THE PROCESS OF IMPLEMENTING A RF FRONT-END TRANSCEIVER FOR NASA'S SPACE NETWORK

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ABSTRACT

Software defined radio (SDR) introduces endless possibilities for future communication technologies. Instead of being limited to a static segment of the radio spectrum, SDR allows RF front-ends to be more flexible by using digital signal processing (DSP) and cognitive techniques to integrate adaptive hardware with dynamic software. We present the design and implementation of an innovative RF front-end transceiver architecture for application into a SDR test-bed platform. System-level requirements were extracted from the Space Network User Guide (SNUG). Initial system characterization demonstrated image leakage due to poor filtering and mixer isolation issues. Hence, the RF front-end design was re-implemented using the Weaver architecture for improved image rejection performance.

KEY WORDS

Software defined radio (SDR), Heterodyning, Image Rejection, S-band Single Access (SSA), Weaver Architecture

INTRODUCTION

The RF front-end (RFE) is essential for wireless communication systems. In recent years, the transceiver infrastructure is being challenged by an increase in demand for higher data rates, while minimizing the hardware complexity in the RFE. The concept of SDR, while not new, allows components that have been typically implemented in hardware are instead implemented by means of software on a personal computer or embedded computing devices [1]. This allows communication systems to become more flexible and dynamic. Recently, National Aeronautical Space Administration (NASA) has invested resources in developing SDR technology to support its next generation Space Network [2]. To evaluate future space communication technologies, a SDR test-bed platform is being developed. As depicted in Figure 1(a), the SDR test-bed platform will simulate the space vehicle that communicates with ground station via NASA's Tracking & Data Relay Satellite (TDRS). Also depicted in Figure 1(b) is the block diagram of the test-bed system architecture. In this paper, we present the formulation of system requirements, our previous design, re-implementation and verification of the RFE utilizing the Weaver architecture.

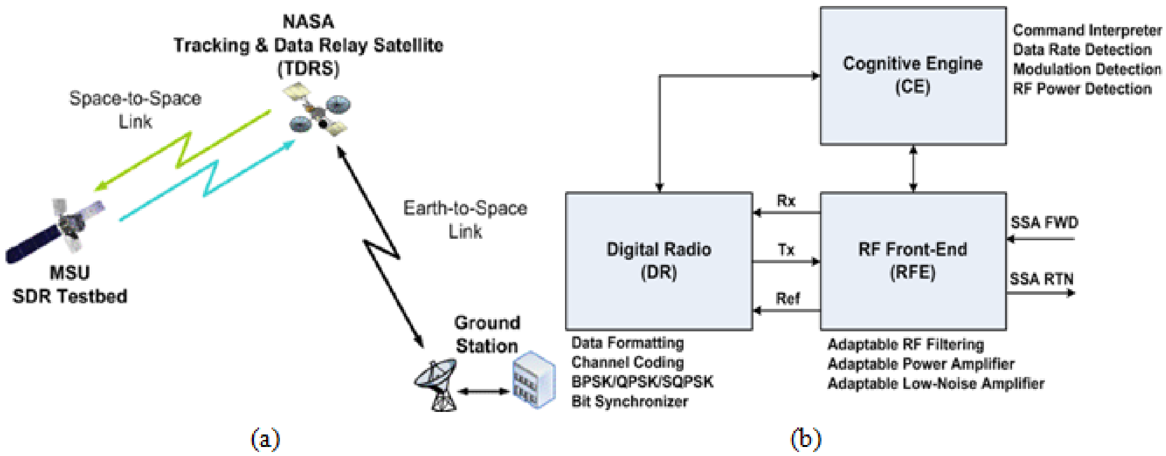


Figure 1: (a) NASA Space Network (b) SDR Transceiver System Architecture

SYSTEM-LEVEL REQUIREMENTS

System level requirements are essential in any design process. In formulating the system-level requirements, a thorough understanding of the Space Network User Guide (SNUG) had to be emphasized. The SNUG provides support to NASA's customers requiring communications across its Space Network (SN). The SNUG covers a broad range of topics; however, our interests focus on supporting the S-band Single Access (SSA) services, which include forward and return communication links. Based on a review of the SNUG, we have extracted the following system requirements in formulation of our SDR testbed platform: 1) SDR test-bed should be compatible with S-band Space Network services; 2) The operational frequencies are 2025.8 - 2117.9 MHz (receiver) and 2200 - 2300 MHz (transmitter); 3) The output power requirement for the receiver is 6dBm $\pm$ 2 dB at 40 MHz given by the analog-to-digital converter (ADC) input requirement[3]; 4) The output power requirement for the transmitter is -2dBm to -25dBm given by the input power level requirement for an adaptable power amplifier; and 5) The input power level coming from the digital-to-analog converter (DAC) into our transmitter chain I Path and Q Path is -13 dBm $\pm$ 1dB at 40MHz. These requirements will guide the development of the RF front-end block of the SDR transceiver system architecture presented in Figure 1(b).

INITIAL DESIGN AND OBSERVATIONS

Hardware implementation of the initial RFE is presented in Figure 2. As depicted, a heterodyne architecture was implemented in order to leverage trade-offs between image rejection, channel selection, sensitivity and selectivity. In forward link (receive mode), an RF to IF (Intermediate Frequency) down-conversion is performed after the band selection and signal conditioning. On the other hand, in return link (transmit mode), an up-conversion process translates the received IF signal onto an RF carrier.

Test results in Figure 2 demonstrate the image leakage and mixer isolation issue associated with our initial design of the RFE, both for transmit and receive chain. In the receiver, the image signal and wanted signal both translate to the same IF. In the transmitter, the isolation between the local oscillator (LO) and the radio frequency (RF) port is poor causing the LO signal to leak and appear at the RF port. Furthermore, due to the low IF frequency, the lower side band (LSB) component appears relatively close to the upper side band (USB) component and the leakage of the LO signal making the filtering operation difficult. To resolve the image issues we re-configured our design using the Weaver architecture [4].

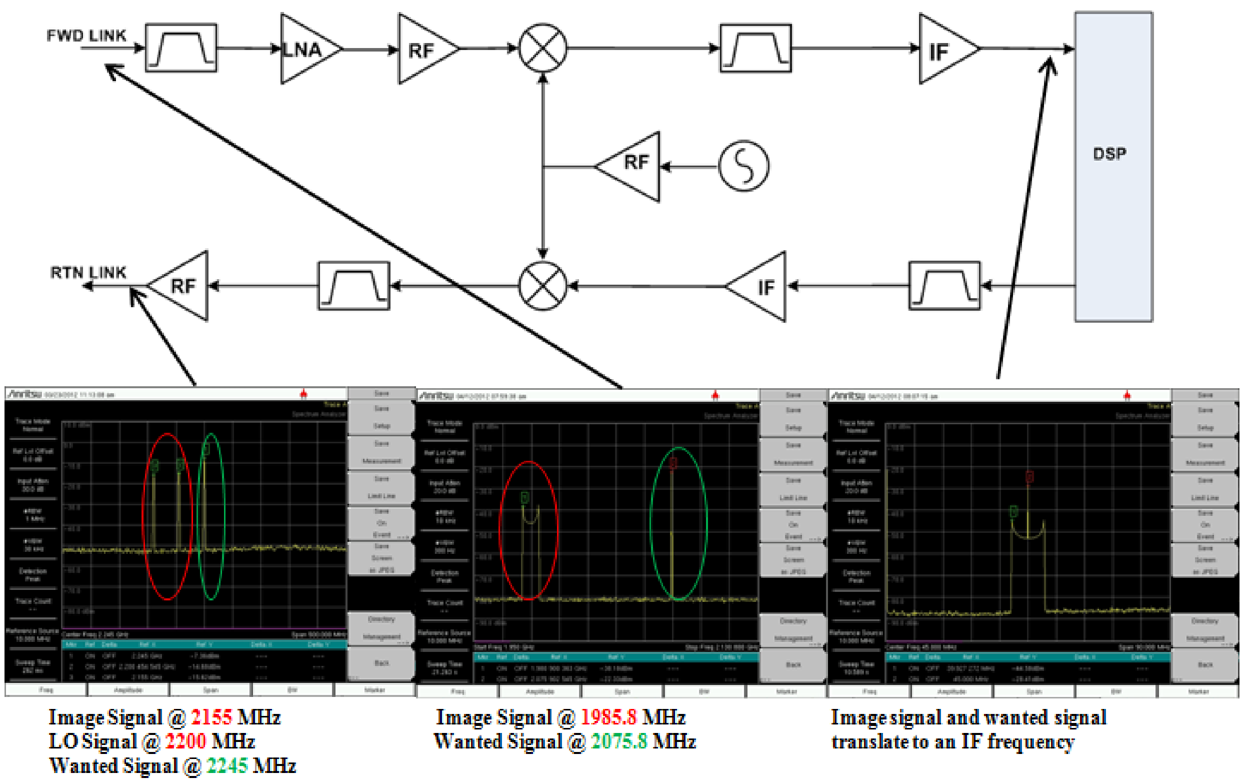


Figure 2 : Illustrates Image Problem in Rx and Tx from Initial Design

WEAVER ARCHITECTURE

The Weaver architecture uses complex mixing to reject the image frequency. Figure 3 demonstrates mixing a real signal with a complex LO yielding a spectrum shift in frequency to baseband. In Figure 3, the red represents the image frequency component and the black represents the wanted frequency component. After performing frequency translation using the negative complex LO, the positive image frequency is still present, but spectrally separated from the wanted signal [4].

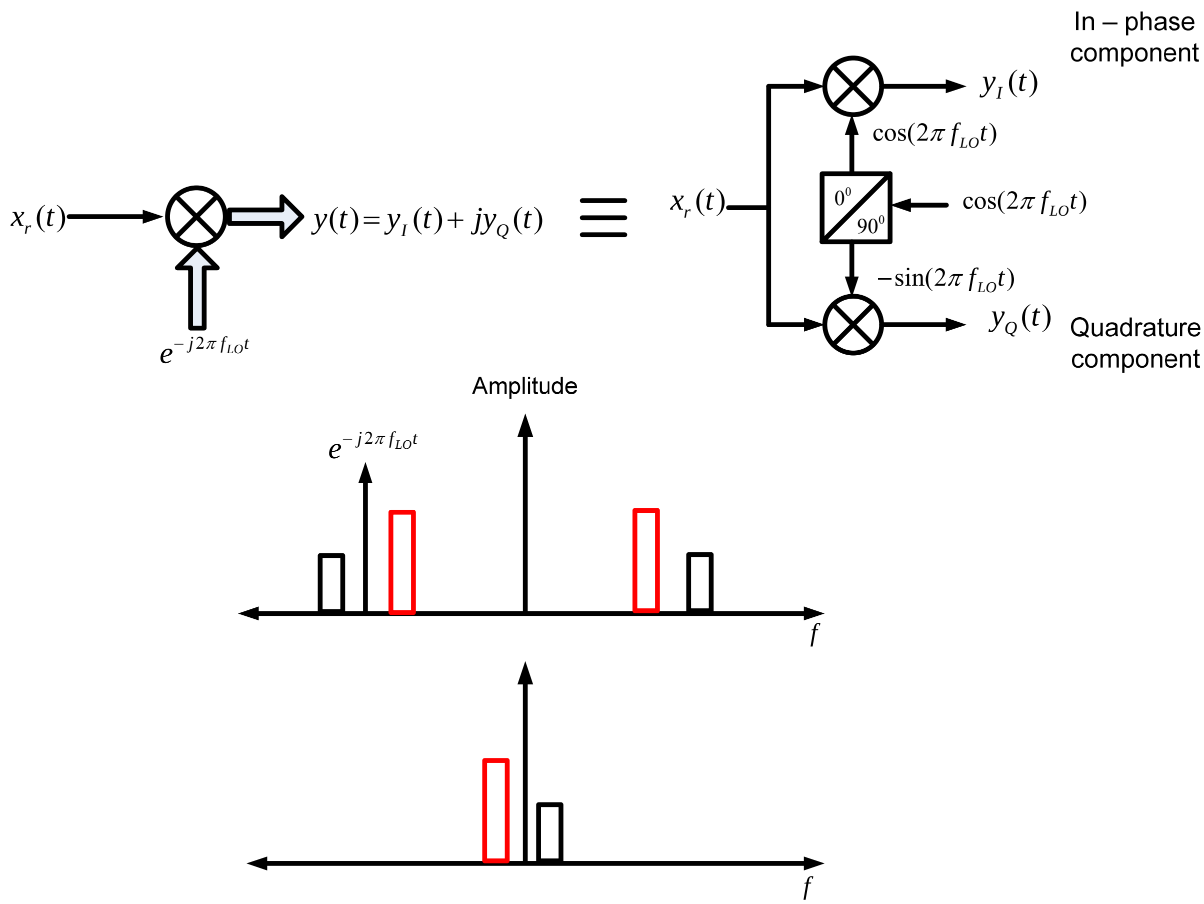


Figure 3: Complex Mixing Concept

Mixing a real signal with this negative-frequency complex exponential gives a complex signal. The Weaver architecture is a two stage frequency translation architecture that generates its output spectrum from the in-phase (I) and quadrature (Q) paths conceptually illustrated in Figure 3. Complex signals are a convenient mathematical representation for a pair of real signals [6, 7]. The mathematical derivation proving the rejection of the image frequency is show below using complex mixing concept.

Assuming the input signal is:

$$s(t) = \cos(\omega_{RF} t) + \cos(\omega_{IM} t) \tag{1}$$

Where ω_{RF} is the wanted frequency in radians and ω_{IM} is the image frequency in radians. Performing the two-stage frequency translation for the I and Q path, we obtain the following expressions:

$$\begin{aligned} I &= s(t) \times \cos(\omega_{LO1} t) \times \cos(\omega_{LO2} t) \\ &= \frac{1}{4}\cos(\omega_{IF2} t) + \frac{1}{4}\cos(-\omega_{IF2} t) \end{aligned} \tag{2}$$

$$Q = s(t) \times \sin(\omega_{LO1} t) \times \sin(\omega_{LO2} t)$$
$$= -\frac{1}{4}\cos(\omega_{IF2} t) + \frac{1}{4}\cos(-\omega_{IF2} t) \qquad (3)$$

Due to the dual nature of the Weaver architecture, summation of the I and Q paths results in the recovery of the image frequency. Conversely, the subtraction of the I and Q paths results in the recovery of the wanted frequency. The red in expressions (4) and (5) indicates the cancelation of the sum product terms after the second down conversion stage. This analysis is demonstrated in the following expressions:

$$\begin{aligned} \mathit{Summation} \quad &= I + Q \\ &= \frac{1}{4}\cos(\omega_{IF2} t) + \frac{1}{4}\cos(-\omega_{IF2} t) - \frac{1}{4}\cos(\omega_{IF2} t) + \frac{1}{4}\cos(-\omega_{IF2} t)] \\ &= \frac{1}{2}\cos(-\omega_{IF2} t)\,(\mathit{image\ signal}) \end{aligned} \qquad (4)$$

$$\begin{aligned} \mathit{Subtraction} \quad &= I - Q \\ &= \frac{1}{4}\cos(\omega_{IF2} t) + \frac{1}{4}\cos(-\omega_{IF2} t) + \frac{1}{4}\cos(\omega_{IF2} t) - \frac{1}{4}\cos(-\omega_{IF2} t)] \\ &= \frac{1}{2}\cos(\omega_{IF2} t)\,(\mathit{wanted\ signal}) \end{aligned} \qquad (5)$$

Our new design incorporating the Weaver architecture is illustrated in Figure 4. The red block, indicates the second down-conversion stage, will be performed in the digital domain. Ideally, this architecture solves the image frequency problem. In practice, the errors in the phase and mismatches between the amplitudes of the I and Q signal paths corrupt the down converted signal [4]. The image rejection ratio (IRR) is a figure of merit used to quantify how well the image signal is being suppressed [5].

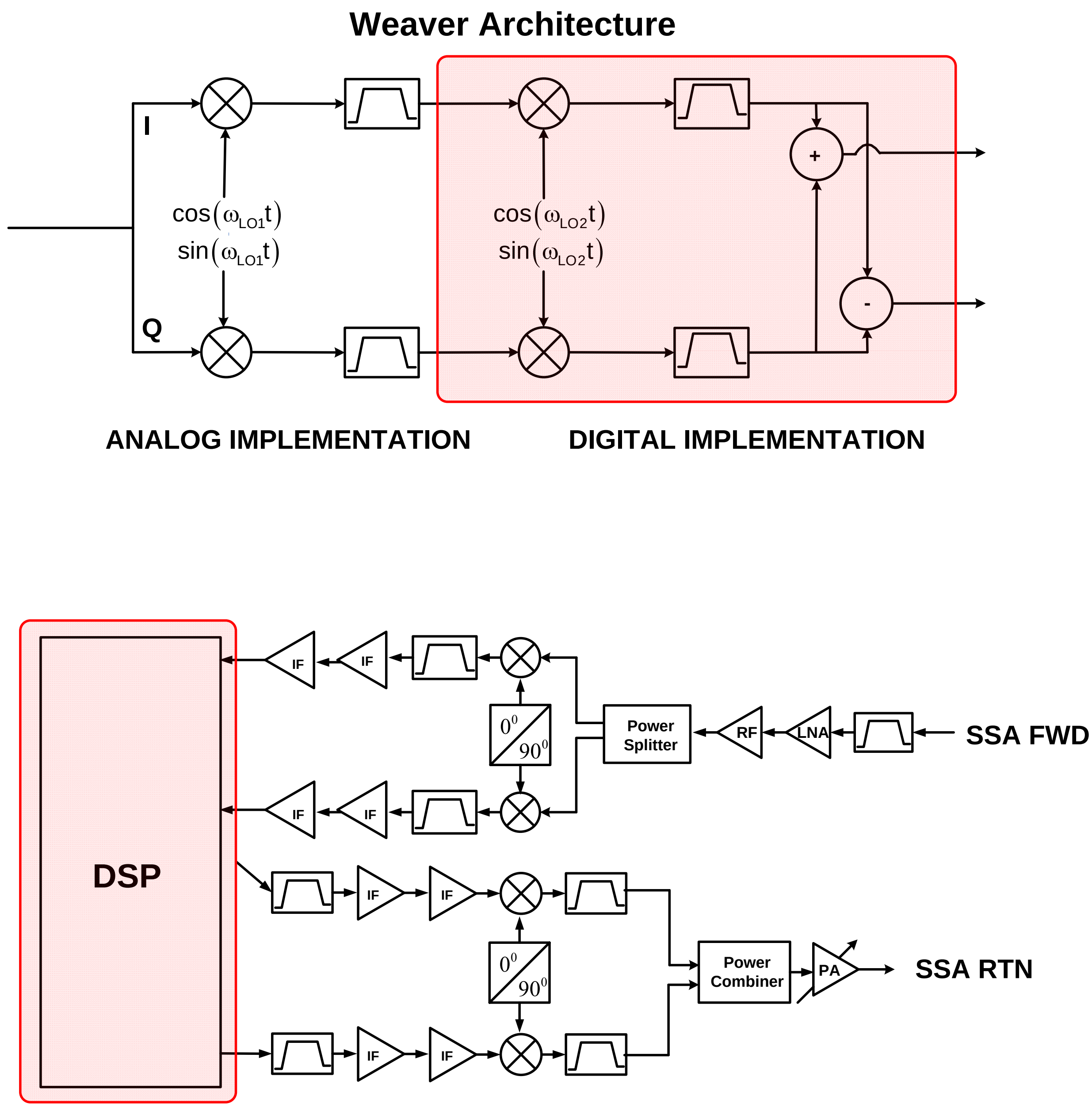


Figure 4: Weaver Architecture Implementation

IMAGE SUPPRESSION EXPERIMENT

Figure 5 demonstrates the lab set-up for testing the Weaver architecture. The purpose of this test was to prove the rejection of the unwanted image signal both at the receiver and the transmitter. For the receiver, there were two input signals for the test. Signal 1 was at 1420 MHz (considered for the purpose of this test setup as the wanted signal) and Signal 2 at 2220 MHz. Signal 1 and Signal 2 are highlighted with green and red circles respectively. Signal 1 was a modulated signal, while Signal 2 was a single-tone carrier. This difference in signals was used to distinguish the signals when they translate to the same IF signal at 150 MHz. Both input signals were chosen such that when they were mixed down with LO1, they would overlap at the IF1 frequency. Figure 6 shows the results for the test conducted for the Weaver architecture.

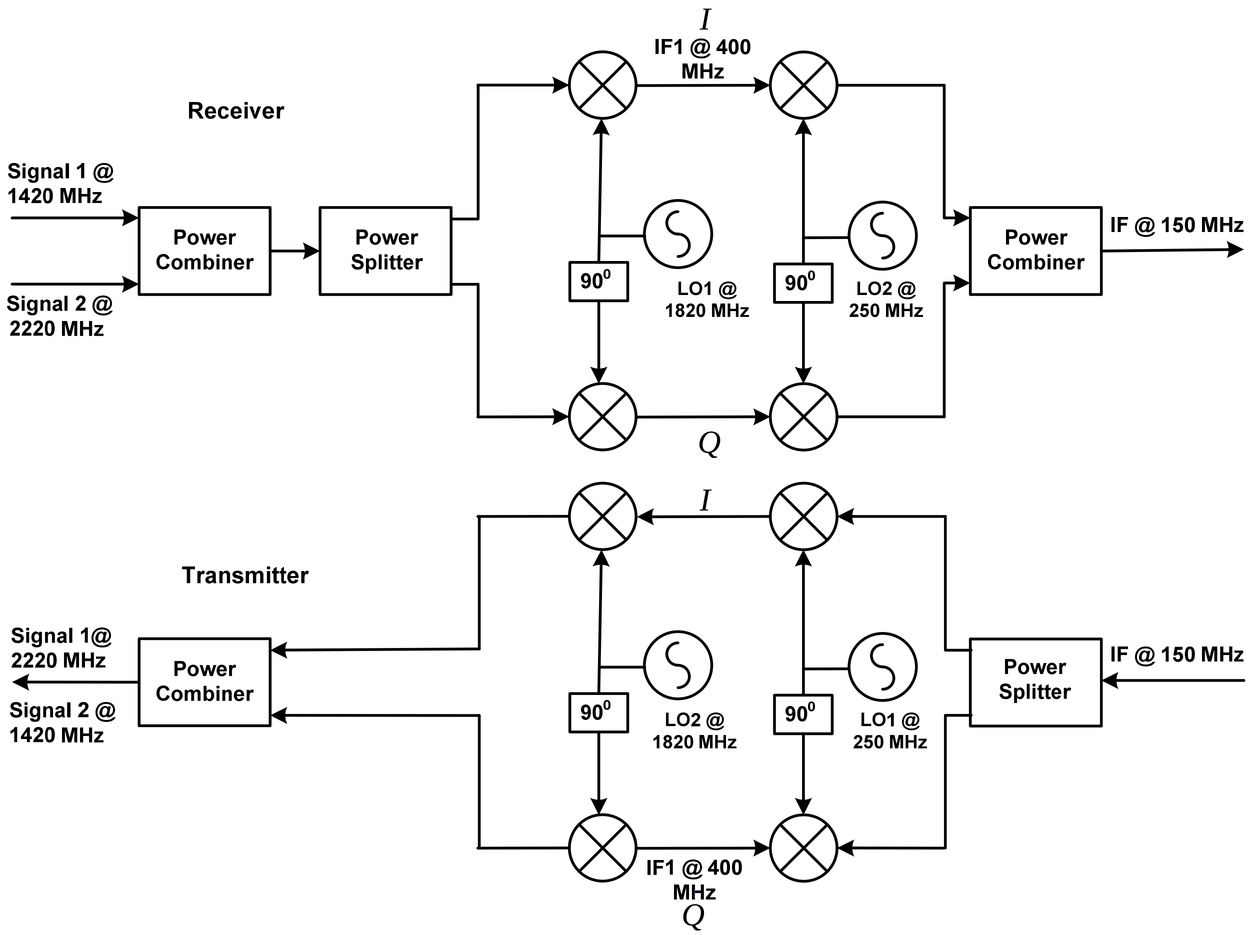
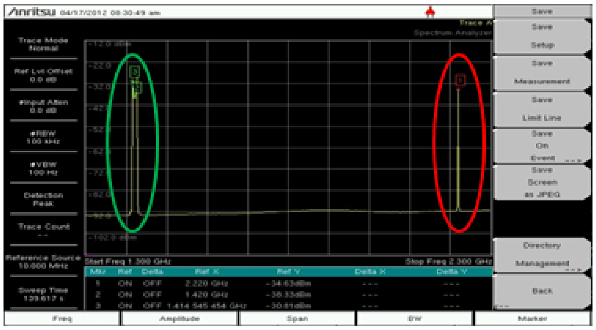


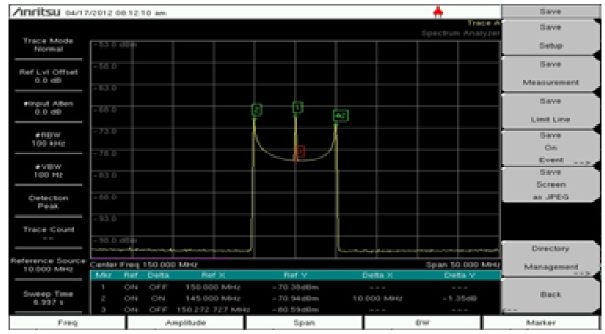
Figure 5: Lab test set up for Weaver Architecture

Figure 6(b) shows the output of I and Q paths before they were combined within the Weaver architecture as shown in Figure 5. It can be seen that both input signals translated to the same IF at 150 MHz. On the other hand, Figure 6(c) shows the output signal when I and Q paths were combined together used to show the rejection of the 2220 MHz signal. To measure the attenuation level of this Signal 2, Signal 1 was removed and the result in Figure 6(d) shows that an image rejection on the order of 15 dB was achieved.

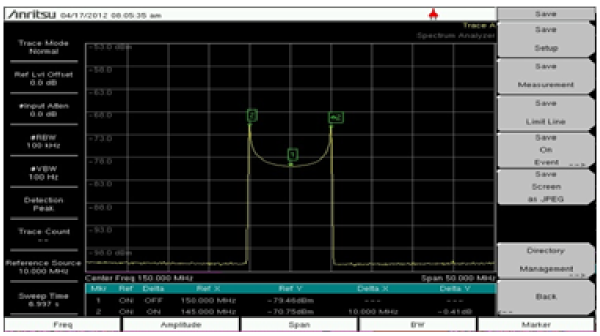
On the transmitter side, an input signal at an IF of 150 MHz was used for RF transmission. Here Signal 1 was the desired signal at 2220 MHz and Signal 2 was the image signal at 1420 MHz. Signal 1 was the USB component and Signal 2 the LSB component of the mixer's output. When the outputs of I and Q channels were combined, an image rejection on the order of 14.74 dB was achieved.



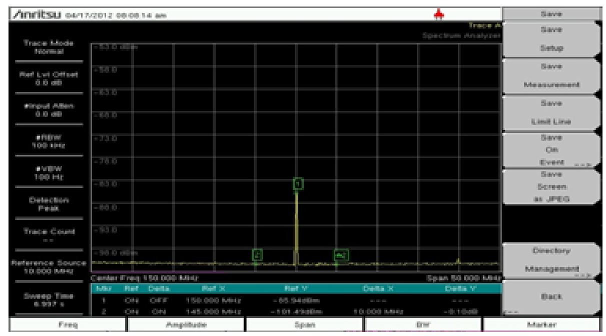
(a)
Input Signals
Signal 1 @ 1420 MHz
Signal 2 @ 2220 MHz



(b)
Output Signal @ 150 MHz (No Suppression)



(c)
Output Signal @ 150 MHz
Signal 2 is suppressed



(d)
Output Signal @ 150 MHz
Signal 2 is suppressed by 15 dB

Figure 6: Weaver Architecture lab test results for receiver

SYSTEM CHARACTERIZATION

A. Interface Requirement Validation

This test was conducted to validate the interface requirements for the RFE. The output power levels of I and Q paths for the receiver were 6.65 dBm and 6.88 dBm respectively. This meets the input power level requirement for the digital radio (DR). The output signal power level for the transmitter was -14.07 dBm which is within the range of the input signal power level requirement of the power amplifier.

B. Third-Order Intercept Test (IP3 Test)

A third-order intercept test (IP3) for the system was conducted to calculate the third-order distortion and the spurious free dynamics range (SFDR) of the system. Theoretically, signal power of the third-order spurs increased by 3 dB with an increase of 1 dB in the fundamental component. For the receiver, the calculated SFDR for the I and Q paths were 25.35 dBm and 28.33 dBm respectively.

C. Noise Figure Measurement

Noise figure is a very important parameter for assessing the sensitivity of the receiver. It is a measurement of the signal-to-noise degradation due to the noise performance of the receiver. The measured noise figure for the receiver chain was 2.268 dB.

CONCLUSION

We successfully designed and implemented the Weaver architecture in the RFE sub-system of our SDR testbed platform. System level requirements for the RFE sub-system were achieved and observations revealed improved image-rejection performance. However, system characterization illustrated the existence of amplitude imbalances between the I and Q paths. Therefore, to compensate for the imbalance between the two paths and to meet the interface requirement with the digital back-end, an automatic gain control (AGC) has to be integrated at the receiver. A variable gain amplifier (VGA) is needed for the transmitter to meet the input power level range requirement of the adaptable power amplifier. The LO leakage is still an on-going problem being considered. Our next steps are the compensation of I and Q paths to improve the IRR performance as well as full integration of the RFE and the DR back-end sub systems.

ACKNOWLEDGEMENTS

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