Report: Single Channel Full Duplex Wireless Communication (D20)

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May 2017

1 Abstract

This report discusses the design of a single channel full duplex wireless transmitter + receiver. We will demonstrate how a node can receive and transmit simultaneously (full duplex) using the same channel (single channel) for communication. It is important to note that our node can be communicating with different nodes during transmission and reception. Hence we will show single channel full duplex property of one node, and this can be extended on similar lines for other nodes. A single node in such a system uses a combination of analog passive and digital cancellation techniques to suppress the self interference signal and receive the signal transmitted by other transmitters. The major advantage of such a system is of saving spectrum while simultaneously communicating efficiently.

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3 Introduction

3.1 Motivation

With the onset of wireless communications, the cost of spectrum has increased exponentially. Further, with the requirement of fast communication the use of full duplex communication systems has also increased enormously. Techniques for saving bandwidth is currently an active area of research. Our project tries to reduce the bandwidth requirement (to half) in wireless communication as required by current full duplex wireless systems by simultaneously transmitting and receiving on the same channel.

Why is it challenging ?
One node has to transmit and receive simultaneously (full duplex).
This can be done by placing a transmitting antenna and a receiving antenna.

The node has to communicate using one channel only.
Since the node is transmitting and receiving signals on the same channel, signals will interfere with each other. The two signals the receiver will receive are (i) self transmitted signal due to the node itself and (ii) transmitted signal due to other node. This will cause the receiver to receive most of what we are transmitting and the actual signal to be received would be buried. Hence there is a need for removing the unwanted part of the signal at the receiver. This is achieved by self interference cancellation techniques [1].

3.2 Objective

We will demonstrate that a node is able to filter the received signal from the self interference signal, hence able to communicate over a single channel and full duplex at the same time. As complete cancellation of self interference signal is not feasible, we aim to cancel the self interference signal by an amount that would push it to noise level, or at least 40 dB. This project will try to demonstrate wireless communication in a single channel as opposed to current wireless systems which use double channel. We have taken two approaches to achieve the same,

- Combining digital cancellation techniques using RTL-SDR+GNURadio with analog passive cancellation.
- Combining digital cancellation techniques using IQ Demodulator Chip+TI DSP 5515 with analog passive cancellation.

3.3 Block Diagram: overview

Shown in Figure 1, node 1 is single channel full duplex, receiving signal from node 2 which is half duplex. Node 1 is transmitting and receiving on the same channel which is causing self interference at receiver of node 1.

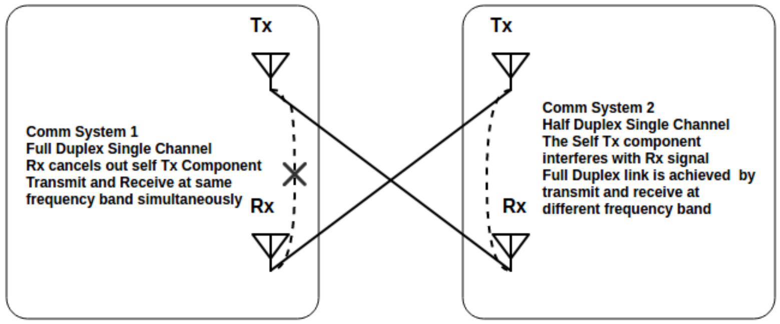


Figure 1: Overview

4 Project Design

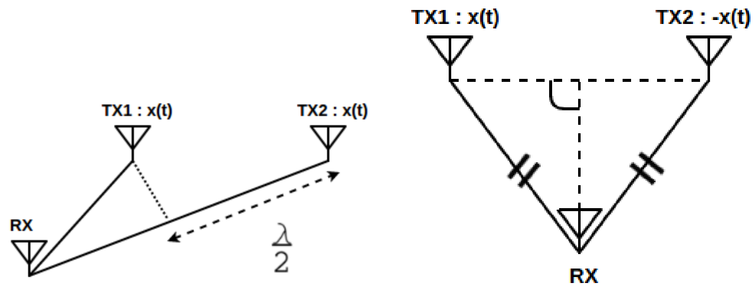
There are three separate techniques to achieve self interference cancellation :-

- **Active analog cancellation**: This method estimates the self interference signal in the analog domain itself using delays and variable gains and cancels the self interference RF signal. A control loop is required for adjusting the gain and delay taps depending on the received RSSI value at the receiver [1].
- **Passive Analog Cancellation**: Placement of the receiving antenna with respect to two transmit antennas (the three form a single node) to obtain maximum cancellation at receiver [1].
- **Digital Cancellation**: We already know what we are transmitting, we can utilise the info of the local transmitted signal for removing it from the demodulated signal in the digital domain so that only the signal coming from the third outside the system remains as output [2]

We have combined (ii) and (iii) techniques in the project, for better suppression. Further, there are two approaches for Passive Analog Cancellation, as shown in figure 2.

In the first approach, both Tx antennas transmit the same signal, but the path difference at receiving antenna is an odd multiple of half wavelength. This ensures that the self interference at receiver is minimised due to destructive interference. In the second approach, signal given to other Tx antenna is shifted (i.e. -1 times) of the signal given to first Tx antenna. Due to this, the whole perpendicular bisector line becomes a location of minimum signal. This was tested using with transmitters being IQ modulator and USRP.

For Digital Cancellation also, we have taken two pathways towards solving the problem. The first one uses RTL-SDR and GNURadio to implement digital cancellation. The Channel Estimation Algorithm used by us is minimum mean square error computed using both gradient descent and direct inverse. The other pathway considered by us was to use a IQ demodulator IC (LTC5575/LTC5585),



(a) Without Using Balun

(b) Using Balun

Figure 2: Passive Analog Cancellation Placement Techniques

and design an interface for it with a DSP (TIDSPCC5515), to implement digital cancellation.

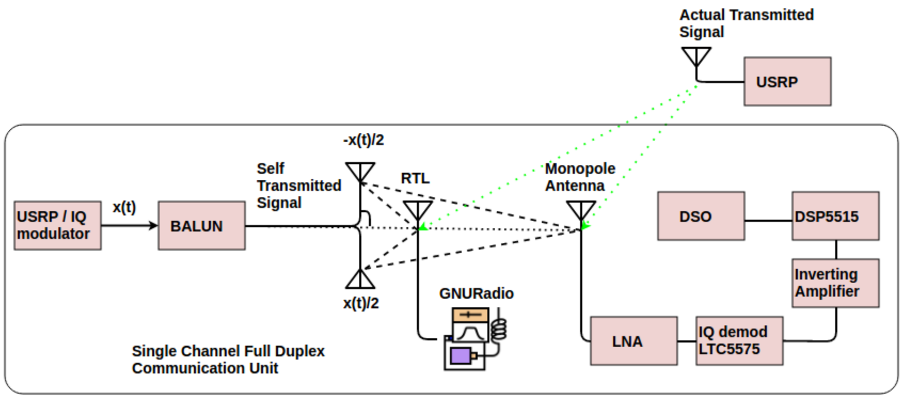
Note: We haven't implemented active analog cancellation due to lack of time and increased complexity of the algorithm. This is a challenging task and can be done as future work.

Modulation Technique : For our demo we have used Amplitude modulation as transmitters (USRPs and IQ modulators employ AM techniques only) However, this scheme is independent of the modulation technique as removing the self interference signal is our main goal which is done after demodulation.

4.1 Block diagram

The block diagram for our system is shown in Figure 3.
Overview: Our node generates a signal to be transmitted from the USRP/ IQ modulator. This signal is passed through a balun thus received two half power differential output signals which are fed to two antennas. This system perform analog passive cancellation. The signal received from the receiving antenna has a self interference component which has to be removed. This is demodulated and fed in the digital domain for further processing and finally we are able to observe the signal we intended to receive.

Figure 3: Block diagram for the proposed system

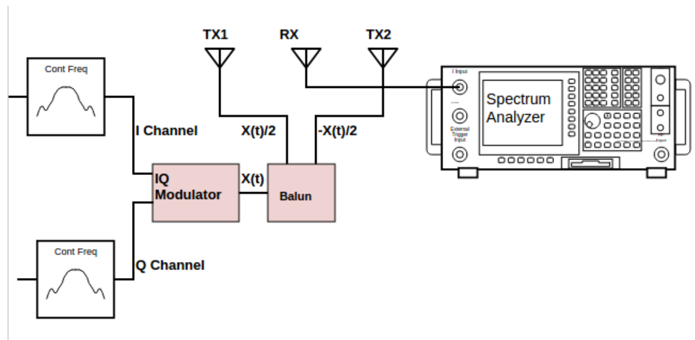


4.2 Components Required

- Monopole antennas (3)- centered around 1.1GHz (check maximum power delivered at which frequency using VNA , and operate at that frequency)
- 2 USRPs as transmitters. Host Laptops must be configured with appropriate USRP drivers.
- 1 RTL SDR dongle as receiving antenna
- GNUradio flowgraph with Custom cancellation block. Preferred version is anything above 3.7.2, and along with that, some extra libraries like (numpy)
- IQ demodulator board LT 5585
- Balun for frequency range upto 3GHz
- Low noise amplifier for 1.1GHz range
- DSP 5515 and aux cable for interfacing with the demodulator
- Signal Generator of GHz range, for LO input to the demodulator chip / Signal Hound generator
- Gain stages to amplify low frequency outputs
  - OPAMP 747
  - Appropriate Resistor Combination
  - +/- 5 V supply
  - High value Capacitors (0.47 F) to null out DC offset before amplification

PREFERRED FOR DEBUGGING OF COMPONENTS
Spectrum Analyzer , Vector Network Analyser

Figure 4: Block diagram for Passive Analog Cancellation



5 Project Implementation

We had implemented our system coupling passive analog cancellation and digital cancellation. One major technique used for self interference cancellation is analog active cancellation which hasn't been done here.

5.1 Passive Analog cancellation

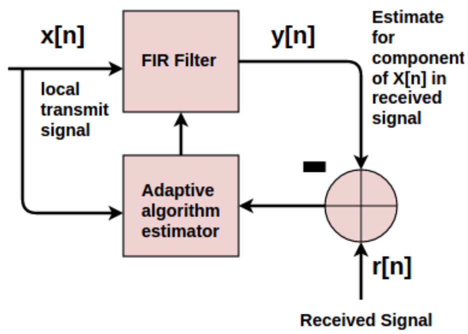
As explained in Chapter 2, there are two very similar methods to do analog cancellation. We tested both of them, and found the equi-distant approach much better, even though it introduces directionality in the system. We implemented the method using Balanced-Unbalanced Transformer (Balun). Balun converts single ended input, to differential ended output, what was needed exactly by us. Overview of setup is shown in Figure 4

We were not able to observe cancellation earlier, as the directivity of monopole antennas were centered at 1.25GHz and these also had low bandwidth,thus work best when transmitted at 1.25GHz. But, the IQ modulators were centered at 1.12 GHz. This was found by testing antennas via impedance matching upon suggestions of Prof. Shevgaonkar and Antenna Lab RA's, and was a critical factor which improved the design. After switching to carrier frequency of 1.25GHz using DIP switches onboard the IQ modulator, we were able to see good cancellation of the transmitted signal.

Since we are not doing active analog cancellation, we need to perform some amount of cancellation in analog domain to prevent the receiving signal to be buried under the strong self interference signal. Using stronger transmitting antennas can give a passive cancellation of close to 20dB and hence reduce the self interference signal drastically to prevent saturation of receiving antenna.

However this technique introduces directionality in this transmitter system. Points lying on the null regions of the two antennas (perpendicular bisector) will have strong destructive interference. Hence other nodes lying on these nulls might have decreased reception in the signal, in addition to attenuation loss due to distance. However since the null region is just on the perpendicular

Figure 5: Block diagram for Digital Cancellation



bisector, there is a very low chance of the node to lie exactly on the null point. On performing signal strength test (heat map shown later) we have observed that even slight movements away from the null can cause the signal strength to increase. Still the problem of directionality remains as points on the circle see different strengths based on the path differences of the 2 antennas

5.2 Digital Cancellation

5.2.1 Theory

The adaptive self-interference cancellation system (ASIC) based on digital adaptive filter is shown in Figure 5, which is proposed as a solution to remove the self-interference signal samples from the residual hybrid received signal in digital domain. Since the receiver is at such a short distance from the two transmitters, we do not expect there to be significant frequency offsets and delay at the receiver. For cancellation we employ a adaptive FIR filter based on the Least Mean Square (LMS) algorithm. A detailed proof is given below which describes why minimizing the mean square error of the local transmitted signal and demodulated signal gives the best removal of component of transmitted/self interference signal from the demodulated signal [2].

As per the block diagram above (figure 5), we have: The received signal,

$$r[n] = y_1[n] + y_2[n] + n[n]$$

where $y_2[n]$ is the desired received signal, n[n] is random additive noise and $y_1[n]$ is the self-interference signal. This self interference signal estimate is subtracted from the corrupted received signal in primary input, to produce an estimate of the desired received signal as the ASIC system output (say z[n]). In such system, a practical objective is to produce a system output that is the best fit in the least squares sense to the desired signal. This goal is completed by feeding the ASIC system output z[n] back to the adaptive filter and adjusting the filter coefficients through an adaptive algorithm to minimize total system output power. Thus we also have:

$$z[n] = y_1[n] + y_2[n] - y[n]$$

Taking Expectation of squares on both sides we get,

$$\begin{aligned} E(z^2[n]) &= E(y_2^2[n]) + E((y_1[n] - y[n])^2) + 2E(y_2[n](y_1[n] - y[n])) \\ &= \mathrm{E}(\mathrm{y}_2^2[n]) + E((y_1[n] - y[n])^2) \end{aligned}$$

$Since the signal power$ $\mathrm{E}(\mathrm{y}_2^2[n])$ is unaffected when the adaptive filter is adjusted. Therefore

$$\min E(z^2[n]) = E(y_2^2[n]) + \min E((y_1[n] - y[n])^2)$$

Hence minimizing the output signal in the least squared sense corresponds to minimizing the the component of self interference signal in the least squared sense We implemented two algorithms for achieving the "best" filter, that is the filter which gives the minimum mean square error. (i) Gradient Descent, (ii) The direct matrix-based solution. The target was to choose the faster algorithm since it was to be implemented on a DSP. A more detailed cost analysis is given below. Since the former is an iterative algorithm we expected that once it reaches the minimum it should take very small number of iterations to stay at the minimum. Further since (ii) also involves inverting a matrix, which is a costly operationO(n3), we expected gradient descent to work better/faster but a more detailed cost analysis and some experimentation indicated that latter method would work better. For the FIR filter we use the past 30 samples for prediction, that is, the length of FIR filter is 30.

The problem described above can be formulated as solving

$$r = Xh$$

The Gradient Descent update rule is (is the step size):

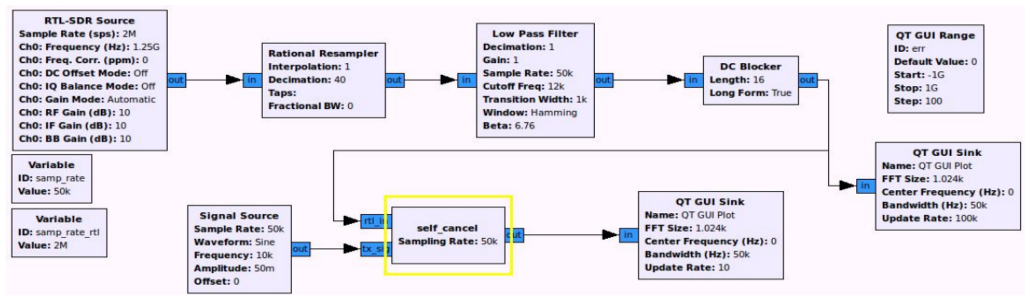
$$h^{(k+1)} = h^{(k)} - \epsilon.((X^T X)h^{(k)} - X^T r)$$

The least squares solution for this equation is:

$$h = (X^T X)^{-1} X^T r$$

The size of $X^T X$ is 30 x 30 as the size of FIR filter is 30. For inverting the matrix we use the Gauss-Jordan method. We now discuss the key differences in the computation costs of the two algorithms described above. It can be easily seen that a lot of computations are common to both the techniques which are: preparation of X, computation of $X^T X$, $X^T r$. However the key differences arise because the matrix based method computes an inverse of a 30 x 30 matrix which costs about 3000 operations (rough estimate, an operation is considered as a single addition/multiplication) whereas gradient descent computes product of $X^T X$ and h for each iteration which costs about 900 x (no of iterations). We found that for getting a reasonably low amount of error we have to allow at least 50-80 iterations. Thus the matrix based solution should work faster.

Figure 6: Block diagram for GNURadio Implementation



5.2.2 GNURadio Implementation: "Self-Cancel" Out of Tree (OOT) module

We created "Self-Cancel" Custom Block in GNURadio for implementing our cancellation algorithm. As any other OOT block, the frontend was in XML files, and signal processing implementation in python, compiled using CMake. The block has 2 inputs (rtl_sig, i.e. the received signal and tx_sig, i.e. the self transmitted signal), and one output, which is essentially the received signal minus the component of tx_sig present in it. The flowgraph followed by us is shown in Figure 6.

Algorithm implemented by our block is as described in 5.2.1. The block takes 2 inputs, the received signal through antenna and self transmitted signal. Here the self transmitted signal is the local pure signal(before modulation) which is made available to the receiver. On applying the filter to this signal we can estimate the effects due to channel and eliminate the self interference signal from the received signal by subtraction. This algorithm takes care of delay and amplitude offsets, thereby filtering out the signal with least error. Since we are using an FIR filter, a delay margin is provided (length of FIR filter) so that if samples received through the channel experience a delay, our algorithm would still work.

Computation Cost - Calculating matrices costs time of order of number of samples and since inverse is over a matrix of dimension of filter length (small), computation cost is not high. Moreover, Python has optimized libraries for matrix computations for the same. This performs remarkably well even if we send complicated signals like piano files (which have a spectrum over a range of frequencies). However this algorithm performs badly if any frequency offsets are introduced in the self interference signal. Even small changes in the frequency cause the algorithm to perform poorly. This is conceivable since we are performing linear estimation and frequency offsets cannot be handled in linear estimators. A offset of 5Hz can cause the cancellation to come down to as low as just 10 dB, whereas we are able to achieve over 50 dB cancellation in case of no offsets.

Using Costa's loop- Eliminate frequency offsets

Since there are frequency offsets in the receiving signal which change with time, we apply costa's loop for frequency error correction. Since major portion of the signal is self interference, the costas loop sees this signal and corrects frequency offset thus enabling us for cancellation in digital domain at the same frequency.
There are several non linearities introduced due to the components and hence further improvement on the algorithm can be done.

5.2.3 Implementation of Code on DSP

The DSP used by us was TI DSP 5515, and we coded up mostly in C, with some registers and functions borrowed from assembly commands. We used CCSv7 as the IDE for the board. The code's logical flow is almost the same as python code written for GNURadio framework. Notable differences in implementation were: (i) Usage of Aux port to get the self transmitted signal instead of hardcoding it (Using codec AIC3204 codec for the same). (ii) Usage of DMA registers so that no sample is dropped by the DSP.

However, due to limited memory available on DSP, we had to decrease memory usage by taking less samples at a time (thus, increasing the importance DMA PingPong functionality further), and writing minimal code for each operation. A further analysis of algorithm gives around 10^5 operations for the complete execution of algorithm (for prediction of 128 samples at a time). The DSP has an operating frequency of 100MHz which amounts to about 1-2 ms computation time and since we are sampling at a rate of 48kHz (128 samples in about 2.5 ms), we expect to be reasonably safe if we use two buffers of the DSP (DMA has double the length of buffer and thus acts like 2 buffers).

5.3 Design of interfacing PCB with Rx antenna

5.3.1 LT 5575 IQ demodulator

We have designed a PCB that performs IQ demodulation. For this purpose, we are using LT5575 chip that performs IQ demodulation. The chip requires an input RF signal and a local oscillator(LO) signal which it will use to demodulate the RF signal. Since our operating frequency is 1.25GHz (with IQ modulator antennas), and the IC is matched to 1.5 GHz, we need a matching network at both the RF and LO end to match the impedance to that of the antenna (50 Ω). The matching network was designed using "Smith Chart". We also found a good source for crosschecking matching network, and also employed some empirical iterative methods for the same, which surprisingly gave us very good results. Refer figure 7 and 8.

A few important things that were essential to the RF PCB design were :

- Thick RF tracks to ensure enough power flow of signal and prevent losses on the length of the track. These were taken care by calculating the microstrip impedance of a 1.6mm FR4 substrate ($\approx$ 3mm)

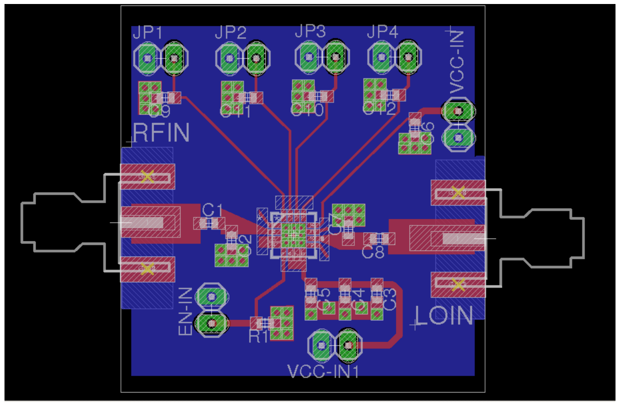


Figure 7: Eagle board view

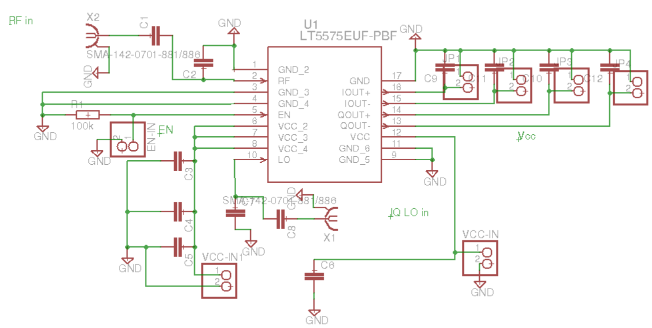


Figure 8: Eagle schematic

- Ensuring enough grounding of the thermal layer of the chip for effective functioning
- Using appropriate capacitance values for matching network, DC blocking and decoupling capacitors

The purpose of making a PCB for IQ demodulation was perform demodulation using an LO matched with the transmitted IQ modulator. Unfortunately due to some shortcomings and after detailed testing, we found that our chip isn't functional. The S_{11} parameter at both RF and LO ends came out to be 0db indicating full reflection and no transmission.

Hence we are using LTC5585 (with evaluation board) as our demodulator for down converting RF to baseband.

5.3.2 Using LTC5585 Evaluation Board

Since the designed PCB for LTC5575 didn't work out for us, we used LTC5585 Eval Board (from Comm'n Lab) as a backup. Although the datasheet mentions

Figure 9: Experimental setup for IQ demodulation DSP cancellation

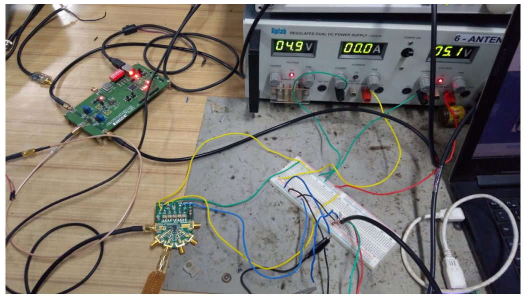
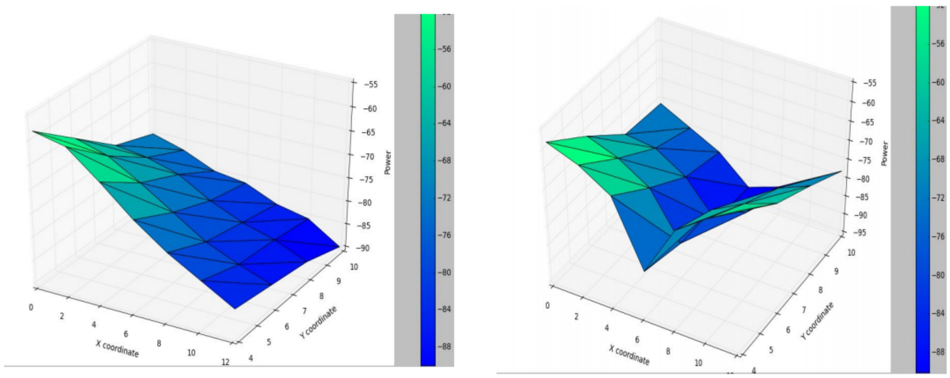


Figure 10: Apperance of harmonics after demodulation, caused due to IQ modulator boards

that it is ideal for usage of only wideband IQ messages (bandwidth¿ 530 MHz), while testing we found it working satisfactorily for smaller bandwidths of 10 kHz as well.

We also interfaced the evaluation board with DSP, and were able to observe input on the DSP. However, there are some issues like frequency offsets (between IQ modulator and LTC5585) of about 6 KHz, and appearing of various harmonics at demodulator output(Figure 10). Hence we switched to transmission using USRP's to get a more stable output waveform.

Figure 11: Results for Passive Analog Cancellation



6 Performance Evaluation

6.1 Evaluation of Passive Cancellation Techniques

Data : Receiver moved in the X-Y plane and plotted vs received power (in dBm) (z axis) Transmitters located at (0 cm,0 cm) and (12 cm,0 cm)
Figure 11 demonstrates:

- Power received due to one transmit antenna
- Power due to 2 transmit antennas with 2^{nd} antenna transmitting phase reversed signal

Two phenomena can be observed here:

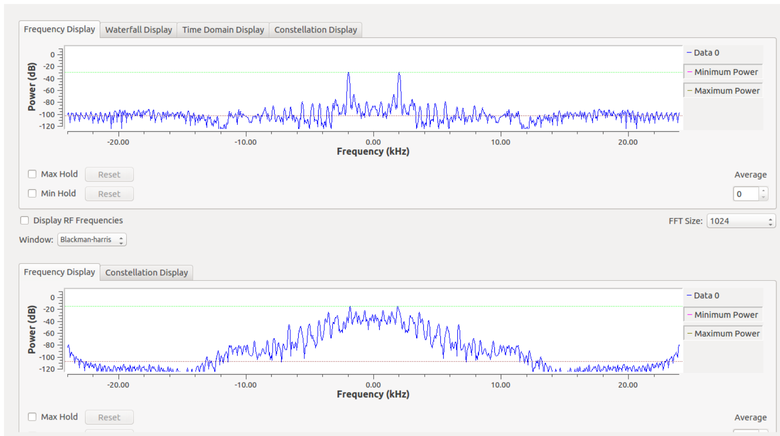
- Attenuation of transmitted signal with distance
- Self interference cancellation due to phase shifted signals

We can clearly see that there is maximum cancellation of self interference signal close to the line perpendicularly bisecting the 2 antennas. Hence we place the receiver here. We observe around 12 dBm cancellation using passive analog cancellation technique

6.2 Evaluation of Digital Cancellation on GNURadio and RTL-SDR

We sent a music signal (as self transmit message) and tried to receive a sinusoidal message (frequency 2 kHz) coming from third party. The top frame contains the output of the block made by us, it suppresses the music signal and gives the sinusoidal signal as the output. The below frame is the raw receiver output, which, as seen clear is clearly polluted due to self interference of the musical signal. This is shown in Figure 12.

Figure 12: Results for Digital Cancellation



6.3 Evaluation of USRP and RTL SDR receiver setup

Due to the reasons mentioned above, we used 2 USRP which transmitted sinusoidal messages (amplitude modulated) on a carrier of 1.1GHz and kept at a distance of around 15cm from the receiving antenna, while the third USRP, which transmitted the "target" signal was kept at a distance of about 1.5m.

At the receiving antenna we observed around 25dB cancellation due to passive analog cancellation. Further we got around 6dB additional cancellation due to digital algorithms. Since there are time varying frequency offsets, a linear filter cannot detect offsets in frequencies and hence the amount of cancellation achieved is much less. If the frequencies are matched we get around 80dB digital cancellation and even if there is a 10Hz offset, we are able to achieve only 10dB digital cancellation. Here, we were able to receive the signal properly as a total of 31 dB cancellation is seen(passive +digital) which reduced the self interference signal to a reasonably lower level than the signal from the third transmitter (around 15-20 dB).

The implementation of digital cancellation can be improved by using costas loop for frequency error correction. We had tried it but we did not find sufficient time to characterize the results systematically.

7 Conclusion and Future Work

In conclusion we have attempted to implement a single channel full duplex wireless communication system (analog). Even though we did not exactly cross the desired mark of cancellation we had set, we got very close to it and at least demonstrated the possibility of such a system and the exciting new challenges it brings. We have used 2 of the 3 most common existing signal cancellation techniques for this in this area of research: Passive Analog Cancellation (Antenna Placement) and Digital Cancellation. Although we have achieved a reasonable amount of cancellation using these two techniques, we are far from implementing this system in a form wherein it can be used in a real communication system. A lot more amount of cancellation is required (at least 40 dB more) which can be achieved by implementing the most effective of the three techniques: Active Analog Cancellation. This technique provides the maximum cancellation but is also the most difficult one of them to implement, So the natural next step towards it's realization would be to implement Active Analog Cancellation. We also hope that in future, the demodulating circuit be prepared more cleanly and in advance since it involves understanding a lot of non-trivial elements.

References

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