration of 15 seconds, IQ data from the eight RTL-SDR radios have been captured for post processing. Using equation (12), a Matlab program is written to measure the degree of coherency of two radios' signals including all possible permutations. Results show an average coherent degree of 97% across all possible combinations of channels signals (Figures 5, 7). The captured IQ data is used to compute the cross-correlation of two-channels receivers R_{xy} sampled data, using equation (10), to estimate the sampling time offset in microseconds, and to illustrate the ADCs time synchronization offset. The figures (9 and 10) show that the received signals are synchronized in the time with a constant offset. The constant samples lag offset is summarized in Table (2). The improve performance is due to the steady and efficient injected signal. The overall system has been continuously run over three hours and results have remained consistent.

	ZFL-500 noise source output power 10dBm	Agilent 8648B output power 0dBm	HP 8654B output power -20dBm
CSL-8-152 splitter pins	Output splitter measured (dBm)		
1	0.33	-9.42	-30.4
2	0.16	-9.6	-30.58
3	0.19	-9.57	-30.61
4	0.05	-9.73	-30.8
5	0.22	-9.56	-30.77
6	0.06	-9.73	-31.07
7	0.08	-9.7	-31.1
8	-0.07	-9.85	-31.35

Table 1. Signals power from sources to the RTL-SDRs through a splitter pins measured.

	Maximum cross-correlation occurs at lag:						
	R2	R3	R4	R5	R6	R7	R8
R1	3	3	1	1	2	1	2

Table 2. Relative delay expressed in term of sample

7. CONCLUSION

This paper presents an injection-locking and a calibration procedure leading to coherent and time synchronization of eight RTL-SDRs dongles. Experimentally and theoretically (mathematical characterization of coherent signals), the key concept of injection-locking, coherent signals, and ADCs time synchronization have been demonstrated and practical requirements are examined. Experimental results show that the proposed method minimally reduces the synchronization time offset between multiple SDRs to few milliseconds. The results described in this project will be further used to improve the number of receivers to sixteen. Though a high efficiency of coherency and time sampling synchronization are achieved with low-cost Software Defined Radio, this project has been developed within a laboratory setting and strictly depends on the laboratory tools which include a function generator that supplies the locked signal derived from the GPS signals and the ZFL-500 low noise source built in the lab. This can therefore be seen as a drawback because the whole system lacks mobility. This approach can be adapted to field testing with additional hardware reconfiguration. It is left for future work. A system based on coherent correlation offers potential performance advantages in several

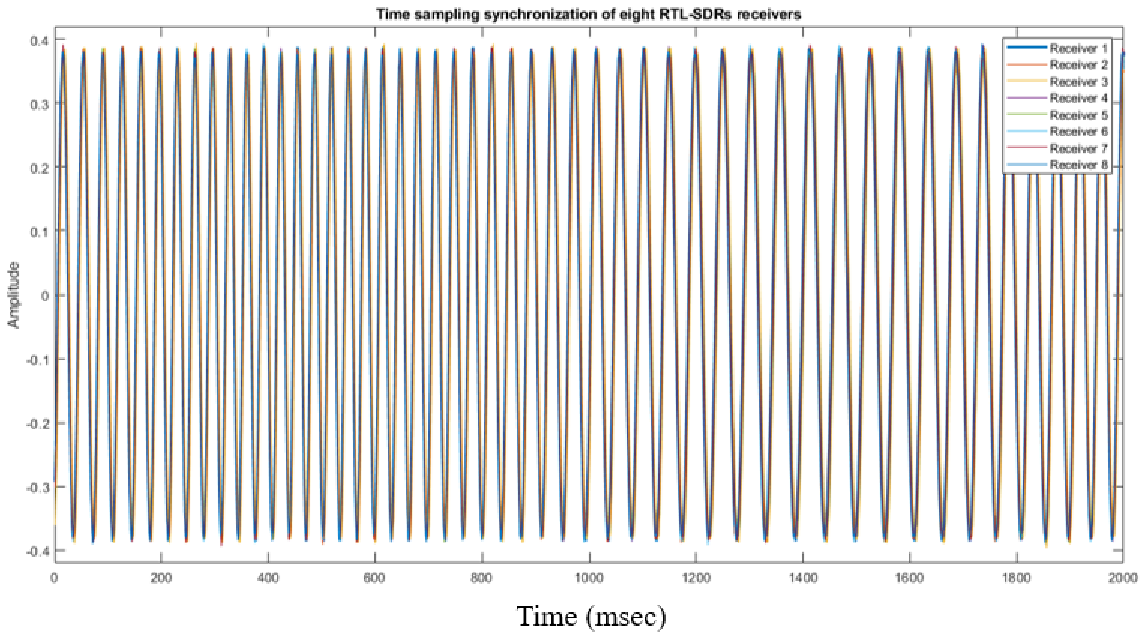

Figure 9. Synchronized sampling time of eight receivers tuned to some desired frequency (100 MHz). R stands for Receiver radio, and X the radio number, X=1,2,...,8

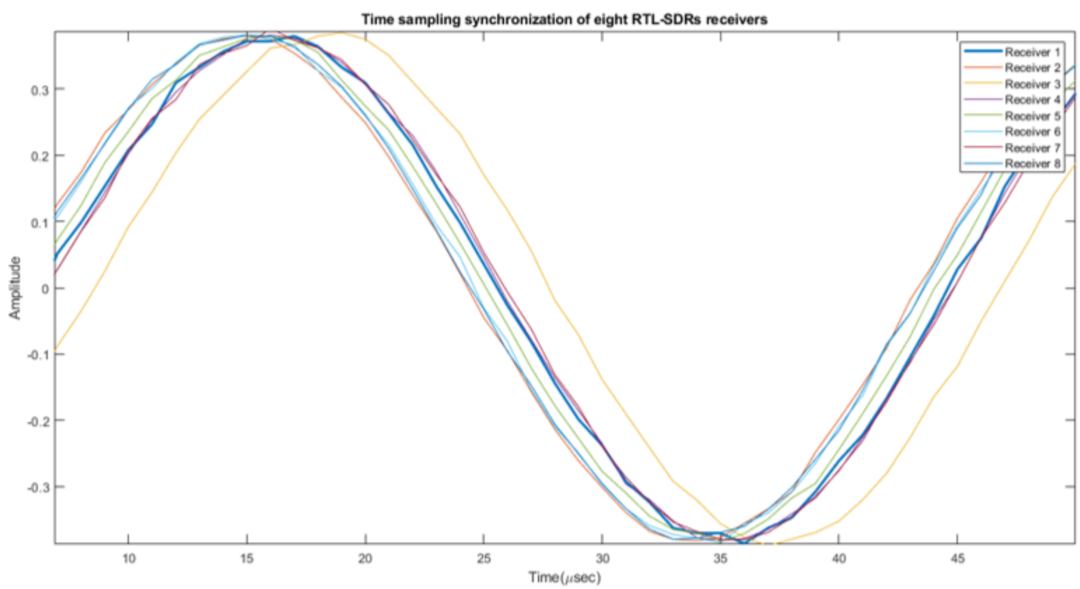

Figure 10. Synchronized sampling time of two receivers tuned to some desired frequency (100 MHz).

important applications. Future work should be aimed at demonstrating the promising potential coherent SDR array applications which include directional spectrum monitoring using digital aperture synthesis, RF source location using near-field triangulation, and RF Green's function estimation. All these applications rely on a mechanism for cohering otherwise free-running or GNSS-disciplined oscillators which serve to generate phase-coherent local oscillator signals used for down conversion and clock signals for analog-to-digital sampling. Even modern rubidium or cesium oscillators exhibit phase noise and drift that precludes coherent SDR array applications.

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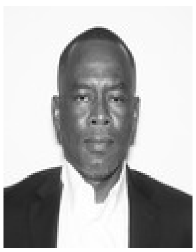
BIOGRAPHY



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