Combining filters and self-interference cancellation for mixer-first receivers in Full Duplex and Frequency-Division Duplex transceiver systems

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***Abstract* -- When combining transmitters and receivers on the same chips interference between the channels is a major problem. Channel isolation is limited, which means that other ways have to be used to reduce the influence of the transmitter on the receiver. This research proposes a system which combines cross-coupled switch-RC mixer-filters and self-interference cancellation which can be used in Full Duplex (FD) and Frequency Division Duplex (FDD) that achieves 50 dB Tx signal rejection in the receiver for a bandwidth of 2MHz.**

1) INTRODUCTION

Previous research rejected the Tx signal in the receiver by self-interference cancellation of the signal for Full Duplex (FD) systems and filters for Frequency-Division Duplex (FDD) systems. This research combines both methods to see if improvements can be achieved when the system is used in FD, FDD or in FDD with a small frequency division. Having a system that works in both FD and FDD has significant benefits. FD has the benefit that it cuts the required bandwidth in half while having the same performance, but it is not implemented widely yet. FD has to be used on both sides in many cases, which is problematic if FD is not widely implemented. It is therefore very useful to be able to fall back on FDD, because that is widely supported. Having a system that can do FD and FDD on the same chip can help with the early adopter problems.

Previous research made a cross-coupled switch-RC mixing receiver that can do the filtering part.[1] This circuit does not contain any self-cancellation, but it has a connection to which a self-cancellation path can be connected. This allows for easy testing of what improvements can be achieved by including a self-interference cancellation path. This paper researches how self-interference cancellation should be implemented and what improvements can be made on Tx signal rejection.

This leads to the following research questions:

- How much dB improvement can be achieved on Tx signal rejection in Rx by adding a self-cancellation path to a cross-coupled switch-RC mixer-first receiver when used in FD, FDD or FDD with small frequency separation?
- How should such a self-cancellation path be made and how should this path be tuned in order to get maximum Tx signal rejection?
  - What is the influence of the phase shift from a cross-coupled switch-RC filter on the maximum achievable Tx rejection?
  - How should a phase shift in the cancellation path be tuned?
  - Does adding a cross-coupled switch-RC filter to the self-cancellation path give improvements on Tx signal rejection?

2) PROBLEM ANALYSIS

A) Full Duplex

A new method in transceiver systems is Full Duplex (FD). This method was previously believed to be too difficult to implement, because it requires extreme isolation between transmitter and receiver. The only way to transmit at one channel was thought to be Half Duplex. The theoretical benefit of Full Duplex is that it cuts the required spectrum in the same while doubling the performance. This is very significant in a world where the radio frequency is very crowded and where performance requirements are getting higher and higher.

B) Using Self-Interference Cancellation

Recently research has proven that Full Duplex is possible, contrary to what was thought before. The key component in making Full Duplex possible is self-cancellation of the Tx signal. In order to get perfect cancellation both attenuation and the delay of the signal through the cancellation path have to match the signal through the interference path. This has been done before using programmable attenuators and delay lines. [2] This method works quite well, but it is difficult to scale down and it is not very energy efficient. Delay lines take up a lot of space and need a specified length for a certain delay. This is why other research solved this by using a vector modulator.[3] This research will look if this approach is still viable when there is a cross-coupled switch-RC in the Rx path.

In the antenna path a circulator is used. A circulator is a 3-port device which transmits the signal from Tx to the antenna and from the antenna to Rx, but not from Tx to Rx. This makes it possible to use a single antenna. The isolation between Tx and Rx is 15-20 dB for off-chip circulators.

If a signal has to be cancelled over a certain bandwidth, the signal through the cancellation path should have the same attenuation as the signal through the antenna path, but also the same delay. There are multiple ways through which the Tx signal can leak into the Rx path. The most significant path is through the circulator at -15 dB. Other paths can be mutual inductance between wires and reflection of the signal that is picked up by the antenna again. Especially the last way can be difficult to deal with, since there are many reflections possible, with each a different attenuation and delay, which will also change when moving around with the system. Luckily the interference through mutual induction and environment are much smaller than the signal leakage through the circulator, which means it can be ignored. This means that the complete interference Tx signal can be modelled as a 2 MHz band with a single and constant attenuation + delay.

As mentioned before, delay lines take too much space and consume too much power. This is why a solution with an attenuator and a downmixer is chosen. It is more feasible to use, but it will give a certain phase error. The phase from the cancellation path is frequency independent, while a delay gives a phase shift that increases linearly with frequency. This phase error causes a residual Tx signal after cancellation that increases linearly with both distance from the optimal cancellation frequency and delay in the wires τ.

C) Combining Self-Interference Cancellation and Filtering

Adding a filter to the system improves the Tx rejection outside the Rx band. This means that the system can also be used in FDD. It is also much more robust to out-of-band interferers that are not generated by the Tx. The design using a cross-coupled switch-RC mixer-filter is used in this design. This system can be seen as a 4-phase mixer followed by a first order low-pass filter for all relevant properties in this research.

This filter can give certain problems. If the signal coming from the circulator is filtered and the signal through the self-cancellation path is not, out-of-band signals produced by non-linearities and intermodulation products in the power amplifier and mixer will pass through the self-cancellation path into the Rx, while those signals would be cancelled if the filter would not be present. This means that requirements for linearity of the power amplifier and mixers go up if there is a filter in the Rx path.

Another potential major problem is the phase shift caused by the cross-coupled switch-RC filter in the Rx path. At the center frequency the phase shift of the filter is 0, so cancellation is still perfect. At the cut-off frequency the phase shift of the signal through the circulator will be 45 degrees, so the cancellation is not working well. Additionally, the amplitude of the signals does not match as well.

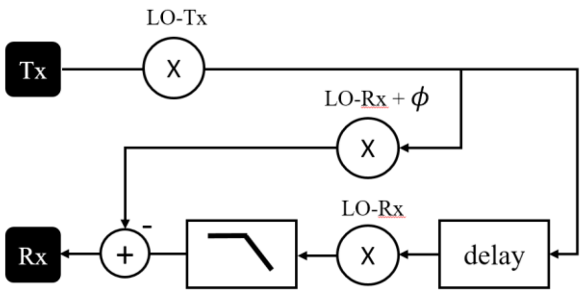

figure 1: cancellation with filter in circulator path

When describing the system in figure 1 mathematically, it appears that the cancellation behaves as a high-pass filter for the Tx signal. It has perfect cancellation at the center frequency, but it degrades very quickly. The only influence of the mixers on the systems is that it phase shifts the signal with $LO_{RX}*\tau$. This has to be compensated for with a phase shift in the cancellation path.

$$\mathrm{Rx} = e^{-j\phi} - \frac{1}{1+j\omega RC} e^{-jw\tau} \quad (1)$$

$$|\mathrm{Rx}| = \frac{\omega RC}{\sqrt{1+\omega^2R^2C^2}} \; for\ \phi = \tau * LO_{Rx} \qquad (2)$$

The system is tested at a few different options for the optimal point of cancellation. As can be seen in figure 2, cancellation is very good at the frequency it is tuned to, but it falls off very quickly. ϕ is set to τ*(LO_{Rx} + ω_{tuning})

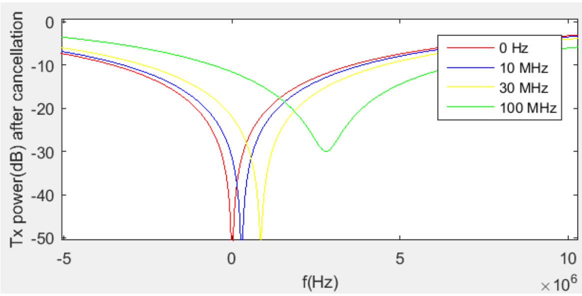

figure 2: plot of Tx power in Rx with cancellation optimally tuned for different values for ω_{tuning}

A solution for the quick fall-off of the cancellation is adding the same filter in the self-cancellation path as well. This will filter the out-of-band signals generated by non-linearities in Tx, so the cancellation of those signals works much better. It also gives a phase shift in the self-cancellation path which equals the phase shift caused by the filter in the Rx path. In short: it compensates for the effect of the filter in the Rx path.

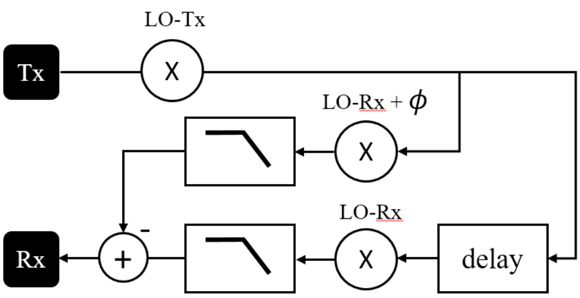

figure 3: filter in both paths

When describing the system in figure 3, it shows some interesting results.

$$\mathrm{Rx} = \frac{1}{1+j\omega RC} e^{-j\phi} - \frac{1}{1+j\omega RC} e^{-j(w+LO_{Rx})\tau} \qquad (3)$$

$$|\mathrm{Rx}| = \frac{2\left|\sin\left(\frac{w\tau}{2}\right)\right|}{\sqrt{1+\omega^2R^2C^2}} \; for\ \phi = LO_{Rx} \qquad (4)$$

This method works much better. It still gives perfect cancellation at 0 Hz, but it goes to an asymptotic value of τ/RC instead of 1. This is plotted in figure 4. It is possible to change the position of the notch by changing the phase shift of the

When a total difference in wire length between the cancellation path and the path via the circulator is estimated to be 10 cm and a velocity factor of 0.8 is chosen, the total delay caused by the wires is 420 ps. The cut-off frequency of the filters is set to 8e6 Hz, according to the specifications of the cross-coupled switch-RC mixers.

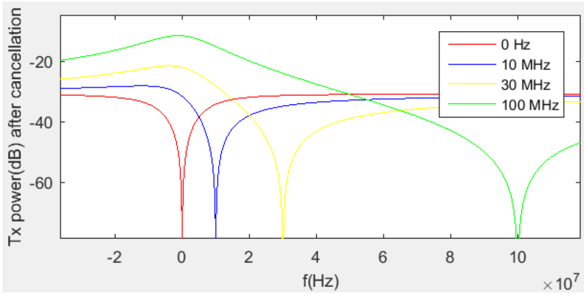

figure 4: plot of Tx power in Rx with cancellation optimally tuned for different values for ω_{tuning}

D) Proposed Design

Based on the theoretical analysis, the best implementation for adding self-cancellation to a receiver with a cross-coupled switch-RC mixer-filter is adding the same mixer-filter to the self-cancellation path. For the chosen delay and cut-off frequency the Tx rejection is about 30 dB better than the system with only a filter in the circulator path. The downmixers in both paths share the same Local Oscillator (LO_{Rx}), while the upmixer uses a different LO-Tx. For using in Full Duplex LO_{Tx} and LO_{Rx} are the same. The phase of LO_{Rx} in the cancellation path is variable, so it can be tuned for the optimal cancellation frequency. This can be done using a phase shift in LO_{Rx} or by implementing a vector modulator. For this system a phase shift in the local oscillator is used, since it is easier to implement for measurements, but both methods are equivalent in working. The system uses a single antenna with a circulator to isolate Tx from Rx. The worst-case isolation is only 15 dB. To compensate for the attenuation in the circulator the self-cancellation path also has an attenuator. The system design can be found in figure 5.

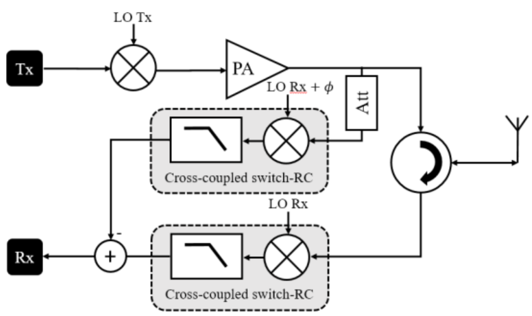

figure 5: proposed design

Summary of Specifications of the System and Corresponding Measurement Results				
		specifications		measurement results
		requirements	comments	
System Definition	Tx output power	-20 dBm		- 20 dBm
	Tx LO frequency	300 - 400 MHz	FD to FDD	300 - 400 MHz
	Rx LO frequency	600 MHz		600 MHz
	Filter bandwidth BW	8 MHz		11 MHz
Tx Rejection	circulator isolation	15 dB		not implemented
	Analog Cancellation	- inf dB		- 45 dB max
	Digital Cancellation	50 dB		not implemented
	Circulator Path Delay	420 ps		± 500 ps

table 1: specifications of the system

3) Simulations and Measurements

A) Test Cases

The system is simulated and tested to verify the theory. 3 cases are compared:

1) No cancellation is used. The filter in the circulator path is there. This case is used to compare how much dB Tx rejection is achieved by adding a self-cancellation path.
2) A cancellation path is added with a filter. This method is expected to give the best results based on the theory.

Table 1 shows the specifications of the system. The circulator is replaced by an attenuator, because circulators for 300-400 MHz are really expensive. The only thing the circulator is used for is an attenuation of 15 dB, so a 15 dB attenuator can be used just as fine. The main difference is that the attenuation of a circulator is not frequency independent and an attenuator is frequency independent. This should not matter when a small bandwidth is used. Since both paths use the same attenuator, both attenuators can be left away completely just as well. The Tx output power is -20 dBm, but for measurements and simulation no attenuator was used. This means that the system is equivalent to a system with a Tx power of -5 dBm when circulator and attenuator were used. To get the influence of the Tx down to the noise floor another 110 dB Tx rejection is needed with cancellation. Digital cancellation can do 50 dB, so the analog filtering and cancellation has to be 60 dB.

B) Simulations

From the system a Simulink model is made, as in figure 6. This model has an I and Q input that lead into a 4-phase mixer. The signal then goes to the circulator path, which consists of a delay and attenuation, and the cancellation path, which only has attenuation. Both paths are then mixed down, split in I and Q, and filtered with a first order filter. The signals from the cancellation path are then subtracted from the circulator path. Next the output signal power is calculated and compared to the input power. The input for I and Q is a DC signal with amplitude 1. For the simulation the attenuation of the circulator is set to 1, because in that way it is possible to directly calculate cancellation.

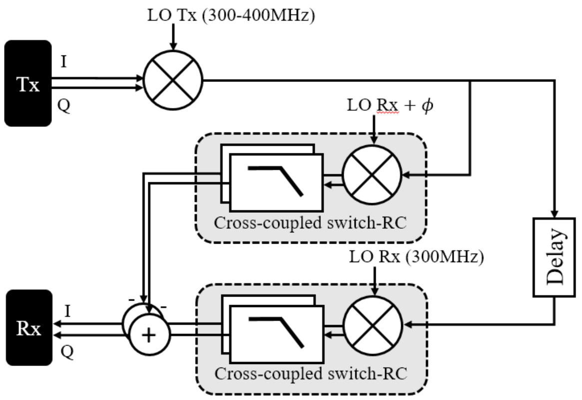

figure 6: Simulink model layout

First the situation without cancellation was simulated. The behaviour should be like a low-pass filter with a cut-off frequency of 8 MHz. The simulation results can be found in figure 7. The difference in power is caused by using mixers, because they only transmit the I respectively Q signal half of the time. This will then also reduce the signal power compared to theory. It is difficult to simulate the system for small frequency separation, because the simulation time will be significantly longer. That is why only 0 Hz and 1 MHz and above are simulated.

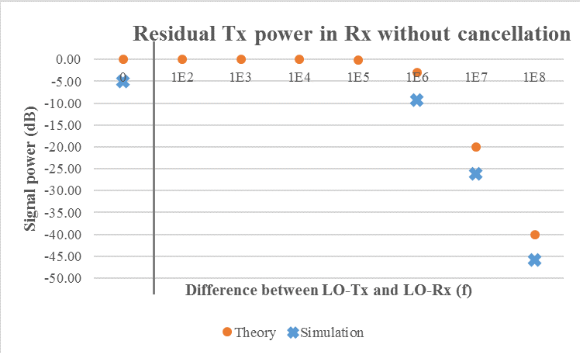

figure 7

The next simulation shows the system with filters in both paths. The outcome can be found in figure 8. The cancellation path is tuned for perfect cancellation. (ω_{tuning} = 0 Hz). The performance of this system is close to the theoretical analysis.

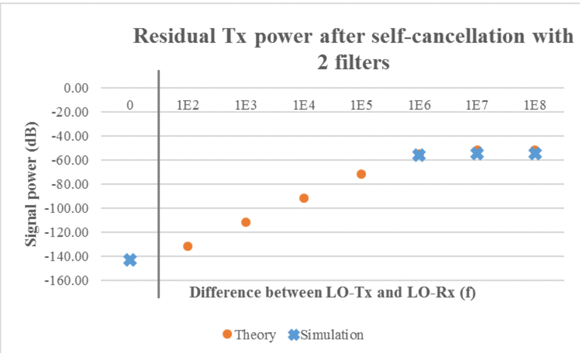

figure 8

C) Measurements

The performance of the design was verified using the measurement setup in figure 9. The RF signal is generated using a signal generator. This frequency is variable and is used to let the system operate in FD and FDD and to test the bandwidth. It is made sure that the antenna path is connected to 10 cm more cable than the attenuator in the cancellation path, to create the expected delay. For the receiver circuits in both the circulator path and the cancellation path the cross-coupled switch-RC mixer-filter is used from the Westerveld paper.[1] They are connected to the same LO_{Rx}, but the LO_{Rx} in the antenna path is phase shifted. The output is then connected to a spectrum analyser to measure the signal strength that is left from Tx. The receiver circuits use a clock divider, so LO_{Rx} has to be at 600 MHz

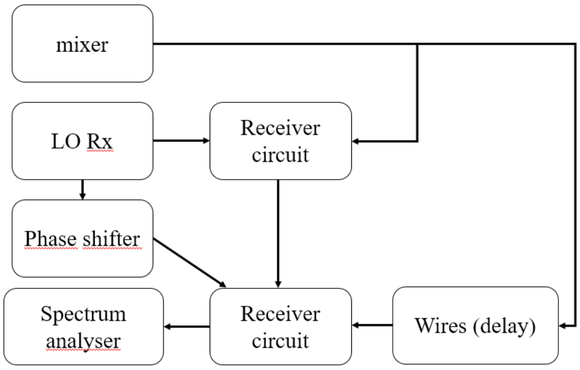

figure 9: measurement setup

4 situations for Tx-Rx separation are chosen: Full Duplex, 10 MHz, 30 MHz and 100 MHz separation. For each version the phase in LO_{Rx} is optimally tuned, after which measurements are done around that frequency to determine how the system behaves for this setting. The output of those measurements are plotted in figure 10, with the dots being the measurements and the lines being the theory.

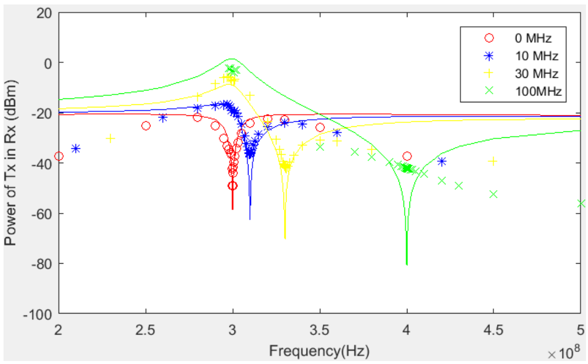

figure 10: measurements versus theory

The theory and measurements line up quite well, but the measurement results appear to be filtered much more. This can be due to filtering of the baseband signal. If a 1th order filter is added with a cut-off frequency of 40 MHz and a 2nd order low-pass filter with a cut-off frequency of 100 MHz are used in the theoretical plot, the results line up much better, as can be seen in figure 11. Those cut-off frequencies are experimentally found for the cross-coupled switch-RC mixer-filter chip.

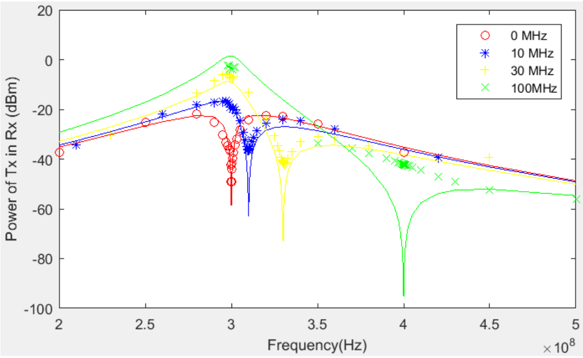

figure 11: measurements versus theory with additional filtering

The measurement results in the notch of the cancellation are not as low as the theory. This is most likely due to mismatch between signal power of the cancellation path and the antenna path, which leaves a residual Tx signal.

4) CONCLUSION

This paper presented a method for Tx signal cancellation that achieves 45 dB signal cancellation for FD and 30 – 40 dB cancellation for FDD when used for a 2 MHz bandwidth. It can therefore be used in both FD and FDD, which makes it compatible with existing systems.

The maximum performance of the cancellation is very sensitive to matching of the output power of the cancellation path and the antenna path. When this is perfectly matched, the cancellation in the notches can be even higher.

Together with the isolation of the circulator of 15 dB a total Tx signal rejection of 45 – 50 dB for FD and FDD can be achieved for a bandwidth of 2 MHz. When digital cancellation of 50 dB is implemented, the total Tx rejection can be as high as 100 dB, which is enough to reduce the Tx influence to noise floor level in Full Duplex.

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