SIRLAB-NETSIG Integration for Environmental Surveillance Monitoring in Wireless Mesh Sensor Networks

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***Abstract*—This paper presents a framework for integrating, in a unified manner (a single architecture), distributed signal processing and wireless mesh sensor network operations for environmental surveillance monitoring applications. The distributed signal processing operations center on the use of time-frequency tools for the analysis of bioacoustic signals and their representations. The wireless mesh sensor network operations center on the efficient transfer of information content from a source to a user through wireless communications optimization techniques under a versatile service oriented paradigm. An open source computational modeling framework, named SIRLAB, was developed to address time-frequency signal analysis and representation in a distributed signal processing, wireless mesh sensor network, environment. An embedded computing module, termed NETSIG, was developed to integrate wireless mesh network routing, coding, and security tasks with adaptive, large-scale, high-bandwidth, signal processing tasks. The integrated SIRLAB-NETSIG concept was tested in the laboratory, with user interface visualization applications being developed on portable digital assistants utilized as network clients. Frame rates close to 30 frames per second where achieved for some user interface visualization operations in a wireless mesh cloud testbed.**

***Index Terms*—Service oriented mesh cloud, distributed signal processing, Bioacoustics, NETSIG, SIRLAB.**

I. INTRODUCTION

This work aims at presenting a framework for integrating, in a unified manner, sensor-based distributed signal processing and wireless mesh sensor network tasks for environmental surveillance monitoring operations. The work is part of a research and development effort in environmental informatics. Environmental informatics is defined as the discipline which applies concepts, tools, methods, and rules from the field of information processing to address environmental problems. Information processing is defined as the treatment of information to effect an observable (measurable) change.

Any observable change of an information state occurs as a result of a process or operation acting on that state; thus, any observable change in information has an associated non-empty set of operators. A signal is defined as any observable entity able to carry information from one event to another in the space-time domain. Signal-based information processing (SbIP) deals with the treatment of signals in order to extract information relevant to a user. When a user is interested in acquiring information about the environment, then it is natural for her/him to think about a space-time configuration setup to carry out a data acquisition procedure. A signal-data acquisition modality using wireless technology seems appropriate nowadays. However, special attention must be given to the nature of the information that the user is interested in acquiring from the environment in order to use the adequate technology. For this particular work, information users are interested in the analysis of bioacoustic signals. Bioacoustics is referred here to the study of natural sounds produced by animals, including humans. Many times, bioacoustic signal analysis involves the study of ensembles of animal species [1] and this is one of the main justifications for the development of the proposed framework. Since sound propagates through elastic media in space-time as a traveling wave, a real-time study of bioacoustic signals benefits from a distributed signal processing approach ([2], [3], [4]), over an associated waveform sensing network such as an acoustic mesh sensing network. This is one of the main reasons for pursuing the integration of distributed signal processing and wireless mesh sensor network operations. In this work, distributed signal processing operations use time-frequency (T-F) tools for the analysis of bioacoustic signals and their representations. Accordingly,

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wireless mesh sensor network operations center on the efficient transfer of information content from a source to a user through wireless communications optimization techniques under a versatile service oriented paradigm. The paper is presented in the following manner. Section 2 provides a formulation of the concept of sensor-based distributed signal processing. Section 3 discusses SIRLAB as a framework and introduces the concept of NETSIG integration. Conclusion and future works appear in Section 4.

II. SENSOR-BASED DISTRIBUTED SIGNAL PROCESSING

K. Lu, D. Rodriguez, et al. proposed in [5] the development of a *sensor-based, distributed signal processing* (SbDSP) infrastructure framework as an overlay network on top of a wireless mesh sensor network (WMSN) for the purpose of gathering environmental information under a wireless mesh bubble, or wireless mesh cloud as it is currently termed. WMSNs have being demonstrated to be useful at integrating tasks such as signal sensing (acquisition), signal communication (conveying), and signal processing (treatment) when conducting observations. The advantage of the proposed SbDSP infrastructure framework is its ability to process large scale, high-bandwidth, signals with space-time attributes such as bioacoustic waveforms. Thus, the infrastructure may allow computationally taxing signal processing tasks at selected integrated network nodes. Time-frequency signal analysis is a good example of such taxing tasks. These selected nodes are termed NETSIG nodes and are described in below.

A SbDSP overlay may be modeled as a directed graph, where the vertices of the directed graph represent linear closed subspaces and the edges represent linear operators. A finite dimensional linear operator $\rho_{m;n} : \gamma_m \rightarrow \gamma_n$, acting on an element of a closed subspace γ_m and producing an element for another closed subspace γ_n, becomes an element of a finite tree computational structure, a computational orbit, or a multicast computational route, denoted by G_m. In certain cases, a closed subspace γ_m may be treated as a linear algebra over a finite field $GF(q)$. If, in such cases, an associated directed graph may be treated as a directed acyclic graph (Figure 1), then, a SbDSP overlay may be treated as a generalized network system where theoretic methods of *linear network coding* may be applied. The computational structure G_m is characterized as a distributed signal processing algorithm. Thus, the computational structure G_m may represent an aspect of acoustic structural content analysis. Structural content analysis of acoustical signals is a distributed signal processing task dealing with the formulation of computational tools for representing and analyzing inherent signal characteristics and attributes that are only indirectly observable in a combined temporal-spectral or spatial-temporal depiction in a time-frequency plane.

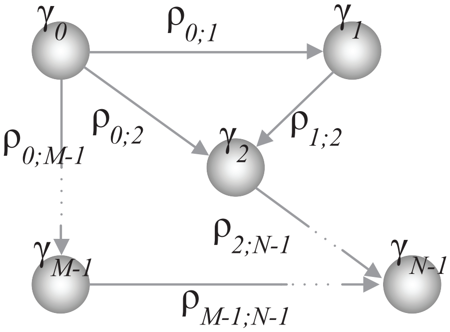


Fig. 1. A directed graph representing a SbDSP

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 SbDSP system associated with a WMSN is modeled spatially as a topological mesh structure associated to an ordered rectangular grid, with each node of the particular SbDSP system or WMSN considered to be an element inside the grid and each square of the grid admitting one and only one SbDSP/WMSN overlay node (Figure 2).

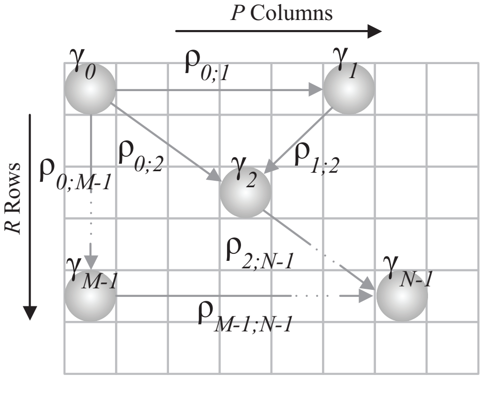
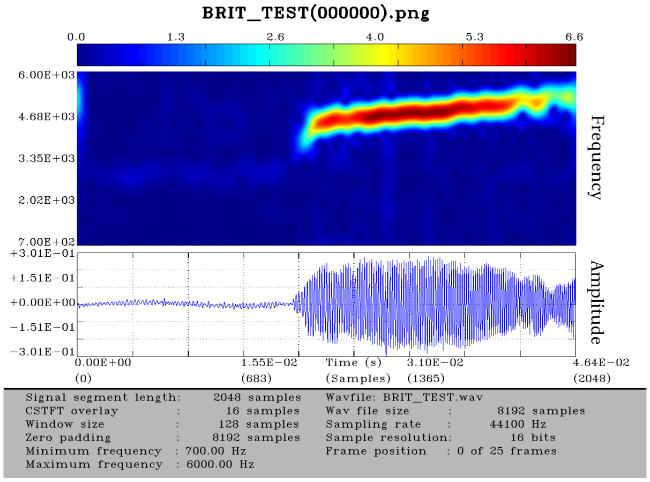


Fig. 2. DbDSP Over a Structural Mesh

It is important to emphasize that in this work SbDSP systems are viewed as overlay networks ([6], [7]) built on top of wireless mesh sensor networks and dealing with bioacoustic signal applications. In these applications either the signal sensing (acquisition), the signal communication (conveying), or the signal processing (treatment) always exhibits some form of space-time distribution. Thus, distributed signal processing always seeks to study these three aspects of an information carrying signal, namely, *signal sensing*, *signal communication*, and *signal processing*, in a unified and integrated manner. An algorithmic treatment is taken when seeking solutions to distributed signal processing problems. The algorithmic treatment concentrates on understanding foundational distributed signal processing principles utilized to *observe*, *quantify*, *represent*, *transform*, *qualify*, and *render* information carrying bioacoustic signals emanating from ensembles comprising many animal species of the native and adventive kinds; avian, terrestrial, and aquatic ([8], [9], [10]).



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Signal segment length:     2048 samples    Wavfile: BRIT_TEST.wav
CSTFT overlay         :      16 samples    Wav file size      :      8192 samples
Window size           :     128 samples    Sampling rate      :     44100 Hz
Zero padding          :    8192 samples    Sample resolution:          16 bits
Minimum frequency   : 700.00 Hz            Frame position     : 0 of 25 frames
Maximum frequency   : 6000.00 Hz
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Fig. 3. Frame for Brittoni Signal.

III. SIRLAB-NETSIG INTEGRATION

This section describes the computational modeling framework [11], termed SIRLAB (SIgnal Representation LABoratory), and how this computational framework may be embedded in a NETSIG (NETwork and SIGnal processing) integration configuration. The NETSIG integration configuration is itself described in the context of a versatile service oriented (VESO) wireless mesh sensor network [12]. SIRLAB is a tool framework written in C-language for a Linux environment and using the OpenCV (Open Source Computer Vision) platform, a software library of programming functions for near-real-time computer vision application development. SIRLAB was essentially developed as an application tool kit for environmental surveillance operations pertaining to acoustic monitoring of birds, amphibians, and aquatic animals. In this setting, it receives bioacoustic raw signal-data and it produces ordered sets of spectrogram frames which may be presented in a streaming video format due to its fast computation modality. Computer speed ups of more than 30 times have been reached when compared with MATLAB implementations utilizing the same computational resources and algorithm formulations. This has allowed to produce, under certain conditions and for some applications, streaming video with a frame rate of 30 frames per second, reaching the ATSC digital television frame rate standard. An important tool programmed in SIRLAB is the cyclic short-time Fourier transform (CSTFT), a time-frequency tool which demands a great deal of computational effort, as it grows in size, when computed at particular node, say a NETSIG integrated node in a wireless mesh sensor network environment (Figure 3).

Let $\mathbb{Z}_N = \{0, 1, \ldots, N-1\}$ denote the indexing set of N non-negative integers and let $\mathbb{Z}_N^{\times} = \{1, 2, \ldots, N-1\}$ denote the natural indexing set of $N-1$ positive integers, with $\mathbb{Z}_N^{\times} \subset \mathbb{Z}_N$. Then, denote by $l(\mathbb{Z}_N)$ the set of all complex signals of order N. The set $l(\mathbb{Z}_N)$ is isomorphic to $\mathbb{C}^N$. Now, let $x \in l(\mathbb{Z}_N)$ be an arbitrary signal to be processed and allow $v \in l(\mathbb{Z}_L)$ to be an associated window function, with $L \ll N$. Introduce $v_s[n] = v[\langle n + L/2 \rangle_N]$ as a zero-padded, shifted, version of the window signal $v \in l(\mathbb{Z}_L)$. Notice that $v_s \in l(\mathbb{Z}_N)$. For convenience, N is always taken to be of the form $N = 2^M$, $M \in \mathbb{Z}_L$. The CSTFT is then:

$$S_{x,v}[m,k] = \sum_{n \in \mathbb{Z}_N} x[n] v_s[\langle mD - n \rangle_N] W_N^{kn}, \qquad (1)$$

where, $W_N = e^{-j\frac{2\pi}{N}}$, $j = \sqrt{-1}$. Here, $D \in \mathbb{Z}_{L+1}^{\times}$ is called the displacement period, $m \in \mathbb{Z}_{N/D}$ is called the time lag, and $k \in \mathbb{Z}_N$ is called the spectral shift. The CSTFT may be interpreted as a mapping from the linear signal space $l(\mathbb{Z}_N) \times l(\mathbb{Z}_N)$ to the linear signal space $l(\mathbb{Z}_N \times \mathbb{Z}_N)$. Since the selected window remains constant, except for shifting, throughout the computation of the CSTFT, we then say that the signal $x \in l(\mathbb{Z}_N)$ is represented by the signal $S \in l(\mathbb{Z}_N \times \mathbb{Z}_N)$. It is expected that this new representation S would reveal information not readily apparent when treating x in its original format. Also, it is expected to recover x from S under certain conditions such as *window attributes* and *signal sparsity*.

The SIRLAB-NETSIG infrastructure configuration is expected to be integrated with personal digital assistant (PDA) user interface visualization capability, to allow the video database management operations to handle video content generated by the SIRLAB computational modeling framework. This is done when computing ordered frame sets in a particular NETSIG node. At the present time image frames can be retrieved from

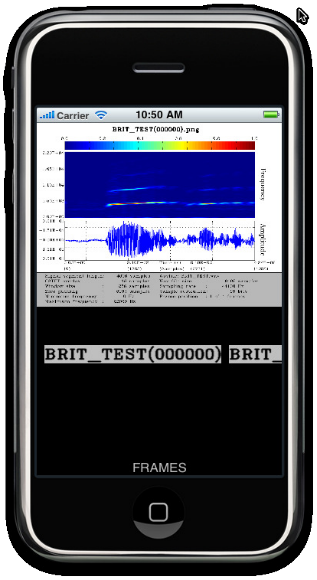

Fig. 4. iPhone Frame Display.

NETSIG node by a PDA unit such as an iPhone/iPad or Android (see Figure 4 and Figure 5).

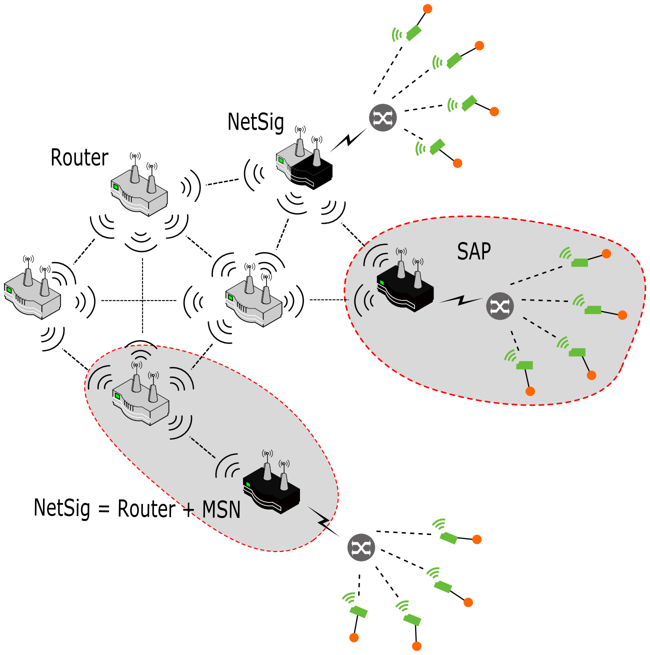

Fig. 5. VESO: An Example of SIRLAB-NETSIG Integration

IV. CONCLUSION AND FUTURE WORK

This paper presented a framework for integrating, in a unified manner (a single architecture), distributed signal processing and wireless mesh sensor network operations for environmental surveillance monitoring applications. The SIRLAB-NETSIG architecture may prove to be instrumental contributing towards automating the task of bioacoustic signal analysis for environmental surveillance monitoring applications.

V. KNOWLEDGEMENTS

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