An Adaptive Spatial Blocker Cancellation Receiver for Multiple Antenna Systems

Rudraneil Saha, *Student member, IEEE,* and Anthony Chan Carusone, *Fellow, IEEE,*

Department of Electrical and Computer Engineering, University of Toronto, Toronto, Canada

***Abstract*—Whereas previous architectures for spatial blocker cancellation were hindered by their scalability with the number of antennas leading to a high increase in the area and power consumption with the increase in the number of antennas, we propose a blocker cancellation technique that overcomes this by having linear complexity with the number of antennas, making it suitable for receivers with a large number of antennas. The proposed cancellation technique attenuates the blocker signals prior to the ADC relaxing its dynamic range requirement, while preserving the field-of-view (FoV) in each antenna element for subsequent digital beamforming/array signal processing.**

***Index Terms*—spatial blockers, adaptive blocker cancellation, beamforming, MIMO, field-of-view**

I. Introduction

WIRELESS communication is witnessing a rapid increase in the number of users and applications in recent years. Although mm-wave communication offers the potential for high bandwidth, it suffers from high spatial loss and its relatively high carrier frequencies are likely to imply additional power consumption. Alternatively, efficient reuse of lower-frequency spectrum is enabled by beamforming, using multi-input-multi-output (MIMO) receivers, including phased-array antennas. Phased arrays also find application in the development of sensors in self-driving vehicles.

Beamforming can be done in the analog front end of the receivers using phased arrays, but the result is a multiple-input-single-output (MISO) system that can focus the array in one direction at a time. To handle multiple signals from different directions, MIMO systems employ digital beamforming techniques including space-time array signal processing. These techniques can only be implemented digitally, thus requiring digitization of each antenna's signal. However, such systems are vulnerable to large-amplitude blockers which can saturate the receive signal paths prior to digitization. In many wireless communication systems, one of the most essential but demanding requirements is blocker cancellation. Blocker signals impinge on a receiver from sources other than the desired communication partner. To avoid saturation of the receive signal paths, an analog/mixed-signal technique is required to cancel the blockers while preserving all the other signals. Extensive research has been done to cancel blockers at frequencies different than that of the desired signals. This paper presents the cancellation of blockers at the same frequency as the desired signals but incident on the antenna array from different directions.

A spatial blocker cancellation technique that preserves the field of view (FoV), using beamformers and noise cancellation LNAs is reported in [1]. The main drawback of this architecture is its inability to handle more than one spatial blocker at a time and the noise injected by the directional couplers used. A baseband spatial notch filter was presented in [2], but was also limited to cancelling only one blocker signal. A spatial filtering technique for digital MIMO receiver arrays capable of handling multiple blockers at the same time was presented in [3]. It comprised a 2-D array of circuit elements performing spatial filtering. Thus the number of elements increased with the square of the number of antennas, making the complexity of the system quadratic with the number of antennas. A technique to cancel spatial blockers was proposed in [4] using analog beamformers with frequency domain multiplexing, which enabled the receiver to have only one ADC for any number of antennas. However, the number of baseband elements required increased with the square of the number of antennas making the system complexity quadratic. An architecture to estimate the angle of arrival of blockers on the fly and cancel it was published in [5]. A cascaded array based higher order spatial filters (ASFs) was used to cancel spatial blockers based on their power levels. Each cascaded ASF element was capable of cancelling only one blocker, so for the worst case scenario (consisting of the maximum number of spatial blockers), a large number of cascaded ASF elements are required, increasing the overall power and area consumption of the system.

This paper introduces a technique to detect and cancel multiple spatial blockers by creating a spatial notch filter in the receiver front end response at specific angles of incidence while otherwise preserving the FoV of the antennas to support digital beamforming and digital array processing techniques. This proposed technique uses digital signal processing to detect the angles of incidence of the blocker signals. Then, the Fourier relationship between the distance separating the antennas and the sine of the angles of incidence of the blockers is used to realize the desired spatial filter. In the resulting architecture, the number of circuit elements increase linearly with the antennas and no previous knowledge about the maximum possible number of blocker signals is required, making it suitable for MIMO receivers. The rest of this paper is organized as follows. Section II introduces the proposed technique and the architecture, Section III shows some behavioral simulation results, demonstrating the proof of concept. Section IV concludes the paper.

II. Proposed Technique and Architecture

The proposed technique for spatial blocker cancellation has three components: the determination of the angles of incidence (AoI) of the blocker signals; setting the proper filtering coefficients to extract the blocker signals; and finally cancelling them. This section is divided into three subsections which describe each of these components.

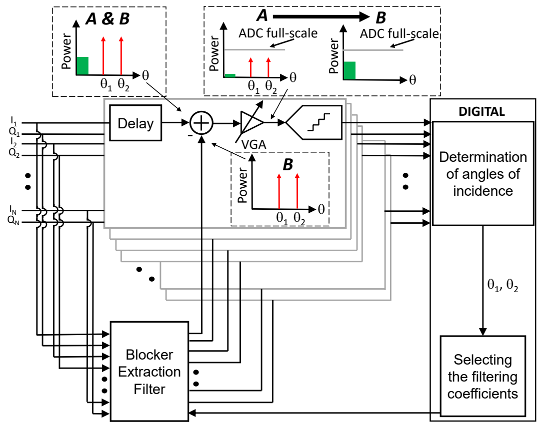

Fig. 1: Detection of the angles of incidence and the cancellation of the blockers.

A. Detection of the angles of incidence of the blocker signals

The proposed method to detect spatial blocker signals is similar to that used for frequency-domain blockers in [6]. When a large blocker is present, the ADC gets saturated, and the ADC outputs are at their maximum absolute values most of the time. This criteria is used for detecting the presence of the blocker signals in real time while the ADCs are operating.
If blocker signals are present and the ADCs are saturated, the next step is to determine their angles of incidence. First the gains of the analog front ends before the ADCs are reduced so that the ADCs come out of saturation. We can then use established digital signal processing algorithms such as the Multiple Signal Classification (MUSIC) method [7] (which is used in this paper) to determine the angles of incidence of the blocker signals, θ_1 and θ_2. Fig. 1 shows a block diagram where the signal of interest is green and the blocker signals are in red. The signal plots labeled A show the signal and the blockers for this phase of operation. Both the signals and the blockers have been attenuated so that the ADC comes out of saturation and the angles of incidence of the blockers are determined by the established DSP algorithms.

B. Setting proper filtering coefficients

Fig. 2 shows details of the blocker extraction filter with N antennas. The received baseband signal in antenna path i is $I_i + jQ_i$. The complex-valued gains in each path, $c_i = c_{I,i} + jc_{Q,i}$, are chosen so that the output of the summer, $S = S_I + jS_Q$, in each path contains only the blocker signals. The in-phase and quadrature components of S can be written in terms of the inputs I_i and Q_i and gains $c_{I,i}$ and $c_{Q,i}$,

$$S_I = \sum_{i=1}^{N} (c_{I,i} I_i - c_{Q,i} Q_i) \tag{1}$$

$$S_Q = \sum_{i=1}^{N} (c_{Q,i} I_i + c_{I,i} Q_i) \tag{2}$$

The gain coefficients can be determined from the angles of incidence of the blockers already determined, θ_1 and θ_2. Specifically, a spatial filtering profile is chosen to have a passband at the angle of incidence of each blocker. The gain coefficients are chosen according to the desired main lobe width and side lobe attenuation properties of the spatial filter [8]. This concept is demonstrated in Fig. 3, where a single blocker with a wavelength λ is present at an angle θ from the normal to the plane of the antenna array (distance separating the antennas being $\lambda/2$). The complex-valued gain in antenna path i is c_i. This filter extracts only spatial blocker signals in the baseband from the received signals.

C. Cancelling the blocker signals

After the blocker signals are extracted, they need to be cancelled from the received signals of the main antenna paths. The extracted signal $S_I + jS_Q$ is passed through the cancellation amplifiers with complex gains as shown in Fig. 2, which are responsible for phase-aligning S and the blocker signals in each antenna path. The resulting signal for cancelling the blockers from the antenna path i is $C_{I,i} + jC_{Q,i}$, and is given by (3) and (4) where $p_i = p_{I,i} + jp_{Q,i}$ is the complex gain of the cancellation amplifier for antenna path i.

$$C_{I,i} = S_I p_{I,i} - S_Q p_{Q,i} \tag{3}$$

$$C_{Q,i} = S_I p_{Q,i} + S_Q p_{I,i} \tag{4}$$

After the blockers are cancelled, the resultant blocker-free signals are digitized by the ADCs after proper amplification by the VGAs. Thus, a notch spatial filtering profile is created with notches at the angles of incidence of the blocker signals while preserving the analog front end gain at other angles of incidence. Fig. 1 shows the cancellation of the blockers from the received signal while preserving the required signals. The signal plots labeled B show the signals and blockers in this phase of operation. The gain of the VGA is increased to amplify the desired (green) signal. It can be seen that the blockers are recreated in the filter and then subtracted from the main path resulting in the blocker free signals. When no blockers are present, the filter path is turned off to reduce the power consumption of the system. Fig. 4 shows the flowchart of the proposed technique.

III. Simulation Results

A fully-differential implementation of the front end is modeled as in Fig. 5 and simulated in Cadence Virtuoso. Ideal transconductance amplifiers were used for this simulation and eight antennas spaced $\lambda/2$ apart are included, where λ is the central wavelength of the received signals. Signals with a bandwidth of 5% of the central frequency gave results with less than 5% error compared to the single frequency signals with wavelength λ. Simulation was also performed with 5 bit resolution transconductance cells and the results deviated from that of the ideal ones by less than 1%, confirming its suitability for this implementation. Fig. 6 shows the simulated blocker extraction filter for blocker signals incident from different angles and the resulting spatial filter with notches at the angles of incidence of the blockers. Fig. 7 shows the resulting spatial filters for two simultaneous blockers incident at -30° and 45°. Different filtering profiles are shown, each designed for different passband and notch width. The spatial filter with the lowest

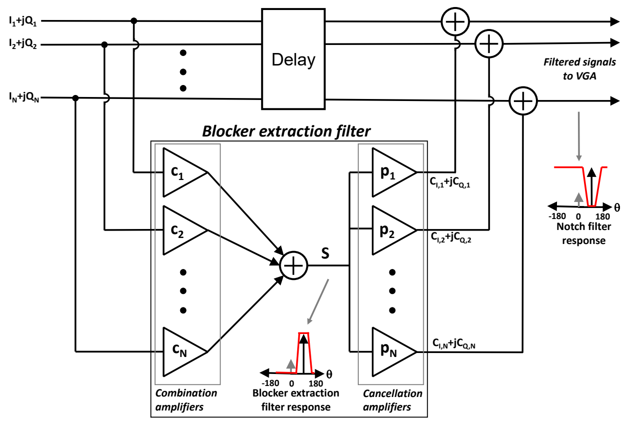

Fig. 2: Proposed filtering to extract and cancel the blocker signals.

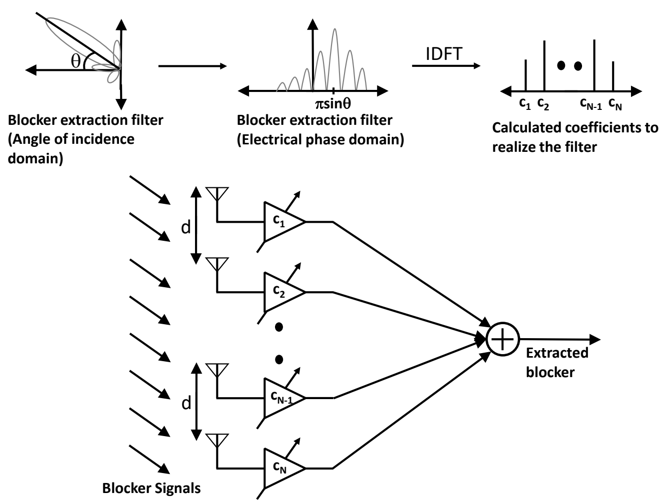

Fig. 3: Determination of filter coefficients for blocker extraction.

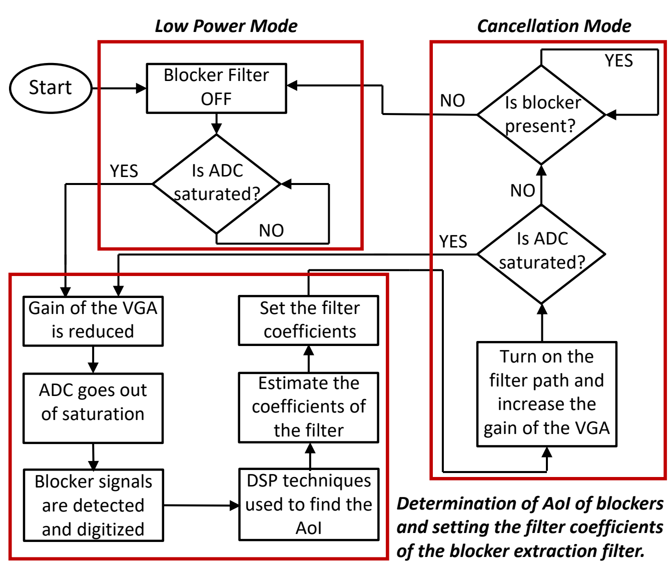

Fig. 4: Flowchart showing the proposed steps for the spatial blocker cancellation.

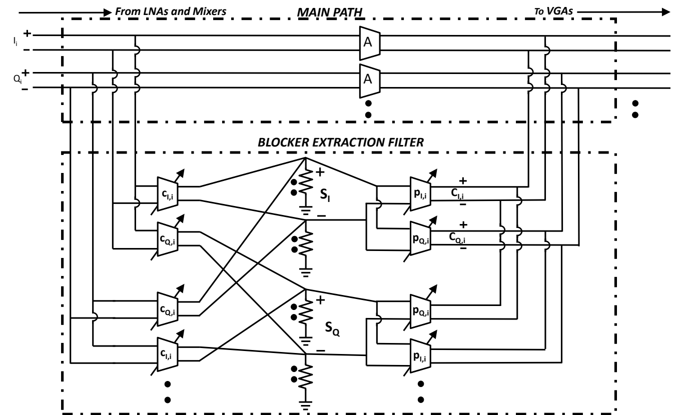

Fig. 5: Circuit level filter implementation.

passband ripple (0.8dB) has the maximum notch width (22° at 10-dB attenuation for 45° AoI) and the one with the minimum notch width (17.5° at 10-dB attenuation for 45° AoI) has the highest passband ripple (3.5dB). Variability and mismatch in the filter's gain stages is a practical inevitability. Fig. 8 shows 20 blocker extraction and notch spatial filter responses in the presence of random mismatch with a standard deviation of 5 percent in the gains of the filter's internal amplifiers for a blocker incident at an angle of 0°. The following simulation illustrates the adaptive technique proposed in the paper. The desired signal (QPSK modulated) is incident at an angle of 30° to the normal and a 20dB larger CW blocker is incident at 0°. An ideal 17-level ADC is incorporated into the model of Fig. 1. Fig. 9(a) shows the output codes when the sinusoidal blocker is present and the gain of the VGA is large, resulting in saturation of the ADC. Then, in Fig. 9(b), the gain of the VGA is reduced by 20dB so that the ADCs come out of saturation. This ADC output signal, which is mostly the blocker signal (as the amplitude of the desired signal is very low) is then processed by the MUSIC algorithm in the digital domain to detect its angle of incidence.[1] Fig. 10(a) is the output of the MUSIC algorithm when the gain of the VGA is reduced by 20dB before the blocker is cancelled. The largest peak is observed at the blocker angle of incidence, and a second peak is present for the desired signal. Fig. 10(b) is the MUSIC algorithm output after the blocker is cancelled from the main path and the gain of the analog front end is increased; it now shows only the angle of incidence of the desired signal. The desired signal at a 30° angle of incidence is correctly detected after the blocker signal is cancelled. Fig. 11(a) shows the received demodulated signal (of the first antenna) before the blocker signal is cancelled, when the gain of the VGA is reduced by 20dB; and Fig. 11(b) shows the demodulated signal after the blocker is cancelled and the gain of the analog front end is increased. In the presence of the blocker, the demodulated signal is dominated by the CW blocker and after the blocker is cancelled, the required QPSK signal is recovered.

[1]Although MUSIC algorithm has been used in this work, other DSP algorithms for detecting the angles of incidence of signals such as [9] could have been used.

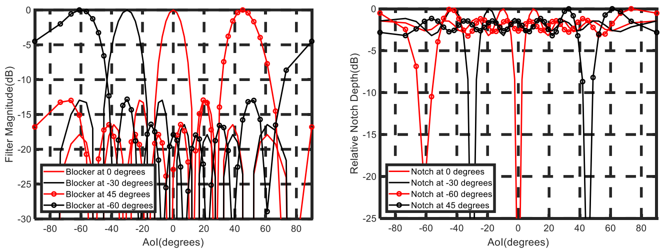

Fig. 6: Simulated blocker extraction filters and the resultant notch filters for different angles of incidences of the blockers.

IV. Conclusion

An adaptive technique for cancelling multiple simultaneous spatial blockers in the baseband of a multiple antenna receiver system is introduced, and a suitable system-level architecture is proposed, which scales linearly with the number of antennas, making it a good choice for next-generation multiple-antenna systems. The blocker cancelling circuits can be deactivated in the absence of any spatial blockers to reduce power consumption. The proposed architecture can also be integrated with spectral blocker cancellation techniques like digital blocker cancellation ADCs [6] for complete spectral and spatial blocker cancellation.

System-level simulation results are presented which show proper blocker cancellation by determining the angles of incidence of the blocker signals, setting the proper filtering coefficients to extract the blocker signals and finally cancelling them, effectively forming notches at the angles of incidence of the blockers. Simulated results for different blocker locations and the resulting blocker cancellation filter responses are shown. The same architecture can be used for other types of antenna arrays by appropriately selecting the filtering coefficients.

References

[1] S. Jain, Y. Wang, and A. Natarajan, "A 10GHz CMOS RX frontend with spatial cancellation of co-channel interferers for MIMO/digital beamforming arrays," in *2016 IEEE Radio Frequency Integrated Circuits Symposium (RFIC)*. IEEE, 2016, pp. 99–102.

[2] L. Zhang, A. Natarajan, and H. Krishnaswamy, "Scalable spatial notch suppression in spatio-spectral-filtering MIMO receiver arrays for digital beamforming," *IEEE Journal of Solid-State Circuits*, vol. 51, no. 12, pp. 3152–3166, 2016.

[3] L. Zhang and H. Krishnaswamy, "Arbitrary analog/RF spatial filtering for digital MIMO receiver arrays," *IEEE Journal of Solid-State Circuits*, vol. 52, no. 12, pp. 3392–3404, 2017.

[4] R. Garg and et al., "A 28GHz 4-element MIMO Beam-Space Array in 65nm CMOS with simultaneous spatial filtering and single-wire frequency-domain multiplexing," in *2020 IEEE International Solid-State Circuits Conference - (ISSCC)*. IEEE, 2020, pp. 80–82.

[5] M.-Y. Huang and H. Wang, "A 27-to-41GHz MIMO receiver with N-Input-N-Output using scalable cascadable autonomous array-based high-order spatial filters for instinctual full-FoV multi-blocker/signal management," in *2019 IEEE (ISSCC)*. IEEE, 2019, pp. 346–348.

[6] Q. Wang, H. Shibata, A. Chan Carusone, and A. Liscidini, "A LTE RX front-end with digitally programmable multi-band blocker cancellation in 28nm CMOS," in *2017 IEEE Custom Integrated Circuits Conference (CICC)*. IEEE, 2017, pp. 1–4.

[7] R. Schmidt, "Multiple emitter location and signal parameter estimation," *IEEE Transactions on Antennas and Propagation*, vol. 34, no. 3, pp. 276–280, 1986.

[8] F. J. Harris, "On the use of windows for harmonic analysis with the discrete fourier transform," *Proceedings of the IEEE*, vol. 66, no. 1, pp. 51–83, 1978.

[9] A. Badawy, T. Khattab, D. Trinchero, T. E. Fouly, and A. Mohamed, "A simple AoA estimation scheme," *arXiv preprint arXiv:1409.5744*, 2014.

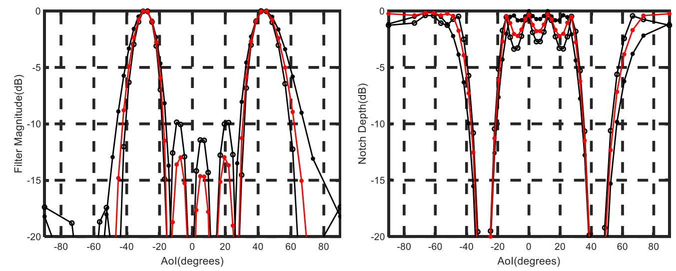

Fig. 7: Simulated blocker extraction filter and the resultant notch filter for blockers present at -30° and 45° angle of incidences.

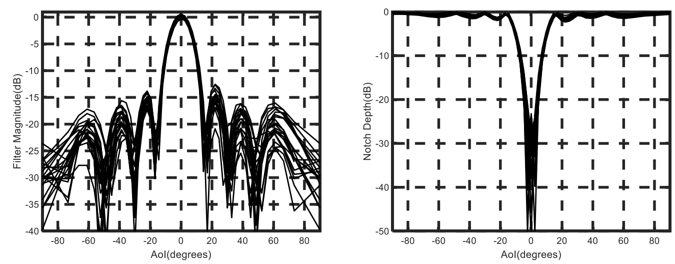

Fig. 8: Blocker extraction and notch filter for 5 percent mismatch in the gains of the amplifiers in the blocker cancellation filter.

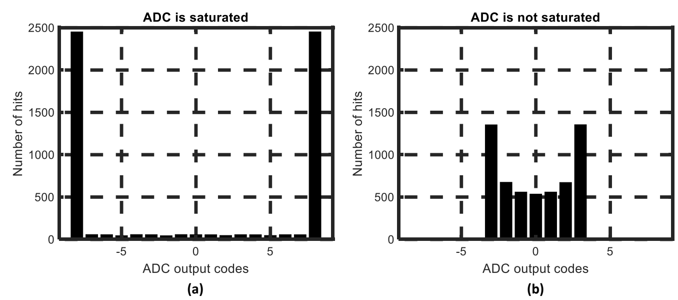

Fig. 9: Output codes of the ADC when (a) the ADC is saturated and (b) when the ADC comes out of saturation after the gain of the ADC is lowered.

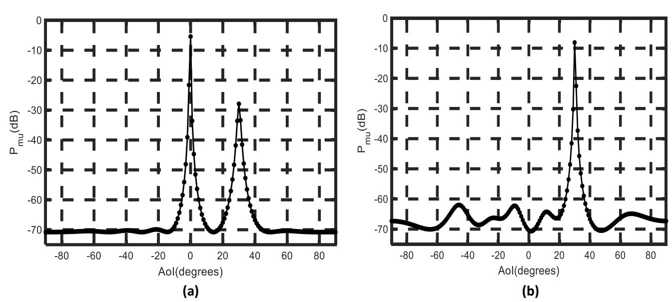

Fig. 10: MUSIC spectrum (P_{mu})(MUSIC algorithm output) (a) in the presence of the blocker and (b) after the blocker has been cancelled. Blocker is present at 0° and the desired signal at 30° AoI.

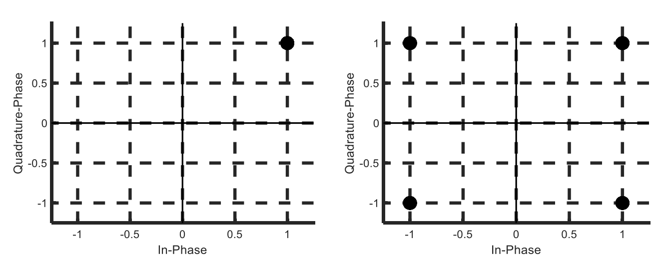

Fig. 11: Constellation diagram of the received QPSK signal (a) in the presence of the CW blocker (b) after the blocker is cancelled.