Acoustic Source Localization with High Performance Sensor Nodes

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ABSTRACT

Distributed wireless sensor networks consisting of several single sensors are becoming very popular in many important applications. The widespread proliferation of low-cost sensor nodes is plagued by several technical challenges namely resource (e.g. bandwidth and battery power) constraints, reliability and health of sensors, and more importantly computational limitations of the nodes. The computational capabilities of low-cost distributed sensor nodes can be enhanced by inexpensive sensor boards that give the nodes the ability to preprocess the captured signals for sensor-level detection, feature extraction and direction of arrival (DOA) estimation. This paper presents a custom designed sensor board that can be interfaced with typical zigbee-based motes for multi-channel sensor-level data processing. The design is around FPGA supporting real-time data processing using five acoustic channels that can be used for numerous applications such as vehicle detection and tracking and acoustic transient (e.g. gunshots) localization. In this paper, the results on acoustic transient detection using our custom designed board sources will be presented.

Keywords: Unattended wireless sensors, acoustic transient detection and localization, FPGA-based signal processing.

1. INTRODUCTION

Distributed wireless sensor networks consisting of several single sensors with different sensing modalities such as acoustic, seismic and IR offer numerous important benefits for a multitude of applications including surveillance, situation awareness and monitoring, urban warfare, remote sensing, border patrol, and homeland security. Among these benefits are: simplicity and ease in deployment, larger coverage area, robustness to sensor failure, better spatial resolution for separating multiple closely spaced sources, less hardware complexity and hence significantly lower costs, and more flexibility in configuring different sensor array configurations.

Information System Technologies, Inc. (ISTI) has recently demonstrated and field-tested a wireless sensor network consisting of 15-20 mote-based acoustic sensor nodes for direction of arrival (DOA) estimation and vehicle localization. In a separate effort, Institute for Software and Integrated System (ISIS) at Vanderbilt University[1] demonstrated the usefulness of distributed wireless acoustic sensors for detection and localization of gunshots of various calibers. All these results are strong evidence of great potential and usefulness of the distributed wireless sensor networks for a wide variety of important applications. Nonetheless, the wireless distributed sensor network area also faces some challenging technical issues that must be addressed especially in realistic operating environments. Among these barrier issues are: efficient sensor localization, inherent inaccuracies in sensor localization and their impact on source localization, bandwidth limitations, computational limitations at the sensor-level, effects of weather and environmental conditions, and effective communication and routing of the

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source attributes to the base station. Clearly, there are other system related issues such as tolerance to adverse environmental conditions and sensor power management that are also critical for success of these systems.

The goal of this research is to address some of these critical issues and limitations in order to design and develop a low-cost and reliable wireless sensor network for several acoustic and/or seismic sensing applications. More specifically, we address the issues of onboard computational limitations and the ability to self-localize using an FPGA sensor board that can be interfaced with the available zigbee motes. Our sensor board enhances the computational capabilities of these distributed sensor nodes by enabling them to preprocess the captured signals for sensor-level detection, feature extraction and DOA or time of arrival (TOA) estimation. This added capability in turn leads to better utilization of the limited resources e.g. battery power and bandwidth for long-term operations.

The organization of this paper is as follows. In Section 2, we present the architecture of our custom designed multi-channel sensor board. The description of the constituent subsystems and components of this sensor board including the FPGA processor, five acoustic data channels, memories, a separate radio for self-localization. Section 3, introduces a new power-based sensor-level transient event detection algorithm. Some simulation results are also presented. Section 4 discusses the implementation issues of the proposed detection algorithm on the sensor boards while Section 5 presents our preliminary field-testing results on acoustic transient event detection and localization using a distributed sensor network consisting of five sensor nodes. Finally, Section 6 gives our concluding remarks and observations on this work as well as some important topics for future research.

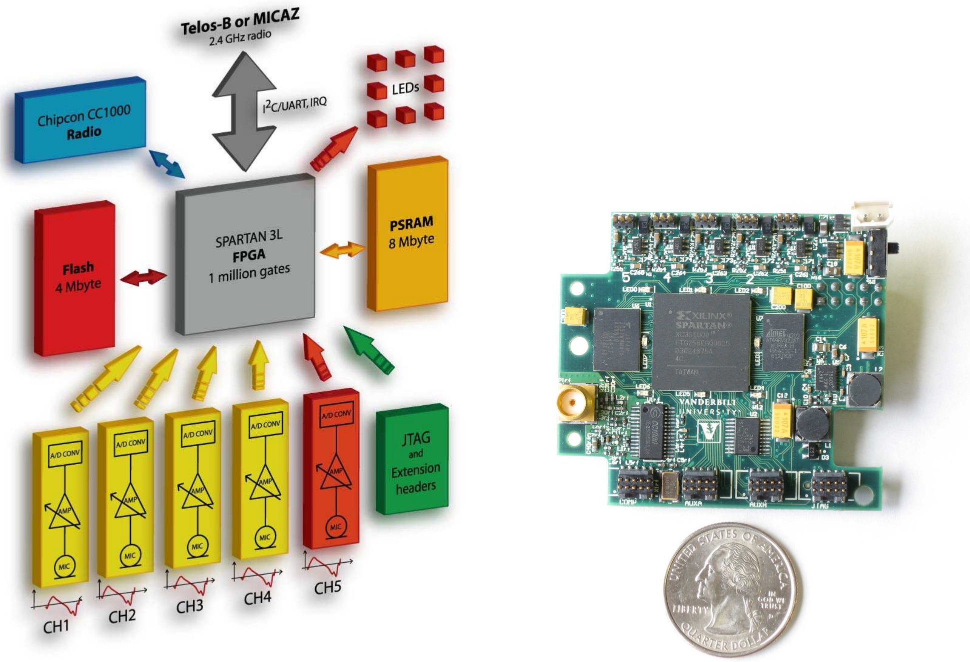
2. FPGA-BASED SENSOR BOARD DESIGN AND ARCHITECTURE

A major goal behind our design and development is to build a hardware prototype for all possible acoustic sensor-level operations needed for source detection, localization, feature extraction, data compression and encoding. As a design constraint we required that our hardware system be implemented using generic readily available components. Our joint effort with Vanderbilt University led to the design of a new sensor board using the powerful Xilinx FPGA chip. The new designed sensor board (see Figures 1(a) and 1(b)), referred to as Sensor Board 2 (SB2) in the sequel, is a four-layer PCB on which a high performance FPGA, on-board memories, one precision and four fast analog channels and an ISM-band radio have been placed. This board is a new generation of the one used by Vanderbilt University[2] with several additional features and capabilities that are described below.

Figure 1(a) shows the block diagram of the new multi-channel sensor board and its modules and architecture while Figure 1(b) shows the actual sensor board. The system is built around the Xilinx Spartan-3L FPGA having 1 million equivalent gates. The configuration process of the FPGA starts automatically from a Xilinx Platform Flash after applying the power source. The FPGA requires three different voltages that are provided by the Texas Instruments TPS75003 triple-supply power management IC. This component also guarantees the order in which the power supply voltages appear and assure the monotonic voltage ramps. These digital power supplies are separated from the analog parts of the board by power and ground planes. The SB2 operates from four AA batteries and requires an input voltage between the minimum of 4V to the maximum of 6.5V (5V typical). The sensor board also powers the mote hence no separate power arrangement is needed.

The SB2 has two types of memories. The first is a 8Mbyte (4Mx16) pseudo-SRAM having 70ns clock cycle, while the other is a 4Mbyte (2Mx16) NOR-type flash with 90ns cycle period. Both of the memories are connected directly to the FPGA pins. There are no shared pins which provide simultaneous transactions. Operating from the on-board 20MHz quartz crystal oscillator the maximum memory bandwidth for the PSRAM is 107Mbit/s in single word mode. The PSRAM can be used as sensor data buffer or as the temporary storage for intermediate variables.

The SB2 has five analog channels, as opposed to only four in the previous generation,[2] to allow for combined vehicle detection and tracking and transient event detection and localization applications. Four channels have 12-bit A/D converters supporting sampling frequencies up to 1MSPS providing a temporal resolution as low as 1μs, which is needed for the gunshot localization. These channels are operated synchronously from the FPGA. The fifth channel has a 16-bit A/D converter and supports sampling frequencies up to 100kSPS. This channel has



(a) (b)

Figure 1. (a) Multi-channel Sensor board Modules and Architecture, (b) New Sensor Board 2.

separate control lines and will be used primarily for the vehicle tracking. All five channels have a two-stage gain amplifier with an overall gain of 165-1815x (44-65dB) which can be controlled separately for all the channels in 64 steps with digital potentiometers. The first stage has an amplification of 33x (30dB), the second stage can be varied within the range of 5-55x (14-35dB). In order to reduce noise coming from the digital switching parts of the SB2, the analog channels have separate power and ground planes. Even the first amplification stage (which is the most sensitive to noise) has been separated from the second stage. The ground planes are connected at one point using inductors. The analog channels support two types of microphones by installing or removing a resistor.

The configuration of the FPGA can be done from the Platform Flash as mentioned before. The JTAG header makes it possible to use either an original Xilinx cable such as Platform Cable USB or any custom-made solutions supporting JTAG, such as the LOGSYS development cable, which not only supports configuration of the components but also allows serial communication with the board at a data rate of 1Mbit/s. This is advantageous when developing applications for the SB2. The SB2 can be used together with either the TELOS-B or MICAz/MICA2 motes, but not both at the same time. The SB2 connects to these motes via I^2C, SPI or UART. Several general purpose input/output and interrupt pins of the motes are also connected to the FPGA. As mentioned before, the SB2 supplies power to the mote. To reduce the power consumption, the power to the FPGA can be switched off by the mote in sleep mode. In this mode the digital parts of the SB2 (including the FPGA) and the second stage of the analog channels are off, hence the power consumption is very low ($5mA$). If TELOS-B mote is used the FPGA can be waken up by continuous monitoring the output of the fifth analog channel. While for the MICAz/MICA mote the same can be accomplished via one of the four other channels.

The additional Chipcon CC1000 radio module on the FPGA sensor board is intended primarily for phase interferometric-based sensor localization.[3] This is mainly due to a very special feature available on the board that employs high resolution frequency tuning. The received signal strength can be measured with a 12-bit A/D, which is of the same type that is used for the four analog channels. There are also three extension headers on the SB2. These 8-bit connectors allow the connection of optional components such as digital compass or GPS.

Signal processing applications can either be implemented directly using FPGA logic or by instantiating a microprocessor system inside the FPGA (System-on-a-Chip). In the latter case, the NOR-type flash can be used as application storage. It is also possible to use dedicated logic for time critical processes and implement control in a soft processor using assembler or C, which speeds up development.

3. SENSOR-LEVEL TRANSIENT EVENT DETECTION

In the distributed transient event detection the sensors need to determine and agree on the presence of a transient signature, its time duration, and more importantly its onset. This is crucial to the success of the subsequent operations including transient localization. In a distributed sensor network several sensor nodes are coordinated by a gateway at the center of the cluster with certain radius. There could be multiple sensor clusters in a distributed sensor network. We assume that the sensors sample the received signal at a fixed sampling rate and each sensor clock is synchronized. The clock synchronization method in,[1] which is based upon message routing, can be used to synchronize the sensor nodes. The sensor positions are also assumed to be known to the base station. Transient signals, such as the flash of an explosion, the launch of an RPG, or machine gunfire are received by a subset of the sensors, especially the ones closer to the source. These transient signals are usually wideband and occupy only a small time duration.

The transient signal model for muzzle blast in presence of noise and multipath is as follows. Most of the time, the sensors only receive background noise due to the transient nature of the signal of interest, i.e. $x_k(m) = n_k(m), \quad k = 1, 2 \ldots, K$ where K is the number of the sensors. We model background noise $n_k(m)$ as zero-mean white Gaussian noise with variance σ_k^2. If at time T_0, a transient signal (e.g. muzzle blast) $s(m)$ is emitted from a wideband source, then the k^{th} sensor received signal is

$$x_k(m) = \begin{cases} \alpha_k s\left(m - \frac{d_{k,s}}{c}\right) + n_k(m), & m = T_0, T_0 + 1, \ldots, T_1, \\ n_k(m), & 1 \leq m < T_0 \text{ and } T_1 < m \leq M, \end{cases} \tag{1}$$

where $\alpha_k \propto \frac{1}{d_{k,s}}$ represents the effect of signal attenuation which is inversely proportional to distance travelled, $d_{k,s}$, between the source and the kth sensor, c is the speed of sound in air, and $T_1 - T_0$ is the time duration of the transient event.

The first step in the process is to detect the presence of the transient events in the signals recorded by all or a subset of the sensor nodes. Here we develop a simple and yet very effective power-based algorithm for transient signal (muzzle blast) detection that performs two tasks. One is transient signal detection at each sensor and the other is decision fusion using sensor networks. Although most of the existing transient signal detection methods are based upon hypothesis testing, here we would like to determine not only the existence of the transient but also its onset and time duration. Our power-based detector is closely related to the Nuttall's maximum detector[4] with the difference that we also estimate the onset and duration of the transient. The statistical performance of this detector is also derived.

The proposed simple power-based detector goes like this. For each sensor, we take a snippet of L samples. The energy of recorded signal at sensor k within the snippet is computed using

$$\xi_k(iL) = \sum_{l=iL+1}^{iL+L} x_k^2(l),$$

This provides the statistic for signal detection assuming that the background noise is a stationary Gaussian process. Here $iL + 1,\ i = 0, 1, \ldots,$ is the onset of the snippet. In the absence of transient signal, ξ has a scaled Chi squared distribution with degree of freedom L. To decide the presence of a transient signal, the sensor checks if there are two consecutive snippets with energy $\xi_k(iL), \xi_k((i+1)L) > \gamma_1 \sigma_k^2$ where γ_1 can be chosen according to some prescribed false alarm rate (FAR). Note that FAR should be very small. For instance, if the length of a snippet is 10 ms, then a FAR 1% implies that there will be on average one false alarm each second, which is generally unacceptable. For some low FAR P_{FA}, we can find the threshold γ_1 such that the following probability condition holds

$$Pr\left(\frac{\xi_k(iL)}{\sigma_k^2} > \gamma_1, \frac{\xi_k((i+1)L)}{\sigma_k^2} > \gamma_1\right) = P_{\text{FA}}, \tag{2}$$

which is equivalent to

$$Pr\left(\frac{\xi_k(iL)}{\sigma_k^2} > \gamma_1\right) Pr\left(\frac{\xi_k((i+1)L)}{\sigma_k^2} > \gamma_1\right) = Pr\left(\frac{\xi_k(iL)}{\sigma_k^2} > \gamma_1\right)^2 = P_{\text{FA}}, \tag{3}$$

because the background noise on each sensor is assumed to be temporally white. Note that in the absence of signal, $\frac{\xi_k(iL)}{\sigma_k^2} \sim \chi_L^2$. Hence γ_1 is easy to determine. Once the kth sensor detects two snippets with $\xi_k(iL), \xi_k(iL+L) > \gamma_1\sigma_k^2$, then it announces the advent of a transient signal and marks the beginning point as $iL+1$. Now, to detect the end of the transient signal, the sensor would check if there are consequently 3 snippets having energy lower than $\gamma_2\sigma_k^2$. If there is no transient signal, the probability of having 3 consecutive snippets with energy less than $\gamma_2\sigma_k^2$ is

$$Pr\left(\frac{\xi_k(iL)}{\sigma_k^2} < \gamma_2, \frac{\xi_k((i+1)L)}{\sigma_k^2} < \gamma_2, \frac{\xi_k((i+2)L)}{\sigma_k^2} < \gamma_2\right).$$

Similar to (3), we determine γ_2 by solving

$$Pr\left(\frac{\xi_k(iL)}{\sigma_k^2} < \gamma_2\right)^3 = P_{\text{D}}, \tag{4}$$

where P_{D} stands for the probability of detecting the end of the transient signal.

As can be seen, the developed detection method not only detects the existence of an acoustic transient in the sensor recorded data but also the onset and duration of the detected signal. This feature of our scheme is crucial to the success of the TDOA or TOA estimation methods. This would also allow for accurate time stamping of the transient event, which can be used in the overall assessment of the military scene. Moreover, the simplicity and power-based nature of this algorithm makes it ideally suitable for inexpensive low-power portable units.

Here, we present some results on a transient signal associated with 20mm gunfire. The noise-free gunfire acoustic waveform is shown in Figure 2(a). (The .wav files are downloaded from http://www.rcexchange.com/) The sample rate is $F_s = 4410$Hz. The signals received by four sensors in the distributed network at different distances from the source are shown in Figure 2(b)-(e). Note that here a simple distance-based signal attenuation model is imposed. As a result, the prominence of the received transient signal depends only on the distance between the acoustic source and the sensors and hence no phase perturbation, e.g. due to atmospheric effects, is considered. Figure 3 shows the plots of the snippet energy of four sensors. In our simulation, we choose the snippet length of 42, which corresponds to a time window length of 9.5 millisecond. It can easily be seen from Figures 2 and 3 that different sensors may have different conclusions on the existence of a transient signal as well as on the duration of the signal.

In the next section, we present one possible implementation of the proposed transient detection algorithm in this section on FPGA including communication with Telos-B mote and data storage.

4. SENSOR BOARD IMPLEMENTATION OF TRANSIENT DETECTION

The detection algorithm requires computing the signal energy of the last three snippets. In order to provide these, the detector module accumulates and stores the energy content of three consecutive snippets. The decision logic is activated after new snippet commences. Using the power values and the thresholds a decision is made. If two consecutive snippets have power values higher than the onset threshold, the start of transient event signalled to the memory controller. If the power value is lower then the end threshold for at least three snippets, the end of transient event is signalled. The decision only takes $50ns$, $1.25\mu s$ with the additional delay of the data path. More importantly, this time is deterministic and is not affected by the number of active analog channels as they are working fully parallel.

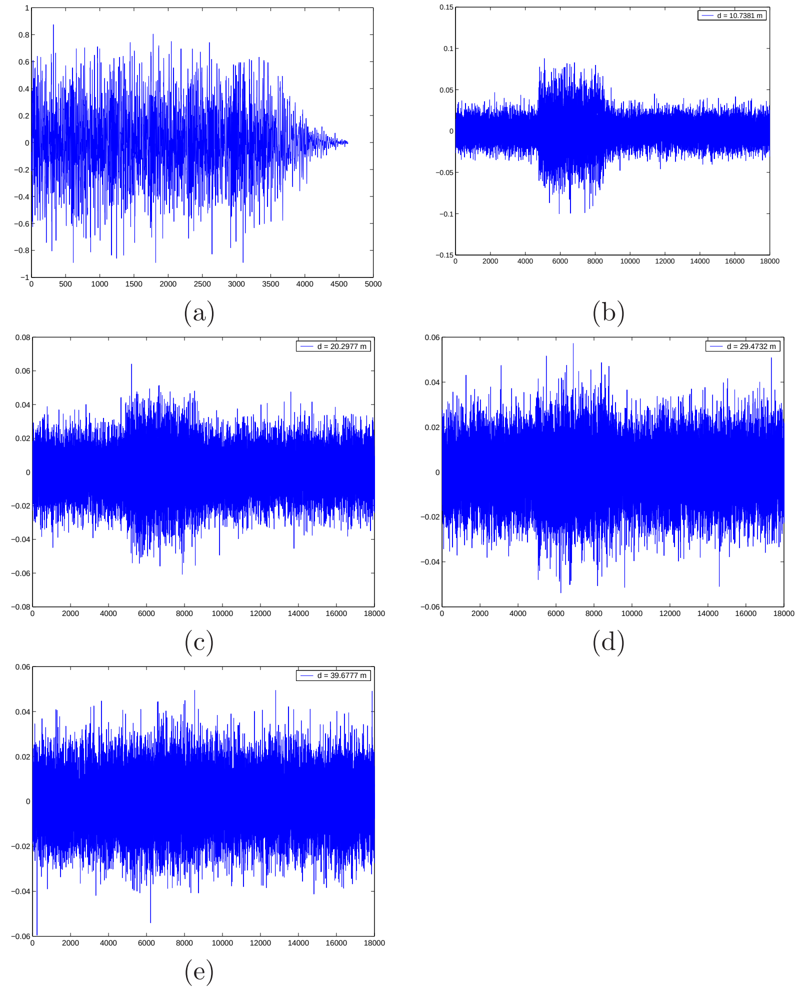


Figure 2. (a) The original 20mm gun fire acoustic signature and the received signals of different sensors for (b) $d_{1,s}$ = 10.7381m (c) $d_{2,s}$ = 20.2977m (d) $d_{3,s}$= 29.4732m (e) $d_{4,s}$=39.6777m.

The implementation of the detection algorithm requires several modules which construct the data path. Figure 4 shows not only the structure of the data path but also the entire application. The 12-bit A/D converters are used in continuous sampling mode providing new samples every $61\mu s$ ($f_s = 16384Hz$). The detector module implemented in the FPGA should receive squared mean compensated sample values. There are two major ways to implement mean compensation on the FPGA. One of them utilizes a low-pass FIR filter. This structure should only be used if the sampling frequency is high since it consumes a large amount of FPGA fabric, especially when high tap-count filter is considered. If the ratio of the FPGA clock frequency and the sampling frequency is high, more than the length of window required for mean compensation (present case), a second method yields more economical realization using a block RAM for accumulation and summation of the elements after every single incoming sample. The squaring module calculates the squared mean compensated sample values in two FPGA clock cycles ($100ns$). The memory controller is responsible for data transfers, reading and writing both the SRAM and the flash, copying from one to the other and also takes care of meta data that should be written to the flash.

Each sensor node is formed of a Telos-B mote, a SB2 attached to the mote, five acoustic channels with Panasonic WM-64 omnidirectional microphones and wind screen, external antenna, and battery pack. Figure 5 shows a sensor node without the microphones casing and battery pack. In this application, the Telos-B motes

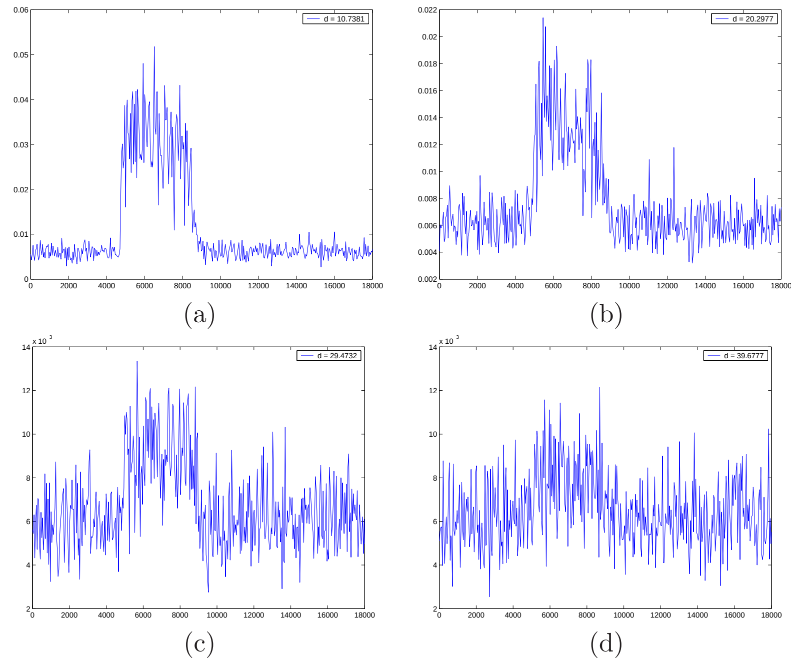


Figure 3. The output of the power detector applied to the signals in Figure 2.

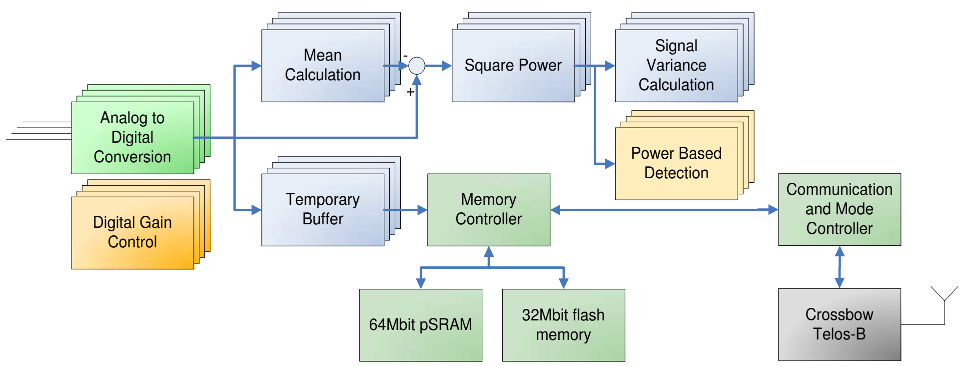


Figure 4. Block diagram of transient detection application

are only responsible for wireless command and data transmission services and time synchronization. They are also used as gateways to control the SB2's from the base station (a mote that is connected to the PC). The entire system consisting of several sensor nodes is controlled globally via a MATLAB based GUI running on a PC at the base station. A set of commands is implemented for both the Telos-B and the SB2, which can be sent by the user via the GUI. These commands include: activating the nodes for detection, updating the detection parameters, requesting for recorded time series from the SB2's and subsequent transmission schedule to the base station. The user interface allows to graphically keep track of the status of all the nodes in the network.

After deploying and switching on the nodes, the nodes are in 'idle state' unless activated by the user. The user at the base station can wirelessly send the parameters for the detector namely γ_1, γ_2 and L to the deployed nodes. Having received the right parameters set, it is necessary to update the ambient background noise variance on each node depending on the environment in which they are deployed. Additionally, the variance for each acoustic channel should also be determined separately due to slightly different sensitivity of the microphones.

Figure 5. A sensor node - consisting of Telos-B mote and Sensor Board 2

The SB2 calculates the variance based on a two second snapshot of mean compensated input samples and sets the thresholds for the detectors using all the received parameters. At this time, the detectors are still in the idle state i.e. not seeking for any event.

The user at the base station enables the nodes to look for transient events. Once the nodes are activated an event is considered to be detected when the energy in two successive blocks of data is greater than $\gamma_1\sigma_k^2$ as mentioned in the previous section. Upon detection, the SB2 should notify the mote that an event occurred and also needs a time stamp to be stored in the flash along with the appropriate segment of time series. The fastest method of notification is asking for an interrupt on a dedicated I/O connection line between the SB2 and the Telos-B from the mote. The interrupt latency of mote-TinyOS is typically $25\mu s$. Upon receiving this interrupt request, the mote saves its periodically updated time stamp and also sends it to the SB2. The onset of the transient event is detected two snippets after the actual start of the event due to the properties of the detection method. In order to capture the whole transient event, buffering is used in the SB2 to retain the two snippet size worth of data. The buffers are realized with dual-port block RAMs. After the onset detection, all the data in the buffer is copied to the SRAM on SB2 along with the new samples. This temporary buffering is transparent, i.e. all samples are immediately forwarded to the SRAM. The recording is continued until the detectors of all used analog channels on a single node declare the end of the transient. For reliability purposes, the SB2 also stores the transient events sequentially in the onboard flash memory with meta data (e.g. length of the transient event, time stamp). Thus, all the events detected by a node are also available for off-line access and analysis even if radio packet loss is high. After finishing with storage operations, the FPGA sends the duration of the transient event to the mote which also means it is ready for data transmission. The mote requests for packets of data from the SB2 and forwards them wirelessly to the base station. The data from the nodes is transmitted in a sequential order to the base station.

5. RESULTS ON TRANSIENT DETECTION AND LOCALIZATION

In this section, we present some preliminary results of acoustic transient event detection and subsequent localization. In our experimental setup, five sensor nodes are randomly deployed in an area of 20m $\times$ 30m. The coordinates of the sensor nodes are obtained using a GPS unit. The Flooding Time Synchronization Protocol (FTSP)[5] developed by the Vanderbilt University is used to synchronize the local clocks of the Telos-B mote in the sensor nodes. In the FTSP method, a root node sends periodic synchronization message. The nodes receiving the synchronization message utilizes the MAC layer times-tamping and linear regression to provide an estimate of the root node's clock (global clock) based on its own local clock. Thus, the FTSP method enables the mote to provide a highly (within $60\mu s$) accurate global time stamp of the transient events which is very important for the subsequent localization of the transient events. The TDOA between sensor pairs are computed at the base station by cross-correlating the acoustic time series of the transient event. The reference node is chosen to be the one that has the highest signal variance. The robust source localization method in[6] was then used to estimate the source position based upon the computed TDOA's. This method is robust to erroneous TOA or TDOA estimates and outliers caused by false alarms, clock synchronization error, and non-line-of-sight and multipath problems that are prevalent in MOUT scenarios.

An acoustic transient event is generated from a known location. If an event is detected at any of the five deployed nodes, the acoustic time series of the event and the event time stamp are wirelessly transmitted to the base station using the mote radio. Figure 6 shows the time series of a typical acoustic event detected in all the five nodes. Figure 7 shows the position of the sensor nodes, the true target location and the estimated target location marked 'o', $'\triangle'$ and $'\times'$, respectively. The transient event is generated from the same location at six different instances and in all the six instances, the transient event was localized within a radius of 50cm. The average localization error radius was found to be around 38cm. In one of the cases, only three out of the five sensors picked the transient event, which yields only three TDOA estimates. However, the robust source localization algorithm was still able to localize the source within an error radius of 50cm. It must be pointed out that the GPS used to determine the sensor locations has approximately 20cm localization error.

These initial results show the usefulness of our simple transient detection algorithm as well as the power of our low-cost sensor board that makes sensor-level detection, collaboration and feature extraction a reachable reality for distributed acoustic sensor networks.

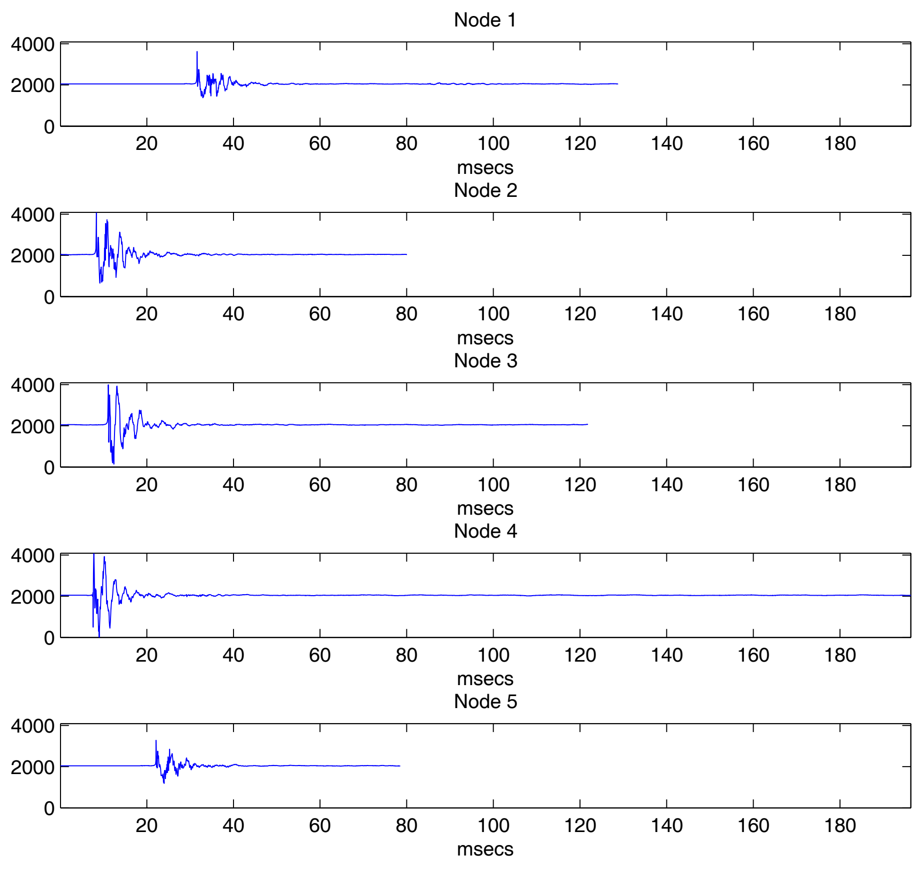


Figure 6. Acoustic data of the detected event in the five nodes.

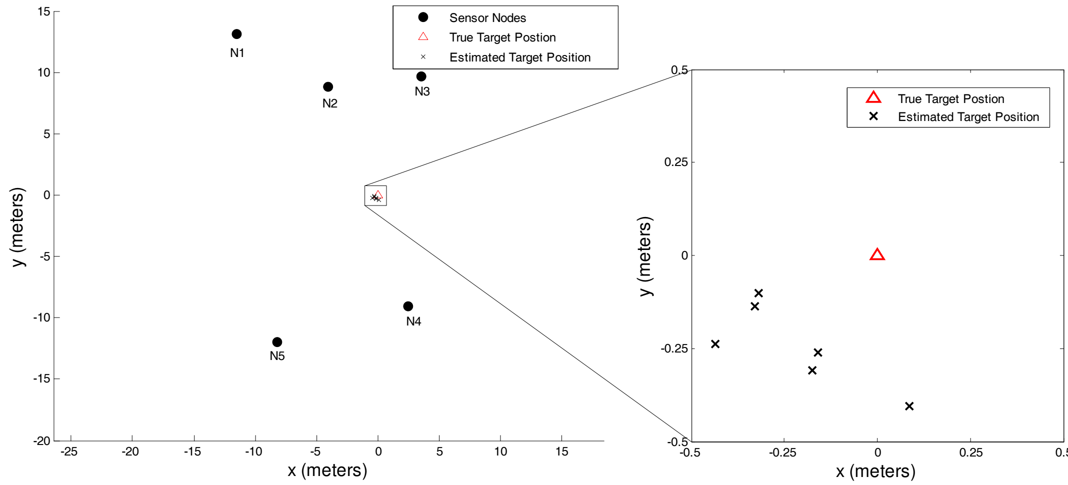


Figure 7. Plot showing the deployed sensor nodes, the true target position and the estimated target location. Also shown is the portion of interest around the true target position.

6. CONCLUSIONS

This paper addresses the problem of sensor-level signal processing for low-cost distributed sensor networks. The design and architecture of a new multi-channel FPGA-based sensor board is presented. This sensor board can either be used as a stand-alone node or easily integrated with available low-cost zigbee-based motes such as TELOS-B or MICA-Z. The multiple acoustic channels and the onboard memories allow for high level signal processing tasks, such as transient detection, feature extraction and DOA/TOA estimation, to be carried out on each node. The Chipcon CC1000 radio module can be used for self-localization using the phase interferometric method in.[3]

A new power-based method for acoustic transient event detection is also presented. This method not only detects the existence of an acoustic transient in the recorded sensor data but also the onset and duration of the detected signal. This feature, coupled with its simplicity makes this method ideally suitable for sensor-level implementation. To this end, we implemented this algorithm on our FPGA-based sensor board to capture the signature of the transient events and efficiently transmit the detected transient signals or its features to a base station where source localization and classification can be carried out. Preliminary results presented in this paper show the promise of our sensor board to carry out computationally laborious sensor-level signal processing operations for acoustic transient event detection and localization.

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