Characterization of Signal-based Automated Information Processing in Distributed Systems for Environmental Surveillance Monitoring

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***Abstract*—The work presents results of on going research on signal-based automated information processing in distributed systems. Some results are presented in the context of a grid services infrastructure for environmental surveillance monitoring applications. The research work uses concepts, principles, rules, and techniques of information-based complexity, non-abelian signal processing, graph algebras, and signal-based holomorphic information processing to characterized flow and computational complexities of information-to-user (I2U) processes in a distributed information processing environment, calling this approach information-to-user processing complexity. Information flow characterization in a distributed information processing (DIP) system is defined as the study of attributes associated with the structure, content, transferring, and meaning of information as it is carried by signal-messages coded from observable entities in the physical world to an information user through a distributed information processing environment. The work deals, in particular, with information flow characterizations of ultra-wideband (UWB) signals for wireless communications and sensing operations pertaining to imaging applications. Holomorphic signals and systems modeling, based on linear combinations of polynomial phase complex exponential signals and classes of linear operators, is utilized to aid in the study of multi-input multi-output wireless communications channels in sensor imaging applications.**

I. Introduction

This report informs on some of the research work being conducted as part of a project entitled “An Infrastructure for Wide Area Large Scale Automated Information Processing” (WALSAIP), supported by NSF under the Grant No. 0424546. The report describes a proposed framework for signal-based distributed signal processing (SbDSP) at the physical layer of an open grid infrastructure which interacts with a distributed sensor network (Figure 1). A SbDSP system may serve as an infrastructure for processing signals arriving from sensors interacting with an environment in order to extract information important to a user. The SbDSP framework is based on an operator algebras approach for the treatment of information carrying signals which are modeled as vectors in a linear signal space (Figure 2). An operator algebras setting allows for a formal study of computational complexity issues associated with signal-based information processing using concepts and techniques of information-based complexity theory [1]. It also allows for the characterization of information from the multiple nodes of the distributed signal processing infrastructure to an information user. To characterize information flow, all acquired time-depending signals are represented as images in a mixed time-frequency plane. Information-theoretic procedures are then used to address information content. In this context, information content could be measured at each node as a function of time/space, allowing for the concept of space-time information flow (flux). At each node of a SbDSP system, analytic signals are utilized to model a large class of signals interacting with the environment, thus, allowing for another concept, namely, signal-based holomorphic information processing. Two particular applications are addressed by the SbDSP framework: acoustical signal beamforming and chirp radar parameter estimation. Section 2 describes how the proposed SbDSP framework is utilized in acoustical signal processing applications. Section 3 describes some results of using the SbDSP for chirp radar parameter estimation in point targets scattering systems dynamics [2].

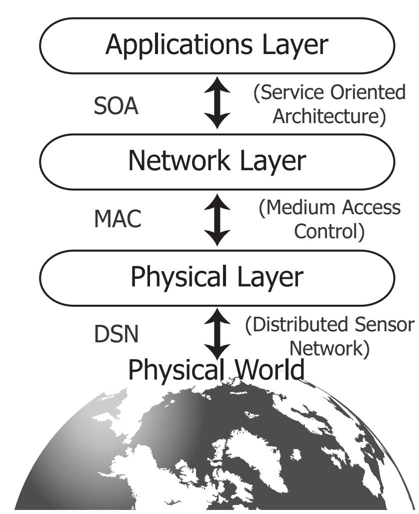

Fig. 1. Basic Open Grid Infrastructure Model

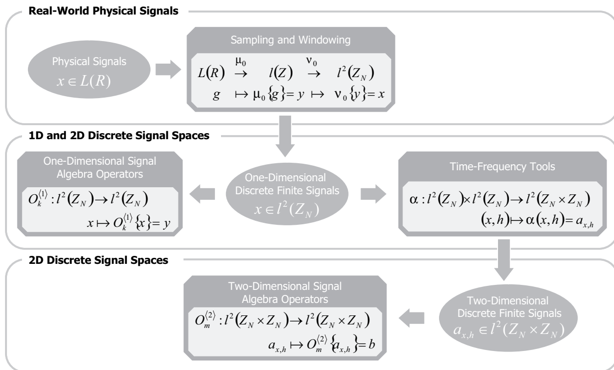

Fig. 2. Operator Algebras Framework

II. Acoustical Signal Processing

This ongoing work studies formal concepts and fundamental principles for the characterization of acoustical signals in sensor-based distributed signal processing (SbDSP) systems. A SbDSP system deals with the treatment of signals acquired from a prescribed set of physical, chemical, or biological sensors which are spatially distributed and which have an associated network topology such as a wired or wireless sensor network. The treatment of signals is accomplished through the implementation of computational signal processing methods which usually require a combined system level hardware/software co-design approach. Here, a computational signal processing method is defined as a structured set of computational signal processing algorithms. A computational signal processing algorithm is defined as a finite composition of operators. Of special importance to this work are SbDSP systems associated with wireless sensor networks which treat acoustical signals acquired from physical sensors in generalized environmental observatories. A particular wireless sensor network testbed is currently being developed at the Jobos Bay National Estuarine Research Reserve (JBNEER) environmental observatory situated in the southern part of the island of Puerto Rico. JBNERR encompasses a chain of 15 tear shape mangrove islets known as Cayos Caribe and the Mar Negro area in western Jobos Bay. The reserve is home to the endangered brown pelican, peregrine falcon, hawksbill sea turtle, and West Indian manatee. It is managed by the US National Estuarine Research Reserve System of the National Oceanic and Atmospheric Administration.

For modeling monitoring activities in an environmental observatory, a one-to-one mapping is established between each node of a wireless sensor and each node of a SbDSP. A fundamental problem considered by this work is how to appropriately map a computational signal processing method to an SbDSP system associated with a wireless sensor network for the structural content analysis of acoustical signals modeled as finite length discrete-time signals. The set of all discrete-time signals of a particular, say L, is said to form a finite dimensional linear space denoted by the expression $\ell(Z_L)$, and $Z_L = \{0, 1, 2, \ldots, N-1\}$ is the standard indexing set. A finite length discrete-time complex signal $x \in \ell(Z_N)$ is denoted by the expression $x : Z_N \to C$, where C is normally taken to be the set of complex numbers. Closed subsets of $\ell(Z_L)$ are used in this work, with an arbitrary closed subset denoted by the symbol $\gamma_k \subset \ell(Z_L)$. Each node in a SbDSP system is assumed to be endowed with the following inherent parameterized attributes: i) a raw-data storage unit capable of storing finite length digital signals, ii) a digital signal processing unit with direct access to the digital raw-data storage unit, iii) a finite number of analog to digital conversion (A/D) units, iv) a finite number of digital to analog conversion units, and a general purpose processor (GPP), with a cache unit serving as local memory, sharing the raw-data storage unit which serves as extended or external memory.

Each SbDSP system node is modeled as a system, transform, or operator which takes as its input a single finite length digital signal and it produces as output another finite length digital signal, not necessarily the same length as the input signal. To generalize the distributed signal processing theory formulated in this work, digital signals are modeled mathematically as discrete-time signals except when it is necessary to specify a signal's quantization technique utilized in a particular application. A SbDSP node, with its inherent attributes, can then be modeled as a point in a linear space of operator algebras, this space denoted by $L(A)$. Thus, an operator $\rho_m \in L(A)$ becomes a point of this algebra.

The SbDSP system model presented in this work is simplified by assuming that all operators are linear, with special attention given to finite dimensional, linear, and/or discrete-time shift invariant operators. These types of operators always admit a matrix representation with respect to a particular signal basis. A basic sensor-based distributed signal processing (SbDSP) system may be modeled as a directed graph, where the vertices of the directed graph represent linear closed subspaces and the edges represent linear operators (Figure 3). A linear operator $\rho_{m,n} : \gamma_m \to \gamma_n$, acting on an element of a closed subspace γ_m and producing an element γ_n , then becomes an element of a finite composition, orbit, or route which has been defined here as a computational signal processing algorithm.

A SbDSP system is also spatially modeled as a topological structure associated to an ordered rectangular mesh, termed a performance evaluation testbed (PET) mesh, with each node of the particular SbDSP system considered to be an element inside the rectangular mesh and each square of a rectangular mesh admitting one and only one SbDSP node (Figure 4).

Flow characterizations of computational signal processing methods is being utilized in this work as an approach at assisting in the problem of mapping computational signal processing methods to SbDSP systems. In essence, a computational flow characterization is defined as the information-based complexity associated with a computational signal processing method [1]. This work addresses computational signal processing methods in structural signal content analysis and acoustical waveform beamforming operations in environmental observatory applications.

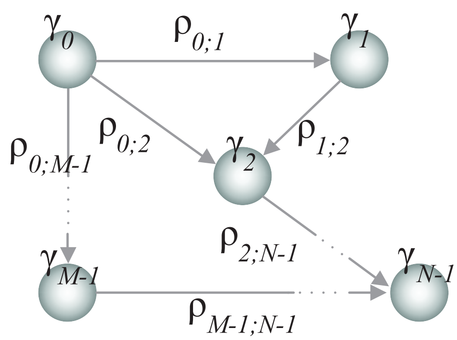

Fig. 3. A directed graph representing a SbDSP

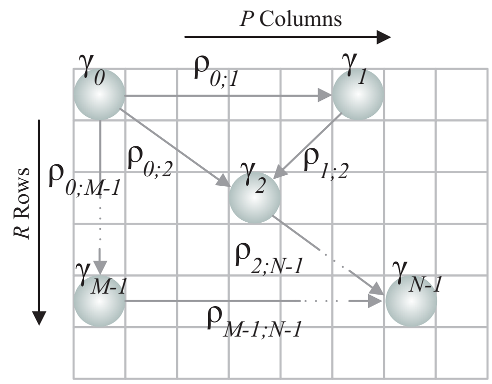

Fig. 4. DbDSP Over a Structural Mesh

In these environmental observatories, SbDSP systems are modeled as overlay networks built on top of wireless sensor networks and deal with applications where either the signal sensing (acquisition), the signal communication (conveying), the signal processing (treatment), or a combination these aspects exhibit some form of space/time distribution. Distributed signal processing seeks to study these three aspects of a signal, namely, signal sensing, signal communication, and signal processing, in a unified and integrated manner.

Structural content analysis of acoustical signals deals with the formulation of computational tools for representing and analyzing inherent signal characteristics and attributes that are only indirectly observable in a combined temporal and spectral depiction in the time-frequency plane.

Examples of these computational tools are the chirp Fourier transform, the fractional Fourier transform, Wigner distribution, the Weyl-Brezin transform, the Zak transform, the short-time Fourier transform, and the cross-ambiguity function. It has been demonstrated that the processing nature of these tools can be studied in a unified manner using concepts of Weyl-Heisenberg systems and non-abelian signal processing.

Also, Kronecker products algebra, a branch of finite-dimensional multi-linear algebra, can be used as a tool to aid in the formulation of computational frameworks such as those utilized for unitary discrete signal transforms [3].

Emphasis on *modular and scalable* computational signal processing (CSP) methods is given in this work for implementation on targeted DSP and GPP units. These methods deal with the algorithmic treatment of *finite duration* signals in order to extract information important to a user or software/hardware agent. The modular and scalable approach to these computational methods implies that the functions and structures of the algorithmic treatment should adapt to changes in scales of an associated target system as well as to the size or dimensionality of the signals to be processed. The algorithmic treatment concentrates on understanding fundamental distributed signal processing principles utilized to *observe, quantify, represent, transform, qualify, and render* information carrying signals emanating from a physical environment such as an environmental observatory. The CSP methods concentrate on algorithms designed for the integrated digital communications and/or processing of signals in SbDSP systems overlaying distributed sensor networks. This work also addresses computational frameworks for acoustic waveform beamforming, a signal processing operation used widely in wireless communications, radar, and sonar applications to estimate the direction of arrive (DOA) of a propagating waveform source when the waveform is received by an array of antennas or sensors. Beamforming can also be used to steer a transmitted beam in a particular direction when sensors are replaced by transmitters (Figure 5).

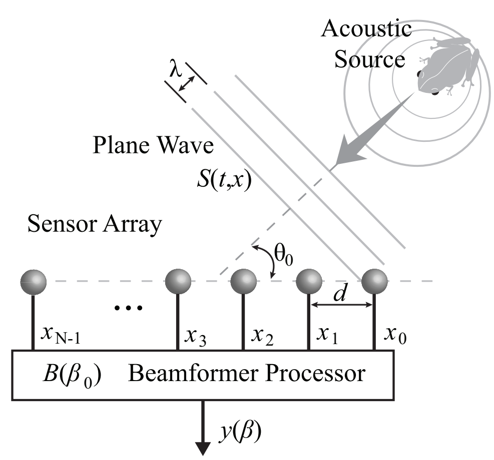

Fig. 5. Basic Beamforming Operation

III. Chirp Radar Parameter Estimation

Chirp radar signal parameter estimation operations are time consuming and computationally taxing processes. A discrete chirp radar signal is usually modeled as a discrete multi-component polynomial phase signal as follows:

$$x[n] = \sum_{k=0}^{K-1} A_K \cdot e^{j\sum_{m=0}^{M-1} \alpha_{k,m} n^m} + \rho[n] \ , \ n \in \mathbf{Z}_N \qquad (1)$$

Here, K and M are positive integers, A_K are complex scalars, ρ is a discrete noise signal or interference signal, and $\alpha_{k,m}, \ k \in \mathbf{Z}_K, \ k \in \mathbf{Z}_M$, are the parameters to be estimated. For a multi-component binomial phase discrete signal, a discrete chirp Fourier transform (DCFT) may be applied to extract the desired parameters. The DCFT of a discrete signal $x[n], \ n \in \mathbf{Z}_N$, is defined as follows:

$$X_c[k,l] = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} x[n] W_N^{kn+ln^2} \quad , \quad k,l \in \mathbf{Z}_N \qquad (2)$$

Here, $W_N = e^{-j\frac{2\pi}{N}}$, and $\mathbf{Z}_N = \{0, 1, 2, \ldots, N-1\}$.

Computing the DCFT of the discrete signal $x[n] \in \ell^2(\mathbf{Z}_L)$, where $\ell^2(\mathbf{Z}_L)$ is the linear space of all discrete complex signals of length N, is equivalent to performing N discrete Fourier transform (DFT) computations.

A. Modeling Time-Critical Targets

Part of this work centers on modeling time-critical targets through multi-component polynomial phase discrete complex signals. The model uses a scattering channel which takes as input a single component polynomial phase signal and it produces a multi-component polynomial phase signal. The channel attributes are then encoded in the polynomial phase signal parameters and a parameter estimator may then be used to extract these parameters. The parameter array space can further be treated to extract further intelligence (Figure 6).

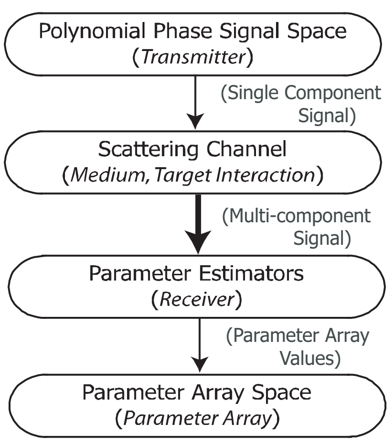

Fig. 6. Information Flow for Parameter Estimation

B. DCAF Implementation

The discrete cross-ambiguity function (DCAF) may be computed between a transmitted signal x_R and a received x_T through the use of the following expression:

$$A_{x_T,x_R}[m,k] = \sum_{n \in \mathbf{Z}_N} x_T[n] \cdot x^*[\langle n+m \rangle_N] e^{-j\frac{2\pi}{N}kn} \qquad (3)$$

The DCAF may be used as a parameter estimator for single component binomial signals and it may be implemented using a linear operator approach (Figure 7).

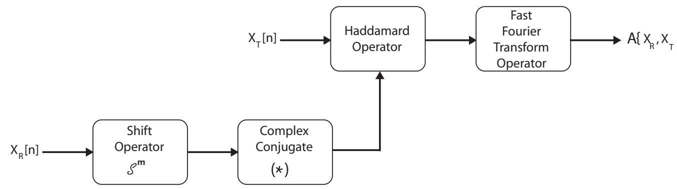

Fig. 7. Cross-Ambiguity Function Block Diagram

C. DCFT Implementation

The DCAF is very useful for time delay/Doppler estimation as well as for modeling point target response functions. Under certain signal to noise ratio (SNR) conditions [5], the DCFT performs better than the DCAF for estimating multi-component polynomial phase signal parameters due to the lack of cross-terms effects. A new algorithm has been formulated for the computation of the DCFT. The algorithm has been formulated using Kronecker products algebra, a branch of multi-linear finite dimensional algebra. The algorithm for computing the DCFT of an N - point multicomponent polynomial phase signal may be formulated performing N matrix-vector computations where each matrix may be expressed as the composition of sparse matrices through the following theorem:

Theorem 3.1:

$$C_N[l] = ((F_N) \otimes I_2) T_{N,\frac{N}{2}} (\Gamma'_{N,2}[l] \otimes F_2) P_{N,2}^{-1} \qquad (4)$$

Where,

$$\begin{aligned}
T_{R,S} &= diag([D_{N,S}^0, D_{N,S}^1, \ldots, D_{N,S}^{R-1}]) \\
D_{N,n} &= diag([1, W_N, \ldots, W_N^n - 1]) \\
P_{N,2}^{-1} &= \text{Permutation Matrix} \\
F_N &= \text{Fourier Matrix} \\
\Gamma'_{N,2} &= ([1, W_N^l, \ldots, W_N^{\frac{N}{2}-1^2}])
\end{aligned}$$

Table I below provides some implementation results for the DCFT on single general purpose processor (GPP) and digital signal processor units. The first column of the table describes the length of the signal. The second column provides computational time, in seconds, for the DCFT computation on a single GPP (Pentium III - 1.26 GHz). Algorithm efficiency is currently being evaluated for cluster implementations. The third column provides FFTW algorithm numbers for comparison purposes. The last two columns present the computation of the DCAF and the FFT, respectively, on a TMS320C6713 DSP processor, again, for comparison.

TABLE I
SINGLE PROCESSOR IMPLEMENTATION RESULTS

Samples	DCFT FFTW Pentium III	FFTW Pentium III	DCAF DSP TMS320C6713	FFT DSP TMS320C6713
32	8.6E-04	5.9E-05	5.7E-02	3.6E-05
64	3.1E-03	1.3E-04	2.9E-01	8.0E-05
128	1.2E-02	1.5E-05	1.3E+00	1.8E-04
256	4.6E-02	2.7E-05	5.8E+00	4.0E-04
512	1.8E-01	5.1E-05	2.5E+01	9.0E-04
1024	7.4E-01	1.1E-04	1.4E+03	2.0E-03
2048	3.0E+00	2.3E-04	8.8E+03	2.5E-02
4096	1.3E+01	5.3E-04	3.8E+04	5.5E-02

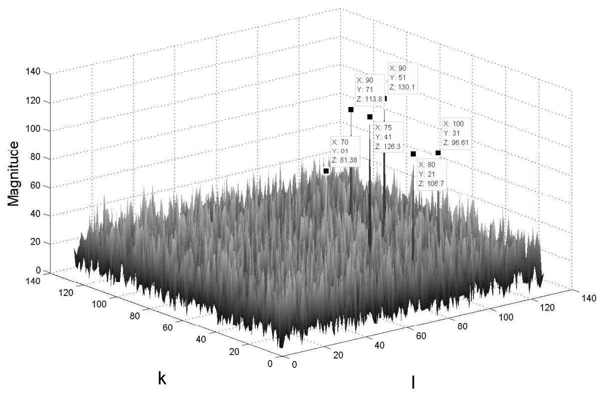

Fig. 8. Multicomponent DCFT Output

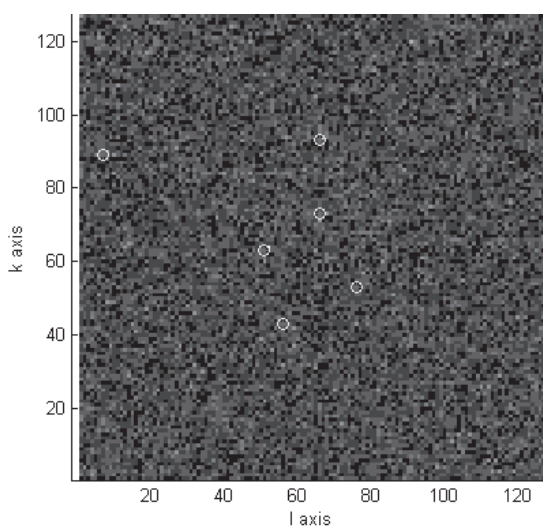

Fig. 9. Unsuccessful Multicomponent Estimation

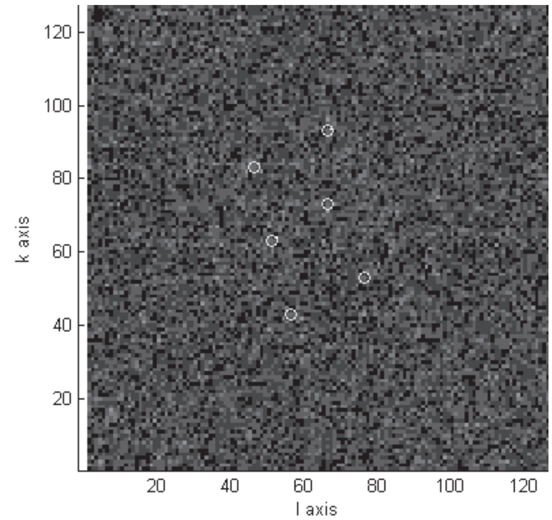

Fig. 10. Succesful Multicomponent Estimation

IV. CONCLUSION

A framework has been proposed for signal-based distributed signal processing (SbDSP). This framework may be instantiated as an infrastructure for the processing of signals acquired from environmental sensors. The processing operation effects an algorithmic treatment on sensor acquired signals. The SbDSP framework was described in terms of operator algebras. Signals are represented as images in mixed time-frequency plane to study their information content using information theoretic measures. Information flow in a SbDSP system is characterized by expressing the information theoretic measures as a function of space/time.

The work presented here is part of a collaborative work within the WALSAIP Project aiming at formulating a novel framework that can be used to guide the design of future wireless sensor networks (WSNs) providing environmental monitoring services. The focus of the WSN framework is a network layer design. In this framework formulation the following considerations are observed: 1) the future WSN shall be heterogeneous, 2) the network layer design shall better meet the requirements of applications and services, 3) the network layer design shall be able to utilize advanced wireless communications and signal processing technologies, and 4) the network layer shall provide monitoring functionality.

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