Transmitter Leakage Analysis When Operating USRP (N210) in Duplex Mode

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Abstract—The main challenge of operating a radio in full duplex mode, is the direct feedback from its transmission to its reception which is the self interference. However, the internal leakage within the radio has the potential to distort the received signal. This paper presents the measured leakage observed in N210 one of the Universal Serial Radio Peripheral (USRP) family of devices. Also, suppression mechanism has been evaluated in both hardware and software.

Keywords—Transmitter leakage, self interference, Software Defined Radio (SDR), Universal Serial Radio Peripheral (USRP), Single Pole Double Throw (SPDT), GNU Radio.

I. INTRODUCTION

Radios in full duplex mode establish bidirectional communication link operating simultaneously, in other words the transmitter and the receiver are operated in the same time. Generally, separate antennas are used by the transmitter and the receiver. In addition, the RF carriers can be same frequency or different frequencies for the transmitter and receiver [2]. There is a ongoing interest to operate a single antenna in full duplex mode with single RF carrier frequency especially in the field of Radar communication [3] [4].

Most of the radios today are generally half duplex, which means there is no simultaneous operation of transmitter and receiver. One main challenging factor which prohibits us to achieve full duplex is transmitter feedback to the receiver [5]. There are many cancellation technique put forth to cancel out the feedback from the transmitter. The solution to achieve full duplex can redefine the entire schematic for building the radio. Nowadays the radios are supporting MIMO where there multiple antennas for transmission and reception, which increased the complexity to achieve full-duplex because the self interference is not from a single antenna but from multiple antennas [6] [7].

The advantage of full duplex wireless radio has a large scope to increase the efficiency by utilizing the transition period between transmission to reception. There are three main benefits which can be achieved by full duplex namely, timing efficiency, nodes no more wait for the other node to response (no handshake to avoid collision), both the entity transmitter and receiver enjoy full bandwidth.

In addition to the self interference, most radio suffer transmitter leakage due to the design and inability to isolate the transmitter and receiver path significantly. Due to the design constraint, transmitter and receiver paths are multiplexed, thus yielding to internal transmission bleed to the receiver path distorting the weak received signal. It also occur when a duplexer is used when a single antenna is deployed for transmission and reception. Though there are many cancellation technique to overcome the self interference, the transmitter leakage can be avoided by better design and choice of better isolators between transmitter and receiver path.

In case of full duplex radio with single antenna, where the transmitter and receiver path shares the same antenna, the transmission leak from the transmitter to receiver path can be avoided by deploying isolator providing high isolation between them. Recently, the signal cancellation based on electrical balance using hybrid transformers has been proposed to improve isolation between transmitter and receiver path [8].

II. USRP N210 RADIO

The USRPs are general purpose the Software Defined Radios (SDA), which are mostly used in academic and research field. The USRP N210 version provides high-bandwidth, high-dynamic range processing capability with modular design supporting it to operate from DC to 6GHz. The radio typically used in N210 is WBX, which operates in wide frequencies ranging from 50 MHz to 2.2GHz and provides 40MHz of bandwidth capability.

The radio offers two antenna ports TX/RX and RX2. TX/RX port one can be operated both as transmitter and receiver, whereas RX2 can be operated only as receiver. Both the antenna ports can be used simultaneously enabling radio to support full duplex mode. The selection of the antenna ports for transmission and reception are controlled by application like GNURadio which is supported by USRP Hardware Driver (UHD), providing the host driver and APIs. The Gigabit Ethernet connectivity is available to stream data to and from the host system.
III. TRANSMITTER LEAKAGE CANCELLATION

Transmitter Leakage is a key challenge as discussed before, since the adverse effect caused at the receiver end brings down the performance of the radio. In general the common cancellation technique is to cancel or suppress by mixing the phase shifted version of the known transmitted signal to the received signal. This is the most adopted method to suppress the transmitter signal in the receiver path.

The phase shift can be fixed or computed dynamically on the fly and then applied to the transmitter signal. The dynamic estimation can be achieved by deploying a micro-controller [9] which processes the received signal and estimate the phase to be applied to the transmitted signal for mixing. These cancellation techniques hold good for single tone transmission but for real-time data transmission, the micro-controller will face hard to estimate and counter the leakage in a timely manner.

There are implementations of transmitter leakage estimation and cancellation in the digital front end which is independent of the RF front-end used. Though these cancellation techniques are capable of cancelling the leakage, they fail when the transmitter leakage is significant such that the Low Noise Amplifier (LNA) gets saturated and there is no room to retrieve the information from its output[10][11]. Even if the transmitter leakage is not enough to saturate the LNA, they will be amplified and still increase the difficulty in retrieving the information.

Even in case of Frequency Division Duplexing (FDD) systems where the transmitter and receiver use different frequency, the transmitter leakage still prevail key issue which has to be mitigated since high power transmitter signal leaked to receiver path can saturate the receiver or interfere the weak received signal [12].

Current CMOS technology is exploited to nullify the transmitter leakage. In some application like CDMA, a transmitter leakage canceller circuit [13] was proposed and implemented in 0.18-µm CMOS technology. This circuitry is a feed-forward canceller sampling the reference transmitter signal and injects its amplitude-adjusted and phase-rotated signal in the receiver path.

IV. TRANSMITTER LEAKAGE IN WBX

The WBX radio supports operating the transmitter and receiver port simultaneously. Besides the self interference is caused by the transmitter distorting the received signal, there is another factor in the WBX radio which significantly affects the received signal due to the internal bleed of transmitter signal to the receiver path. This is by the design, since the transmitter antenna which can perform the reception shares the receiver path of the other antenna which does only reception.

This leakage issue was earlier noticed and hardware workaround was proposed. However, these do not address the underlying issue [15] [16].

The WBX daughter card uses two Single Pole Double Throw (SPDT) switches (HMC174MS8 [17]). One of the switches switch transmitter adn receiver path feeding to/from TX/RX port. The second switch switches between the receive path from TX/RX and RX2 port to the receiver. The transmitter leakage is observed because of the second SPDT switch where the transmitter chain TX/RX leaks to the receiver chain of RX2.

Fig. 3: Schematic of WBX granddaughter card TX/RX antenna port, based on [18].

Fig.4 illustrates more clear representation of the two SPDT switches and their respective connections with the transmitter and receiver path.

When operating simultaneously the TX/RX port as transmitter and the RX2 port as receiver, the TX_RX port of TX/RX SPDT switch receives a portion of energy from the transmitter chain and a portion from the transmitted signal port. This is then propagated to the receiver chain’s SPDT switch and affects the received signal. This is due to SPDT switch providing lower the isolation between the two RF input ports, and between input and output ports of SPDT switch.
The isolation between the two RF ports RF1 and RF2 of HMC174MS8 is in the range of -25 dB to -30 dB for the frequency range of 500 MHz to 1 GHz. For the same frequency range, the isolation between RF ports RF1/RF2 to RFC is -26dB. Typically, the desired isolation is more than -60dB.

A. Hardware Fix

As mentioned the primary cause of transmitter leakage across the SPDT switches in the RF board is due to the common connection. Hence, the better option is to remove the common connections between the switches and physically isolating them. This was achieved by removing the coupling capacitor C1 which is encircled in Fig.3.

![WBX Granddaughter card with hardware fix](image1)

Fig. 6: WBX Granddaughter card with hardware fix.

Fig. 6a shows the WBX granddaughter card with the coupling capacitor and Fig. 6b shows the WBX granddaughter card without the coupling capacitor between the SPDT switches.

B. Digital Filtering Approach

Beyond the hardware fix provided to the RF board, there can be transmitter leakage because of the existence of the open circuit between the switches. Irrespective of hardware fix, we can perform adaptive cancellation technique to suppress the transmitter leakage. The output of this block to suppress the transmitter leakage, if the LNA is not saturated by the leakage.

Recursive Least Squares (RLS) filter is a FIR of length $M$ with coefficients $b_k, k = 0, 1, 2, \ldots M - 1$. The input stream $f(n)$ is passed through the filter to produce the sequence $y(n)$. At each time-step the filter coefficients are updated using an error $e(n) = d(n) - y(n)$, where $d(n)$ is the desired response (usually based on $f(n)$). [20]

$$y(n) = \sum_{k=0}^{M-1} b_k f(n - k)$$  \hspace{1cm} (1)$$

Filter Coefficients, $b(n) = b(n-1) + k(n)e(n)$  \hspace{1cm} (2)$$

where,

$\lambda$ is weighting factor

$$KalmanGain, k(n) = \frac{R^{-1}(n-1)f(n)}{\lambda + f^T(n)R^{-1}(n-1)f(n)}$$  \hspace{1cm} (3)$$

$$R(n) = \sum_{i=0}^{n} \lambda^{n-i} f(i)f^T(i)$$  \hspace{1cm} (4)$$

$$e(n) = d(n) - y(n)$$  \hspace{1cm} (5)$$

RLS [19] adaptive filtering can be used to suppress the transmitter leakage. Since the transmitter signal is known, the RLS adaptive filter algorithm rapidly converges in estimating the filter coefficients.

V. RESULTS AND ANALYSIS

The measurements were collected using two USRPs (N210), one with original WBX and other with coupling capacitor C1 removed as shown in the Fig.7. A 10dB attenuator was connected to the RX2 port to prohibit any reception of transmitter power. Addition of attenuators to the RX2 port did not affect the received power and hence 10dB attenuator was connected for the experiment. The TX/RX port was connected to an antenna such that the reflection power is nominal.

GNU Radio [21] application was used to perform the analysis which connects to the radio via UHD drivers. The project was set up to monitor the power level of received signal without connecting an antenna to the RX2 port such that there is no received signal.

Fig. 7: Block diagram of the experiment setup.

Both the radios are fed with the same signal for transmission. The received signal from the radios have been captured and analysed for frequencies ranging from 50MHz to 2.2GHz.

Fig.8 shows the GNURadio project which was developed to record the transmitter power leakage to the receiver path for different transmitter gain with the receiver gain being zero.
A. Results

Fig. 9 shows the power of the generated signal fed to the USRPs for transmission. The parameter which control the transmitter gain provides 1dB for every increment by one. The maximum power output by the transmitter can be achieved by the lower frequencies and drops when proceeding with higher frequencies.

As shown in Fig.9, the generated signal strength is equal to -20dBm. Hence, the transmitter gains 0, 10, 20 and 30 corresponds to transmit output power equal to -20dBm, -10dBm, 0dBm and +10dBm respectively.

Figures 10 and 11 show the reduction in leakage power when the transmitter and receiver path between the SPDT switches was open.

Figures 12 and 13 show the received signal power for different transmitter gain across the frequencies ranging from 50MHz to 2.2GHz.
Comparing the received power from figures 12 and 13, the difference was calculated and plotted for different transmitter gains as shown in Fig. 14. It was observed that the best range of frequencies with maximum isolation between the transmitter and receiver was achieved in the range from 650MHz to 950MHz (UHF band). For frequencies between 550MHz and 1.05GHz the performance got degraded where the isolation was reduced. There was no improvement for other frequencies.

The transmitted and received signals from the radio are saved into files and performed adaptive filtering using MATLAB [22]. The RLS algorithm was employed to perform adaptive filtering to remove the transmitted signal leaked to the receiver block.

The transmitted signal was fed to the RLS algorithm to estimate the filter coefficients which was later applied to the received signal. Fig. 15 shows the block diagram on the deployment of adaptive filter between the transmitter and receiver.

Fig. 16 shows the transmitter leakage observed at the receiver and the output of the adaptive filter using RLS algorithm. Fig. 17 shows the difference in the received power using adaptive filtering using the radios with and without coupling capacitor. As observed from Fig. 14 the maximum isolation was achieved in range between 650MHz to 950MHz.

Fig. 18 shows the power difference observed for different TX gains with and without adaptive filtering, and coupling capacitor removed.
Fig. 18 shows the received power difference for different transmitter gains between the received powers from radio with and without adaptive filtering using RLS algorithm, in addition to the removal of the coupling capacitor.

Fig. 19: Power difference observed for different TX gains with and without adaptive filtering, and coupling capacitor intact.

VI. Conclusion

Hardware solution of physically removing the coupling capacitor, C1 isolating transmitter and receiver has mixed outcome. The removal of the coupling capacitor selectively improved the isolation between the transmitter and the receiver for the frequency ranging from 650MHz to 950MHz. Maximum isolation of -30dB was achieved in the mentioned frequency range. The performance was degraded for lower frequencies between 50 and 500 MHz, where there was 15dB decrease in isolation. There was no improvement across frequencies from 950MHz to 2.2GHz.

The inclusion of adaptive filter at the reception improved the performance by suppressing the transmitter leakage signal irrespective of the hardware fix. But, this suppression technique holds good until the leakage from the transmitter does not saturated the LNA in the initial stage of the receiver. Saturation of initial blocks of the receiver can be avoided by deploying SPDT switch which offers higher isolation more than -50dB between its throw ports. Thus enhancing the performance of the digital cancellation using adaptive filtering. The adaptive filtering using RLS algorithm achieved maximum isolation of -35dB between the transmitter and receiver blocks of WBX radio used in USRP N210.

REFERENCES