A COTS based Asynchronous Distributed Array Processor utilizing Reduced-Rank STAP

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Abstract—Distributed array processing has been a topic of interest due to its added advantage of sensor placement and processing gain for leveraging transmit/receive beamforming configurations. However, having independent local oscillators at each sensor presents a synchronization challenge for a distributed array. We explore the use of reduced-rank signal processing and Signals-of-Opportunity (SOOs) to maintain better-distributed sensor coherency while performing Space-time Adaptive Processing (STAP) when GPS is unavailable for local sensor oscillator synchronization. Reduced-rank signal processing requires fewer samples for STAP convergence, thereby allowing less stringent coherency constraints on the distributed array processor. Less stringent coherency constraints enables the use of SOOs as timing reference beacons in the field of view, thereby eliminating the need to have a dedicated transmitter for sensor synchronization. We explore these concepts utilizing COTS Software Defined Radios (SDRs) providing data to an asynchronous distributed array processor (ADAP). The SDRs are setup to simultaneously sample the SOO and the Signal-of-Interest (SOI) to enable the distributed array processor to achieve both sensor synchronization and reduced-rank STAP on the SOI. Results are presented utilizing FM radio towers as both SOOs and SOIs, but our approach can easily be extended to a variety of other signals such as TV, cellular tower, and satellite signals just to name a few.

I. INTRODUCTION

Distributed array processing provides the flexibility to create sensor networks that enable both distributed receive and transmit beamforming. This paper focuses on a receive only beamforming capability that extends the master-slave architecture for beamforming by replacing the Master Sensor with a SOO. By extending the Master Sensor to be a SOO, we can create a completely passive beamforming receiver system to enhance or suppress SOIs based on an asynchronous distributed array. We seek to demonstrate this proof-of-concept utilizing USB based COTS SDRs that capture both the SOO and SOI in a distributed sensor network. The COTS SDRs are configured to save asynchronous snapshots of data to the ADAP. The ADAP then performs both sensor synchronization and reduced-rank STAP on the SOI. We seek to use a reduced-rank STAP algorithm [1] based on the Multi-stage Wiener Filter (MWF) [2] because of its low sample support convergence properties. We believe these convergence properties will enable the processor to achieve STAP interference suppression even when the SDRs have local oscillators that drift significantly. Low sample support convergence properties [3] translate into better-localized coherency across the array since smaller snapshot samples are more robust to individual SDR local oscillator drifting between repeated synchronization and adaptive STAP convergence.

In this paper, we are leveraging STAP as an interference suppression processor to demonstrate the concept of simultaneous sensor synchronization with STAP suppression of signals. Since the SDRs are operating from their own individual local oscillators that are not slaved to a master clock, they are considered asynchronous SDRs associated with the distributed array. The motivation for utilizing STAP, as an interference suppression processor in this type of application is based on the direct signal cancellation processing that must occur in a passive bi-static radar system before range-Doppler processing can occur utilizing the reflected target echoes.

II. ASYNCHRONOUS PROCESSING APPROACH

A. Distributed Array Snapshot Signal Model

The distributed array processor assumes data are collected from M SDRs (each connected to their own respective omnidirectional antennas). The SDRs can stream data or collect snapshots of data to the ADAP. We assume a snapshot data model for convenience associated with each SDR so asynchronous data is stored locally onto the ADAP as shown in Figure 1. Referring to Figure 1, \( \mathbf{x}_m(n) \) is a \( N \times 1 \) vector containing \( N \) successive samples of the output of the \( m \)-th SDR sampled at a rate above or equal to the Nyquist rate that captures both the SOO and SOI.

\[
\mathbf{x}_m(n) = [x_m(n), x_m(n-1), \ldots, x_m(n-N+1)]^T \quad (1)
\]

The \( NM \times 1 \) space-time snapshot, \( \mathbf{\tilde{x}}(n) \), is formed concatenating \( \mathbf{x}_m(n) \), \( m = 1, 2, \ldots, M \), as
Similarly, the $N$ tap weights associated with the $m$-th SDR are placed as the components of an $N \times 1$ vector as
\[
h_m(n) = \left[ h_m(0), h_m(1), \ldots, h_m(N-1) \right]^T, \quad m = 1, 2, \ldots, M
\] (3)
and the entire set of space-time weights is formed from a concatenation of $h_m, m = 1, \ldots, M$ as
\[
h = \begin{bmatrix} h_1 \\ h_2 \\ \vdots \\ h_M \end{bmatrix}
\] (4)

The output power of the space-time preprocessor is
\[
E\left\{h^H \tilde{x}(n) \right\} = h^H K h, \quad \text{where } K = \{\tilde{x}(n)\tilde{x}^H(n)\}
\] (5)

Assume that the first antenna of the array is the reference antenna associated with the first SDR. To incorporate the unity weight constraint on the first tap of the reference antenna, define $x(n)$ as the $(NM - 1) \times 1$ sub-vector of $\tilde{x}(n)$ containing all but the first element of $\tilde{x}(n)$. Similarly, $h_x$ is defined as the $(NM - 1) \times 1$ sub-vector of $h$ containing all but the first element of $h$.

\[
\tilde{x}(n) = \begin{bmatrix} x_1(n) \\ x_2(n) \\ \vdots \\ x_M(n) \end{bmatrix}^T
\] (6)
\[
h = \begin{bmatrix} h_1 \\ \vdots \\ h_{M-1} \end{bmatrix}
\] (7)

With these definitions, the power at the ADAP output may be expressed as
\[
E\left\{h^H \tilde{x}(n) \right\} = E\left\{x_1(n) + h_x^H x(n) \right\}
\] (8)

Expressing the preprocessor output power in this fashion facilitates an adaptive filtering formulation where the output of the first tap of the reference antenna serves as the “desired” signal and the “error” signal is $x_1(n) + h_x^H x(n)$. As a result, LMS and/or RLS based adaptations are possible, as developed previously for the case of space-only processing.

To determine the asymptotic form of the optimal space-time weights, partition the $NM \times NM$ space-time correlation matrix as follows.

\[
K = E\{\tilde{x}(n)\tilde{x}^H(n)\} = \begin{bmatrix} k_{xx}(0) & k_{dx}^H \\ k_{dx} & K_{xx} \end{bmatrix}
\] (9)

The output power of the preprocessor may then be expressed as
\[
E\left\{h^H \tilde{x}(n) \right\} = k_{xx}(0) + k_{dx}^H h_x + h_x^H k_{dx} + h^H K_{xx} h.
\] (10)

Since $K_{xx}$ is positive definite, it follows that the optimal solution is $h = -K_{xx}^{-1} k_{dx}$ and the minimum output power of the ADAP is $k_{xx}(0) - k_{dx}^H K_{xx}^{-1} k_{dx}$. One practical approach using a finite number of samples and batch mode processing over $L$ samples at each antenna, estimates $K_{xx}$ and $k_{dx}$ by
\[
\hat{K}_{xx} = \frac{1}{L} \sum_{n=0}^{L-1} x(n)x^H(n), \quad \hat{k}_{dx} = \frac{1}{L} \sum_{n=0}^{L-1} x_1(n)x(n).
\] (11)

Recall that $x(n)$ contains all the elements of $\tilde{x}(n)$ except for the first element corresponding to $x_1(n)$. The degree of coherency associated with the estimates $K_{xx}$ and $k_{dx}$ is determined by how well the local oscillators of each SDR are synched to each other. Since the ADAP requires proper convergence and coherency of these estimates to suppress the interference, the ability to synchronize the local oscillators of the SDRs within the necessary samples for proper convergence is critical. This is where we seek to apply the reduced-rank STAP MWF algorithm to achieve the necessary convergence with the smallest number of snapshots while still providing the necessary level of suppression after a block of ADAP data has been synchronized based on the SOO.
B. Asynchronous Distributed Array Processor (ADAP)

Our current software-defined ADAP is designed to perform two major functions once receiving snapshot data from the M SDRs. The first function of the ADAP is to determine how to synchronize the different data snapshots to a common reference broadcast based on the SOOs in the field of view during the collect. The second function is to perform reduced-rank STAP interference suppression on the remaining SOIs. We seek to explore the effectiveness of both functions based on 1) the type of SDR available to perform the data collect, 2) the type of SOOs that impact the synchronization of the M SDRs, and 3) the level of coherency required to meet the sample support requirements of the reduced-rank STAP algorithms to perform STAP interference suppression. More functions will be made available to ADAP as we mature the processing technology. This paper provides some initial results based on FM radio towers.

III. EXPERIMENTAL SETUP AND RESULTS

To test the concept of ADAP using real-world signals, we decided to leverage a COTS SDR that had enough bandwidth to capture multiple radio stations in the FM band simultaneously. We were able to collect two HD FM radio stations simultaneously using this type of SDR providing the minimum signal set to explore the capability of ADAP using one signal as the SOO for M SDR synchronization while using the other signal as the SOI to determine the level of interference suppression achievable. Figure 3 illustrates the spectrum associated with one of the two SDRs used during the experiment. Figure 4 illustrates the geographic map of the locations associated with the two FM radio stations relative to the distributed array.

We started with $M = 2$ to create a simple two element linear array as a representative distributed array so we could focus on the predictability of the coherency and suppression capabilities of our asynchronous collection system. An omni-directional FM loop was used with each SDR. We are still processing the data to show some initial coherency and reduced-rank interference suppression results using the MWF. We plan to have these results in the next revision of this paper in the coming weeks.

IV. CONCLUSIONS

We have presented an innovative way to utilize an asynchronous distributed array of sensors to perform STAP interference suppression on a SOI leveraging a SOO as a reference beacon for distributed array synchronization. COTS based SDRs combined with a newly developed reduced-rank MWF based ADAP approach has been explored leveraging FM radio towers as both SOIs and SOOs.

REFERENCES

