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CSE 591 November Rotation, under the supervision of Neil Patwari

Introduction

The problem at hand involved censoring the output of a time-shared software-defined radio (SDR). By inserting a probe between the radio and the antenna, we can monitor what frequencies users are using the SDR at, and if they are using illegal bands, their hardware would get shut down. One problem regards false positives. Since the antenna can pick up noise and interference from the outside environment and transmit it back down into the probe, the user may be accused of broadcasting at disallowed frequencies, especially since a few of the radios in this project are extremely close to one of AT&T's LTE towers.

Bidirectional Coupler and Signal Reconstruction

The proposed solution is to use a bidirectional coupler for the probe (see below). Signals going in backwards will be significantly attenuated, so the signal measured at R_{x1} will be noticeably different than at R_{x2}.

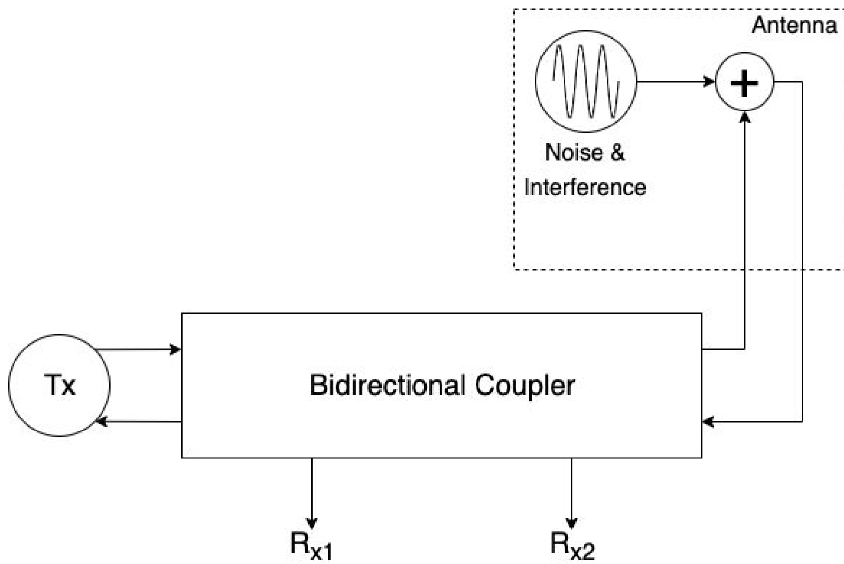

Fig 1.

A formula can be derived such that the inputs from the Tx and the antenna interference/reflections could be multiplied by a 2x2 transform matrix to calculate the outputs at Rx1 and Rx2. Others in the project measure these values experimentally.

$$\begin{bmatrix} f \\ n \end{bmatrix} \begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} R_{x1} \\ R_{x2} \end{bmatrix}$$

Fig 2.

The input for Tx (*f*) is the signal coming out of the SDR. The input for the antenna (*n*) is reflections down the antenna, combined with ambient noise or deliberate interference picked up from the environment. Eliminating the noise and solving for *f*, we have a formula to reconstruct the signal from R_{x1} and R_{x2}.

$$f = \frac{DR_{x1} - BR_{x2}}{AD - BC}$$

Fig 3.

The frequency graph below shows a typical representation of all the signals above, assuming *A, B, C, D* aren't measured perfectly. The peak is the intended signal to transmit, most of its bandwidth in the 3.6GHz CBRS band. R_{x2}, in green, being closer to the noise source, is almost entirely noise. R_{x1}, on the other hand is often so similar to the original signal, no reconstruction is warranted. This example uses noise that is 10dB more than the transmission, so significant noise is seen on Rx1, but that is merely illustrative and not indicative of typical situations.

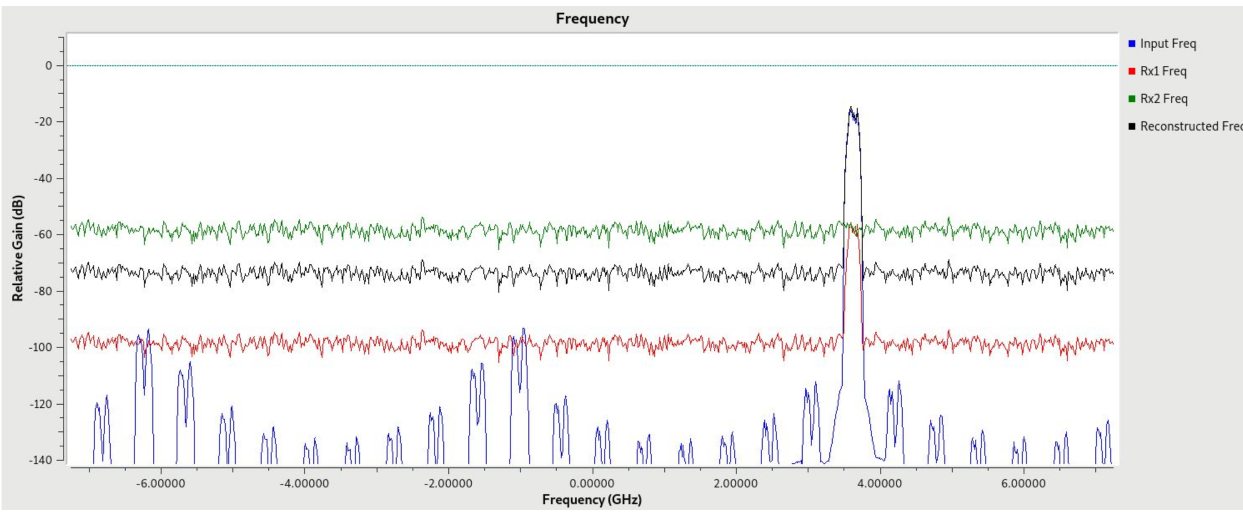

Fig 4.

<u>Properties of Bidirectional Couplers</u>

Now that we've simplified the problem somewhat, it's time to complicate it. The previous amplifier diagram abstracts away some characteristics of the coupler, notably directivity and return loss of the receive ports themselves. All these properties are documented in the coupler's datasheet. Table from an example coupler can be seen below.

Typical Performance Data

Frequency (MHz)	Mainline Loss (dB)	Coupling (dB)		Directivity (dB)		Return Loss (dB)			
	In-Out	In-Cpl Fwd	Out-Cpl Rev	Out-Cpl Fwd	In-Cpl Rev	In	Out	Cpl Fwd	Cpl Rev
700.00	0.07	23.45	23.45	27.55	27.50	34.81	34.65	33.64	33.85
800.00	0.07	22.41	22.41	27.34	27.33	32.60	32.55	31.58	31.93
1000.00	0.09	20.85	20.86	26.91	27.33	29.85	29.89	29.17	29.13
1100.00	0.10	20.24	20.25	26.77	27.44	29.14	29.39	28.78	28.99
1300.00	0.12	19.29	19.29	26.66	27.95	28.17	28.04	27.88	28.11
1500.00	0.16	18.72	18.71	26.90	28.73	29.02	29.00	30.31	30.70
1700.00	0.18	18.26	18.24	27.53	29.85	31.79	32.85	40.91	40.80
2000.00	0.16	18.13	18.11	26.08	27.79	41.10	43.50	31.19	30.29
2200.00	0.13	18.33	18.32	22.74	23.99	33.31	33.65	24.74	24.89
2500.00	0.20	19.29	19.29	18.56	19.52	27.08	27.97	22.95	23.50

Fig 5.

Mainline loss is the attenuation from the input to the output of the coupler.
Coupling is the attenuation from either the input or the output to its closest coupling port.
Directivity is the attenuation from either the input or the output to its opposite coupling. This is measured in proportion to the coupling attenuation of that port.
Return loss is the attenuation at a port when a signal is broadcast into that same port, assuming no ports are terminated and are allowed to naturally reflect.

Below is the updated schematic for the bidirectional coupler, along with typical values of the attenuators, according to the datasheet. τ is meant to be the attenuation within the antenna.

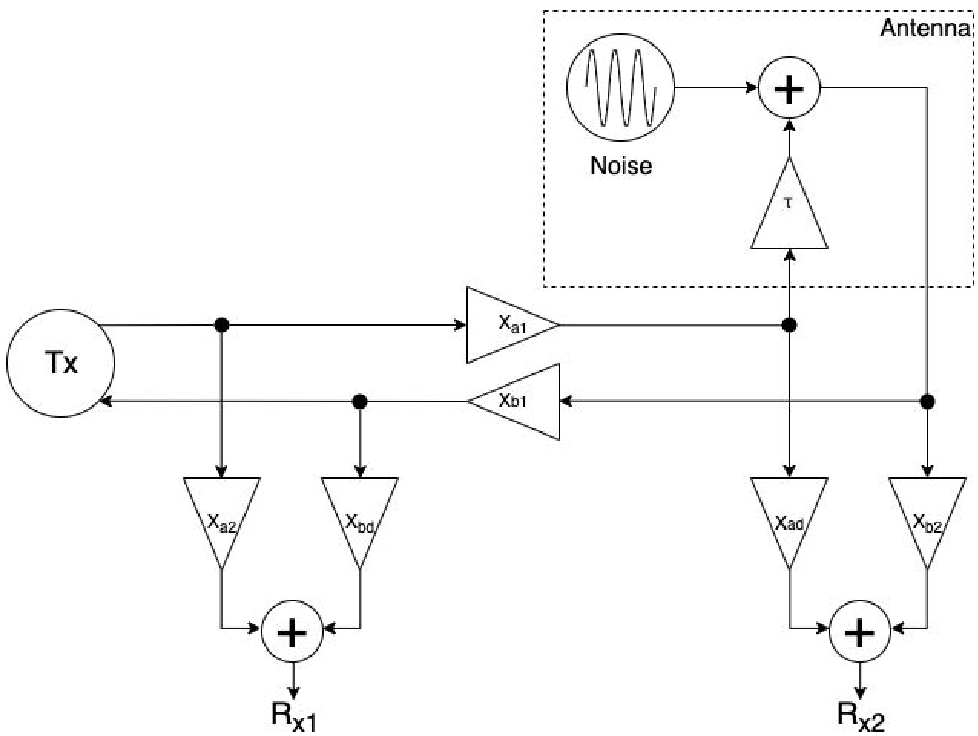

Fig 6.

Variable	Value		Variable	Value
X_{a1}	0.953		X_{b1}	0.00105
X_{s2}	0.01		X_{b2}	0.01
X_{ad}	0.000105		X_{bd}	0.095
τ	0.1			

Fig 7.

It's important to note that since the attenuation increases for lower frequencies, the spread between R_{x1} and R_{x2} would also increase for noise at lower frequencies. This observation will be disregarded for the remainder of this paper.

Incorporating Bidirectional Coupler Properties into Calibration Matrix

My first task was to calculate ballpark figures for the *ABCD* matrix mentioned before. These will be calculated experimentally, so approximations are sufficient to provide insight into how the matrix functions. To that end, I'm going to ignore the fact the forward and reverse variants for both coupling and directivity, since a difference of 1dB does not justify complicating the math.

$$\begin{bmatrix} f \\ n \end{bmatrix} \begin{bmatrix} X_{a2}+X_{a1}X_{bd}X_{b1}\tau & X_{b1}X_{bd} \\ X_{a1}(X_{ad}+X_{b2}\tau) & X_{b2} \end{bmatrix} = \begin{bmatrix} R_{x1} \\ R_{x2} \end{bmatrix}$$

Fig 8.

Assuming the values of the calibration matrix are calculated perfectly, the original function can be flawlessly reconstructed regardless of noise. However, imperfections in measuring this matrix can cause noise to leak through to the reconstructed signal. Not all values in the matrix play an equal role in this, so it's more important to get certain ones right, and others are negligible.

After visual inspection of fig 3, I hypothesize that only *B* and *D* should contribute to noise leaking through to the reconstructed signal, since they are the coefficients of R_{x1} and R_{x2}. Calculating approximate values for the matrix using figs 6 and 7 show that the *BC* term is 3 orders of magnitude smaller than *AD*, so it's reasonable to conclude that *C* has next to no impact on the reconstructed formula, unless it is wildly miscalculated.

Simulating Bidirection Coupler

I used Gnuradio companion to simulate a signal being transmitted through a bidrectional coupler, added to interference in the antenna, and reflected back through the coupler. First, to construct the transmitted signal. I am going to assume the intended signal is being broadcast in the CBRS band, 3.55-3.7 GHz. Therefore the carrier wave is 3.625GHz, our bandwidth if 150MHz, and the sample rate of the gnuradio schematic should be at least 7.25GHz. A quadrature phase modulator will produce our signal wave, which should be no more than 75MHz, or one-half of the 150MHz bandwidth. This message signal will eventually be multiplied by the carrier wave, so the sample rate has to match. By interpolating in extra samples per symbol, I can make the 75MHz signal match the 7.25GHz sample rate. Only issue is the latter is not a clean multiple of the former, so I'm going to adjust it to be 72.5MHz. 100 samples per symbol will make 75MHz signal sampled at 7.25GHz. A random byte source will be fed into the quadrature phase modulator to simulate an unknown data stream.

A series of multipliers serve as the matrix of attenuators seen in fig 5. The noise is simulated with a gaussian generator that is added to the couplers output before being sent back through.

Simulations

Simulations were run where a random message in the 3.6GHz CBRS band was transmitted through the GNUradio setup described above, and the signal was reconstructed, possibly with erroneous values of *A, B, C, and D*. LTE Band 7 (2.6 GHz) was chosen as the “illegal” band to monitor. The magnitude of this band was measured in the reconstructed signal. If it’s too high, this signals us to shut down the user’s equipment under the assumption they are broadcasting in that band.

The first set of experiments measured how each parameter fared by itself against an increasing amount of noise.

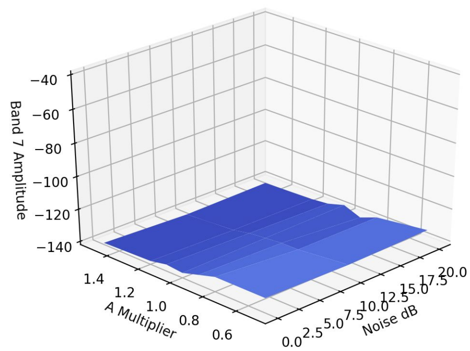

Fig 9. A and Noise

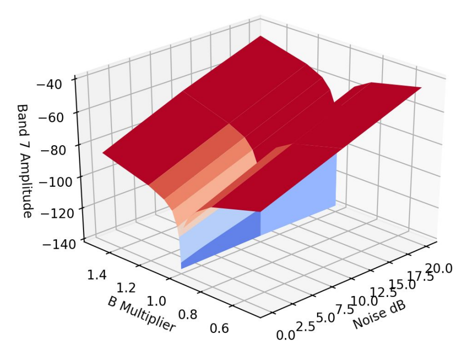

Fig 10. B and Noise

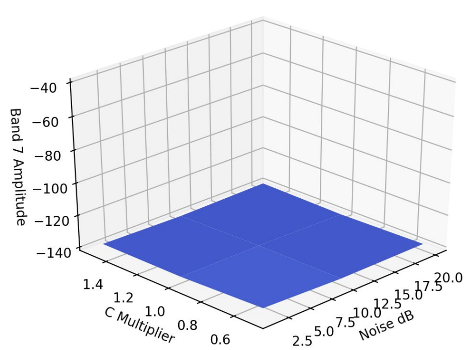

Fig 11. C and Noise

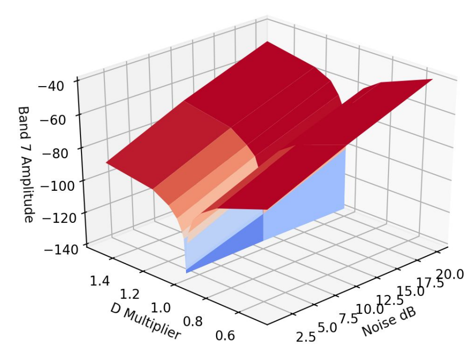

Fig 12. D and Noise

The next set of experiments sought to measure how different parameters interact with each other. *B* was measured against *D*, since these are the two coefficients for R_{x1} and R_{x2}. We also have *A* vs *D* and *B* vs *C*, since each of those pairs are multiplied in the denominator of the reconstruction formula.

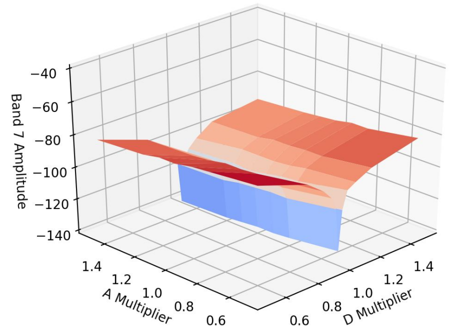

Fig 13. A and D

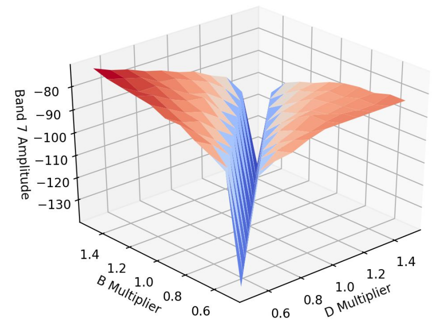

Fig 14. B and D

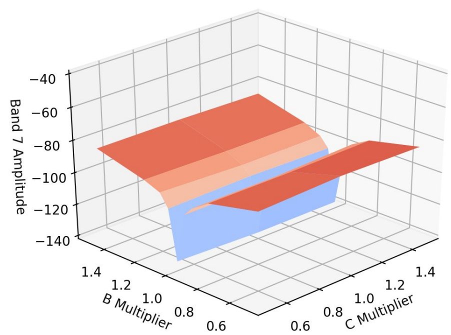

Fig 15. B and C

<u>Conclusion</u>

As predicted, only *B* and *D* allow noise to leak through. *A* merely contributes to the magnitude of the reconstructed signal. Since the *BC* term is typically 3 orders of magnitude smaller than *AD*, the *C* term is practically negligible. The interesting finding was that errors in measuring *B* and *D* can cancel out, assuming the error is in the same direction. Even if they are overestimated by 50%, as long as they are both overestimated by 50%, a near-perfect signal can still be reconstructed.

I measured noise that was 20dB, or 100x stronger than the intended transmitted signal. Accounting this contingency is very unrealistic. Even the strongest deliberate interference will be received at -20dB, so I will focus on the 0db noise data points for my conclusions.

I propose a noise threshold at -100dB. That is, if the reconstructed signal sees illegal frequencies being broadcast at -100dB or stronger, the user's equipment is shut down, even if the user wasn't actually transmitting those signals. To eliminate those false positives, I propose the following tolerances on the calibration parameters:

A	±20%
B	±4%
C	±1000%
D	±4%

Fig 13.

If we cannot guarantee measurements within these ranges, there remains the possibility that users will be unjustifiably punished, because our system is unable to discern whether an illegal frequency is coming from within or without.