Exponent: Arbitrary Bandwidth Receiver Architecture

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Abstract

This paper presents an architecture for receiving arbitrarily wide bandwidth signals using multiple narrowband receivers. Information contained in overlapping spectral regions provides the essential information needed to combine the separate receive channels and recover the original wideband signal as though it were captured by a single wideband receiver. This paper presents details of the digital signal processing and synchronization needed to synthesize the wideband signal from multiple narrowband channels. The method is validated through computer simulations. Preliminary results of hardware implementation are also presented.

1. Introduction

One of the important events in the software defined radio era is the arrival of radio frequency integrated circuits (RFIC). These devices are amazingly capable, offering tunable center frequencies and adjustable bandwidths. Two notable examples are from Lime Microsystems and Analog Devices. Lime Microsystems' LMS6002D (Microsystems, 2019), available since 2011, is tunable from 300 MHz to 3.8 GHz offering up to 28 MHz of bandwidth. In 2014 Lime Microsystems released the LMS7002M which tunes from 100 kHz to 3.8 GHz and is capable of capturing 60 MHz of bandwidth. Analog Devices' AD9361 tranceiver (Devices, 2019a) operates in the band from 70 MHz to 6 GHz and captures up to 56 MHz of bandwidth. Recently, Analog Devices released the AD9371 transceiver (Devices, 2019b) tuning from 300 MHz to 6 GHz and offering bandwidths over 100 MHz. These two examples illustrate a trend in RFICs toward offering both wide tunability and increasing capture bandwidths.

Despite these trends in which vendors are offering radios with increasing capture bandwidths, some applications will always demand more bandwidth than what is currently available using off-the-shelf components and radios. This paper asks whether it is possible to create arbitrary bandwidth receivers by stitching together adjacent and overlapping bandwidths captured simultaneously by separate receivers. The bandwidth of the aggregated signal is beyond the capture capability of any single receiver. How can this be done so that the resulting aggregated signal appears in every respect as though it was received by a single very wideband receiver? Multichannel aggregation may need to be performed for certain types of signal analysis. For example, if the wideband signal is a digital modulation signal, then the wideband signal must be reconstructed before it can be demodulated.

When capturing and combining several narrowband signals to synthesize the effect of a wide RF aperture, one issue that must be considered is synchronization between the different receiver channels. Without careful alignment in frequency and phase, adding adjacent spectral signals can lead to destructive interference giving an effect similar to time-varying frequency selective fading. One of the challenges is that no structure about the captured waveforms is assumed known. In this work, the receiver creates a small amount of spectral duplication in each receive channel which is then exploited for synchronization.

Another consideration is what may be termed the excitation problem. Synchronization generally requires the construction of an error signal to drive a feedback system that drives the error to zero on average. In the absence of a signal to excite the system, the error signal can be zero even though the receivers are not in sync. Therefore, in all of the following work, we assume that signals are present with sufficient strength to drive our feedback loop. We leave to future work an examination of how the proposed receiver architecture will perform in low signal to noise ratio (SNR) regimes.

Many modern RFICs provide reference inputs that allow external local oscillators (LO) to drive and synchronize multiple RFICs. External clocking also enables synchronization of the sampling interfaces, i.e. analog-to-digital conversion (ADC). While these assumptions may apply in special cases, we consider the case in which the receivers use completely independent local oscillators. This leads to phase and frequency drift between the channels which must be compensated prior to combining the channels.

Finally, we note that the focus of this paper is on signal reception. The problem of synthesizing a wideband signal for transmission using independent transmitters is left for future work.

In the field of cognitive radio networks (CRNs), a large frequency band is segmented into a grid of narrow frequency channels. Primary users have priority use of these channels, but secondary users may use idle channels. Through channel aggregation and bonding (Cordeiro & Ghosh, 2006; Khalona & Stanwood, 2006) secondary users may use multiple idle channels at once. Channel bonding refers to treating adjacent channels as one large channel, whereas aggregation combines non-adjacent channels. Our proposed receiver concept may be applied to capture a wide bonded channel using single channel receivers.

Most of the prior research on bonding and aggregation (Jiao et al., 2010; Su & Zhang, 2008; Yuan et al., 2007) investigate issues related to channel capacity without investigating the practical matters of DSP and channel synchronization as is done in this paper. The envisioned application of the proposed receiver concept is the limiting case where the desired capture bandwidth is beyond the capture ability of any single receiver.

The rest of the paper is organized as follows. Section 2 presents the basic multichannel receiver architecture, and Section 3 outlines the essential steps of digital signal processing needed to recover the full wideband signal. Section 4 presents a method for synchronizing two adjacent signals prior to combining them. Results of computer simulations performed to validate the proposed technique are also presented here. Section 5 describes how the signal synchronization and combination was performed on hardware. Conclusions and directions for future work are listed in Section 6.

2. Exponent Receiver Architecture

Given a signal $x(t)$ having power spectrum $X(F)$, suppose that $X(F)$ exhibits energy in a frequency band of interest $F \in [F_{\text{lo}}, F_{\text{hi}}]$ Hz of width $B_x = F_{\text{hi}} - F_{\text{lo}}$ Hz centered at frequency $F_c = \frac{1}{2}(F_{\text{hi}} + F_{\text{lo}})$ Hz. Consider the case in which the bandwidth B_x is too wide to be captured by any single available receiver, but that multiple receivers are available and that the tuning range of each receiver covers the band of interest $F \in [F_{\text{lo}}, F_{\text{hi}}]$. Each receiver has a capture bandwidth of $B_r < B_x$. We consider the scenario where $B_x \approx NB_r$, where $N \geq 2$ is an integer.

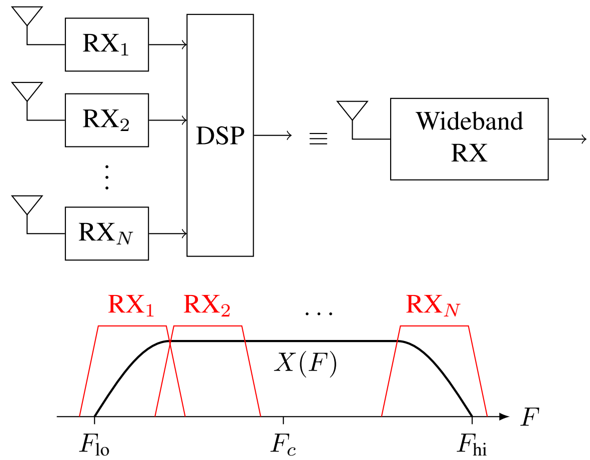

Figure 1. Proposed receiver architecture.

As an example, suppose that the band of interest extends from $F_{\text{lo}} = 1.0$ GHz to $F_{\text{hi}} = 1.5$ GHz ($B_x = 500$ MHz) and that $B_r = 100$ MHz. It would then take five ($N = 5$) receivers to capture the entire frequency band of interest. The set of five receivers would be tuned to the set of center frequencies $\{1.05, 1.15, 1.25, 1.35, 1.45\}$ GHz. The frequency band of interest is captured into five separate channels. If the signal in the band of interest is, for example, a high data rate digitally modulated signal, then the separate channels must be combined to synthesize a wideband waveform before it can be demodulated. This paper considers the details of the digital signal processing needed to synthesize the wideband signal by coherently combining the signals from the separate receive channels.

Figure 1 illustrates the proposed receiver concept. At the top left, we see the proposed receiver architecture in which N receivers $\{\text{RX}_i\}_{i=1}^N$ capture distinct but overlapping portions of the band of interest. Although the figure shows separate antennas for each channel, multiple channels could also be fed from the same antenna. The collection of captured signals are input to a digital signal processing (DSP) block that stitches them together to synthesize the signal occupying the full band of interest. From an input-output perspective, the proposed receiver functions as if it was a single wideband receiver with N times the capture bandwidth.

The lower part of Fig. 1 illustrates the operation in the frequency domain. The wideband signal $X(F)$ is shown extending over the frequency band of interest and centered at F_c. The separate receive channels each capture a portion of the band of interest. Through processing, $X(F)$ is recovered without distortion.

For simplicity the rest of the paper will discuss the two-channel case ($N = 2$). Techniques applied in the two-channel case can be scaled up to combine N channels. Even in the N-channel case, we assume that any individual channel only overlaps with its immediate neighbors so that considerations for the two-channel case are all that is needed to extend to arbitrary numbers of channels and thus to arbitrary bandwidths.

3. DSP for Combining Two Adjacent Channels

Figure 2 illustrates in the frequency domain the process of receiving and combining the two channels. At (A) in the figure the spectrum of the wideband signal $X(F)$ is illustrated as the shaded function. The positioning of the band pass filters $H_1(F)$ (dotted) and $H_2(F)$ (dashed) for receivers RX_1 and RX_2 are also shown. Notice that the two receivers capture an overlapping frequency band around F_c. This redundancy is needed for frequency and phase synchronization discussed later. We assume that the processing gains in each channel are equal so that there are no amplitude errors between channels.

At (B) in the figure, the response of the separate receive filters is shown overlaid on top of $X(F)$. The spectra of the received signals $Y_1(F) = H_1(F)X(F)$ and $Y_2(F) = H_2(F)X(F)$ are shown at (C) in the figure. Notice that these signals are centered at zero frequency. These two signals define the inputs to the DSP block in Fig. 1. The goal is now to reassemble the fullband signal $X(F)$ at baseband. Conceptually, this can be done by shifting $Y_1(F)$ down (in frequency) by $F_0 = F_c - F_{c,1}$ and $Y_2(F)$ up by $F_0 = F_{c,2} - F$ and then adding them back together

$$Y_1(F + F_0) + Y_2(F - F_0), \tag{1}$$

but there are two problems with this approach. First, a portion of $X(F)$ in the overlapping region of $H_1(F)$ and $H_2(F)$ is contained in both $Y_1(F)$ and $Y_2(F)$. Adding as in (1) will double the amplitude in the overlapping region resulting in amplitude distortion of the waveform. This problem may be overcome by reshaping the spectra in the overlapping regions so that they sum correctly there. The reshaping may be done using a Nyquist filter. This is illustrated at (D) in the figure where raised cosine shaped filters $G_1(F)$ and $G_2(F)$ are applied. Notice that the Nyquist filter rolloff spans the overlap frequencies while the rest of the signal spectrum is left unaltered. The output of these Nyquist filters $Z_1(F)$ and $Z_2(F)$ are shown at (E) in the figure.

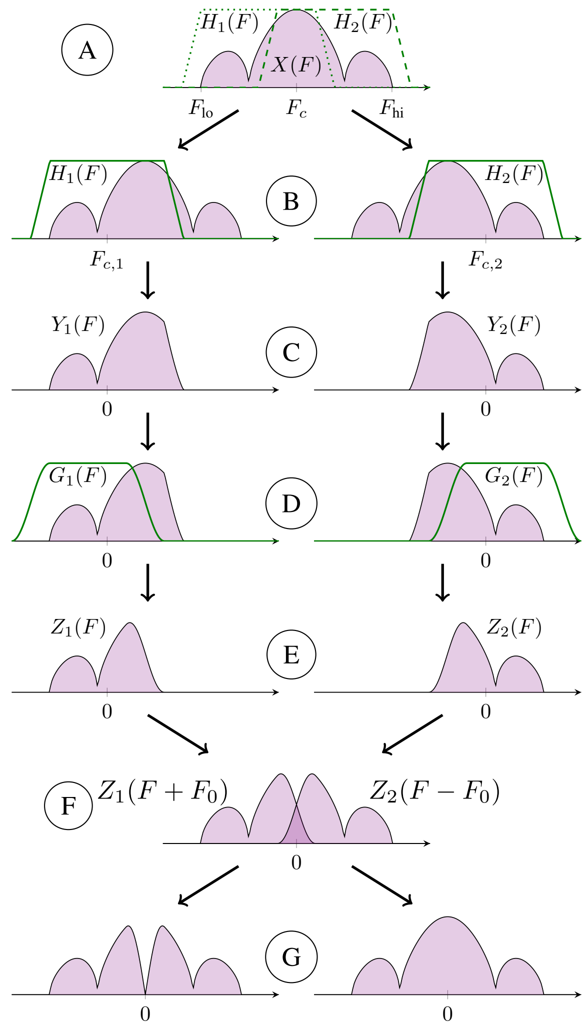

Figure 2. Spectra associated with receiving on two channels (A)-(C) and associated with recovering the full band signal at baseband (C)-(G).

Point (F) in the figure shows the two spectra repositioned so that the reshaped spectral regions overlap. With the spectra in the overlapping region having a Nyquist rolloff, they are ready to be added together if it were not for a second impairment. Due to drift in frequency synthesizer circuits in the two receivers, the two shifted spectra $Z_1(F + F_0)$ and $Z_2(F - F_0)$ may not be perfectly aligned in frequency. Furthermore, phase alignment is also needed or else the two spectra will cancel each other when added as shown on the left at (G) in the figure. If properly positioned in frequency and phase aligned, then adding the two spectra will recover the original signal positioned at baseband $X(F - F_c)$ as shown on the right at (G) in the figure. The topic of synchronization is addressed in Section 4.

We note that the steps described above are only an outline of the processing that must be performed and some

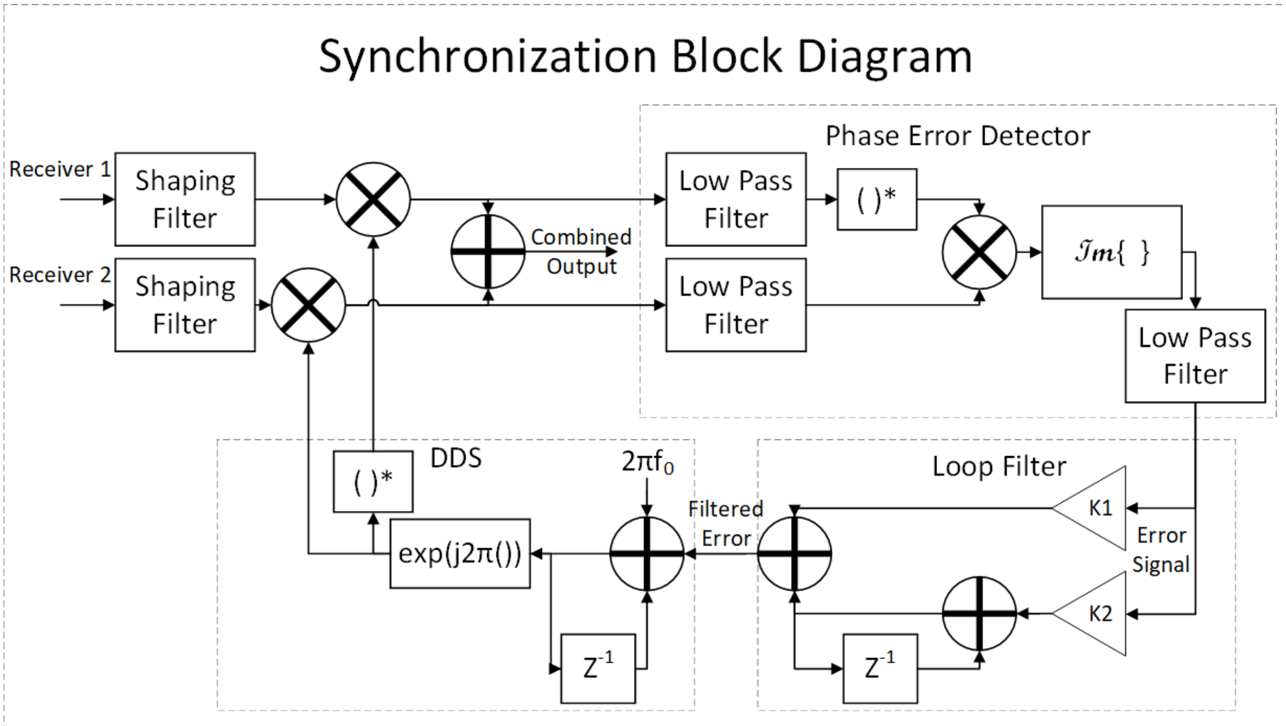

Figure 3. Synchronization loop for combining two adjacent channels.

important steps are left out. The spectra in Fig. 2 are all continuous-time spectra with frequency F expressed in units of Hertz. In practice, the processing from point (C) on down to (G) will all be performed in discrete time. Therefore practical matters associated with sampling rates must also be considered. Specifically at point (F) in the figure, when the spectra are shifted up and down in frequency, some sample rate conversion must be applied to open up room on the frequency axis to accommodate the frequency translations. These practical matters are left to implementation.

4. Synchronizing Two Adjacent Channels

The overlapping spectral region between two receiver channels (adjacent in frequency) provides the redundancy needed for frequency and phase synchronization. Without accurate synchronization, adding the two channels together will lead to a loss of signal amplitude in the overlapping region.

The information contained in the overlapping regions in each channel may be isolated from the rest of the signal by shifting the overlapping region to baseband and applying a low pass filter. The required frequency shift is F_0 and is the same shift needed to reposition the spectra for overlap-add combining shown in Fig. 2 at point (F). Ideally, the raw received signals $Y_1(F)$ and $Y_2(F)$ would be shifted and filtered. However, in experimentation we observed negligible degradation when filtering the Nyquist shaped signals $Z_1(F)$ and $Z_2(F)$, and this saves computation.

Whichever approach is taken, let us begin the discussion of synchronization by assuming that the frequency and phase correction are perfect. In that case, the low pass filtered complex-valued signals are identical in the overlapping region of both channels. When frequency or phase offsets are present, the low pass filtered signals in the overlapping region will differ. This principle may be used to build a detector for sensing frequency and phase misalignment. Conjugate multiplying a pair of complex numbers results in a purely real value (zero imaginary part) only when the two have identical phases. Therefore, the imaginary part of the conjugate product of the low pass filtered signals gives the desired detector. This signal is low pass filtered prior to driving a loop filter in a phase locked loop configuration. The overall synchronization and signal combining operation is shown in Fig. 3.

At the left of Fig. 3 the two received signals $Y_1(F)$ and $Y_2(F)$ enter the processing. We assume that any sample rate conversion has already been applied. These two signals are frequency shifted by $f_0 = F_0/F_s$, where F_s is the sample rate, by mixing with a complex exponential produced by a direct digital synthesizer (DDS) as shown. One channel is shifted up by f_0 and the other down by the same amount to align the overlapping regions as shown in Fig. 2 at point (F). Due to the action of the PLL driving the phase error (imaginary part of conjugate product as described above) to zero, the two signals may be combined by adding as shown and the overlapping regions add to reconstruct the original signal waveform $X(F - F_c)$.

The frequency shifted signals are also fed into the phase detector which has been described previously. The phase detector output is passed through a proportional-plus-integral loop filter where the loop filter constants K_1 and K_2 are chosen using techniques described in (Rice, 2008).

The performance of the proposed synchronizer was simulated in Matlab. A QPSK digital communication signal was taken as the broadband source signal and two receivers were tuned to cover the bandwidth of the source signal and have 20% overlap. The signal to noise ratio was set to 20 dB. After synchronizing and combining the two signals, the QPSK signal was demodulated. The results of synchronization are shown in Fig. 4.

The top plot shows the loop filter output over time. After an initial transient, the error stabilizes near zero as expected. The middle plot shows the eye pattern of the demodulator after signal combing. At the start of the simulation, the eye was closed. The open-eye condition shown occurred immediately following the startup transient (at the position of the dashed line in the top plot). The lower plot shows the spectrum of the combined signal with synchronization (blue) and without it (orange). Notice that without the synchronizer, the combined spectrum exhibits a dip near zero frequency that results from signals being added out of phase in the overlapping region. The dip near zero frequency varies in size depending on the size of the phase error between receivers. Even small phase errors, between the receivers yielded unusable data after demodulation.

Finally, the bit error rate performance of the two-channel receiver was compared with that of a single wideband receiver. The results, which are shown in Fig. 5, illustrate that the two-channel receiver (orange) performs slightly better than the single wideband receiver (blue). This can be explained by recognizing the increase in signal to noise ratio achieved in the low frequency (overlapping) region where the two signals add coherently and the noise does not. This boost in SNR over 20% of the signal bandwidth is responsible for the improvement in bit error rate.

No figures for bit error rate are provided for cases when the synchronizer was deactivated or for cases when small offsets are present in the synchronizer. In such cases, demodulation of the combined signal yielded unusable data.

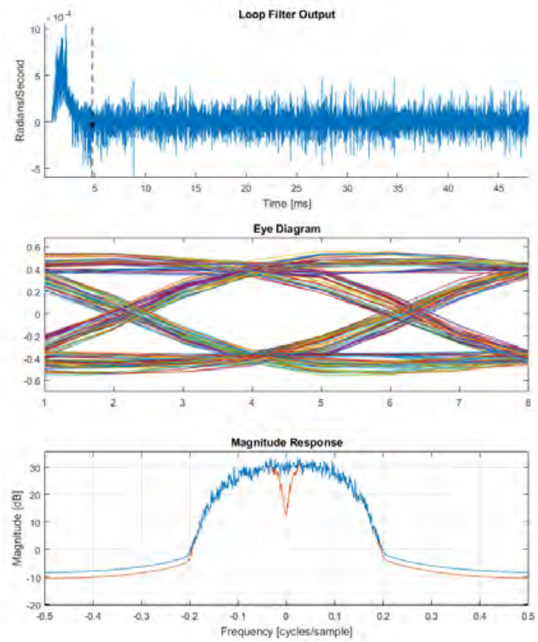

Figure 4. Simulation of a two channel receiver. Top: The loop filter output showing a short initial transient. Middle: Eye pattern in the demodulator following the initial synchronization transient. Bottom: Spectra of the reconstructed signal with synchronization (blue) and without it (orange).

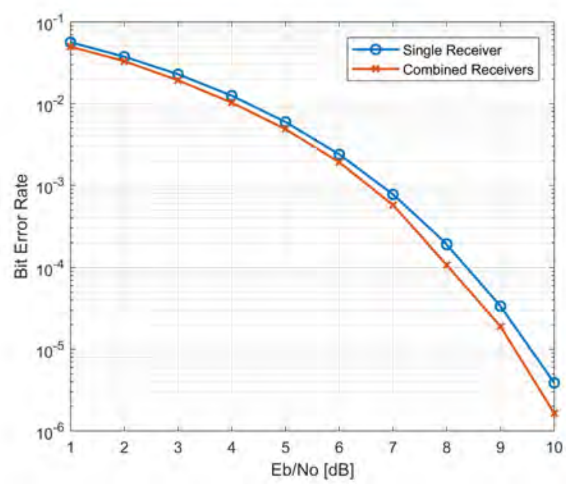

Figure 5. Comparison of bit error rate performance for two receiver configurations: a single wideband receiver (blue line) and two narrowband receivers with overlapping frequency band (orange line).

5. Real-Time Hardware Implementation

To demonstrate received signal combination, a single-channel B205mini USRP transmitter was set up to transmit QPSK symbols. An Analog Devices FMCOMMS5 development board with two coherent channels was used to receive two halves of the transmitted signal.The two channels of data were fed into a XilinxFPGA that performed the combination process in real time. A figure of the basic hardware setup is shown in Fig. 6.

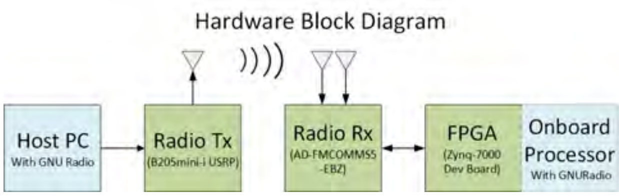

Figure 6. System block diagram.

The signal combination process began on a host computer with a camera attached. Using a combination of GNU-Radio and OpenCV, a video stream was QPSK modulated and transmitted with the USRP. To receive the transmitted video signal the FMCOMMS5-EBZ board was set up using a dual channel system with each channel synchronized to the same sampling clock, but not the same RF oscillator. In this configuration, we don't have to worry about correcting sample timing, but we do have to account and correct for drifting frequency and phase on each channel. Each channel was given its own antenna and was set to receive a separate portion of the transmitted signal spectrum as described in Section 3. The FMCOMMS5 board uses a built-in automatic gain controller to help prevent amplitude errors between the two receive channels.

The FMCOMMS5 board was used as a daughter card to the Zynq-7000 FPGA development board by Xilinx, which was used to perform the combination of the separate data streams. A picture of the receiver hardware setup is shown in Figure 7.

The FPGA development board's reference design was modified to include the signal combination logic in the receive chain. The result was interleaved between the two existing channels and accessed directly from the on-board ARM processor.

The onboard ARM processor ran Ubuntu Linux with GNU Radio. The interleaved QPSK signal was deinterleaved, demodulated, decoded, and packed into image slices using GNURadio. Again using a combination of GNURadio and OpenCV, the image slices were displayed as video on a screen attached to the FPGA development board.

To verify and diagnose the signal combination process, the FPGA used a program called IIOscope to plot the spectra of the signal at various stages of the combination process. Several screenshots of the spectra are shown in Figure 8.

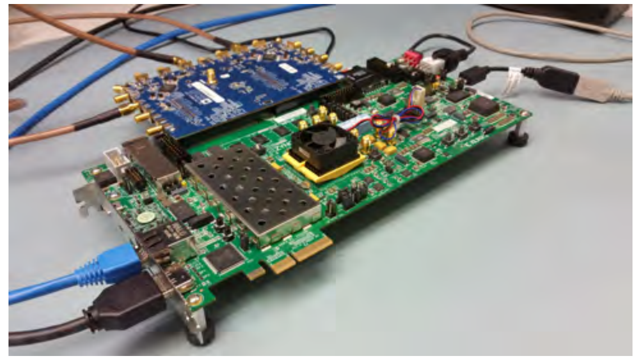

Figure 7. Photograph of the bench-top prototype hardware showing the Analog Devices FMCOMMS5-EBZ board (blue) plugged into the Xilinx Zynq-7000 All Programmable SoC ZC706 board (green).

Note that the figure shows two separate results of the combination process. The first is produced using no phase synchronization and is distorted. Images recreated from this signal contain only corrupted data. The second is produced using phase synchronization and results in undistorted images when demodulated by GNURadio.

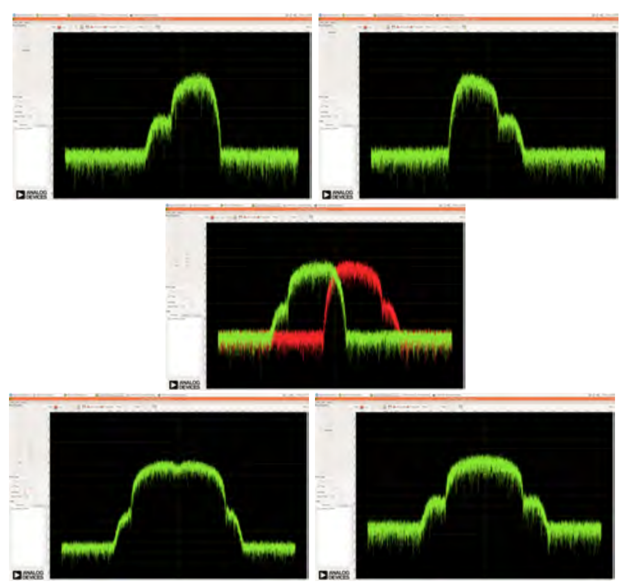

Figure 8. Views of intermediate signals within the FPGA provided by the IIO Oscilloscope application. Top: The two received baseband signal spectra after Nyquist spectral shaping in the overlap region. Middle: The repositioned signal spectra prior to adding. Bottom: The combined signal spectra. Bottom left: Combined spectrum without synchronization. Bottom right: Combined spectrum with synchronization.

6. Conclusions and Future Work

This paper has presented an architecture for receiving a wideband signal using multiple narrowband receivers. Though details for the two-channel case were addressed in this paper, the method may be applied to any number of channels and thus this concept may be used to create arbitrary bandwidth receivers. Digital signal processing consisting of Nyquist reshaping in overlapping spectral regions and frequency/phase synchronization are needed in order to resynthesize wideband signals from multiple narrow receive channels. A frequency/phase error detector was proposed and used in a phase locked loop configuration to validate the proposed technique in simulations. The method was also validated using a real-time hardware implementation. Future work will analyze the pull-in range and test the pull-in range in hardware.

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