Wireless Integrated Network Sensors (WINS)

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ABSTRACT

Wireless Integrated Network Sensors (WINS) provide distributed network and Internet access to sensors, controls, and processors that are deeply embedded in equipment, facilities, and the environment. The WINS network is a new monitoring and control capability for applications in transportation, manufacturing, health care, environmental monitoring, and safety and security. WINS combine microsensor technology, low power signal processing, low power computation, and low power, low cost wireless networking capability in a compact system. WINS networks will provide sensing, local control, and embedded intelligent systems in structures, materials, and environments. This paper describes the WINS architecture and WINS technology components including sensor interface and WINS event recognition systems.

Keywords: Wireless integrated network sensors, WINS, distributed sensors, sensor signal processing, wireless networking

1. INTRODUCTION

Wireless integrated network sensors (WINS) combine sensing, signal processing, decision capability, and wireless networking capability in a compact, low power system.[1-7] Compact geometry and low cost allows WINS to be embedded and distributed at a small fraction of the cost of conventional wireline sensor and actuator systems. WINS are a fundamental advance for network access to densely and deeply distributed sensing, control, and processing systems. Applications for WINS extend from a global scale to a local scale. For example, on a global scale, WINS will permit monitoring of land, water, and air resources for environmental monitoring. On a national scale, transportation systems, and borders will be monitored for efficiency, safety, and security. On a local, wide-area scale, battlefield situational awareness will provide personnel health monitoring and enhance security and efficiency. Also, on a metropolitan scale, new traffic, security, emergency, and disaster recovery services will be enabled by WINS. On a local, enterprise scale, WINS will create a manufacturing information service for cost and quality control. WINS for biomedicine will connect patients in the clinic, ambulatory outpatient services, and medical professionals to sensing, monitoring, and control. On a local machine scale, WINS condition based maintenance devices will equip powerplants, appliances, vehicles, and energy systems for enhancements in reliability, reductions in energy usage, and improvements in quality of service. The embedding of WINS networks enables smart structures, materials, and environments.

The opportunities for WINS depend on the development of a scalable, low cost, sensor network architecture. This requires that sensor information be conveyed to the user at low bit rate with low power transceivers. Continuous sensor signal processing must be provided to enable constant monitoring of events in an environment. Thus, for all of these applications, local processing of distributed measurement data is required for a low cost, scalable technology. Distributed signal processing and decision making enable events to be identified at the remote sensor. Thus, information in the form of decisions is conveyed in short message packets. Future applications of distributed embedded processors and sensors will require massive numbers of devices. Conventional methods for sensor networking would present impractical demands on cable installation and network bandwidth. By reducing the requirements for transmission of measured data, the burden on communication system components, networks, and human resources are drastically reduced.

WINS systems have been developed for applications at multiple tiers. For example, the applications described above for geographically wide distribution of WINS technology demand long range wireless communication links. In contrast, many applications in factory automation or health care require local area networks. In this application, as will be described, WINS networks may exploit the advantages of short range, robust, multihop wireless networks.

WINS network devices will support local sensing[1-3] and control with response requirements ranging from real-time through latency tolerant processes. A critical requirement for WINS networks is the capability for constantly vigilant signal processing and event recognition associated with this sensing and control.[4] This paper will describe recent developments in micropower sensor interface systems and methods for signal processing and event recognition for defense security applications and smart materials and structure applications based on WINS condition based maintenance.

2. WINS NETWORK ARCHITECTURE

The WINS architecture design addresses the constraints on robust operation, dense and deep distribution, interoperability with conventional networks, operating power, scalability, and cost (see Figure 1). Robust operation and dense, deep distribution benefit from a multihop architecture where the naturally occurring short range links between nodes is exploited to provide multiple pathways for node-to-node, node-to-Gateway, and Gateway-to-network communication. WINS Gateways provide support for the WINS network and access between conventional network physical layers and their protocols and the WINS physical layer and its low power protocols. Multihop communication, as will be discussed, also enables low power operation by reducing range and exploiting the power-law dependence of received RF signal strength on transmission range. The reduction in link range afforded by multihop communication is of particular benefit to the many (and greater fraction) of WINS applications that are tolerant to communication latency. Communication latency in the WINS network is, in turn, tolerable due to the inherent latency associated with the response of conventional networks. The reduction on link range is exploited in WINS system design to provide advantages that may be selected from the set of: reduced operating power, improved bit rate, improved bit error rate, improved communication privacy (by reduction of transmit power), simplified protocols, and reduced cost. Of course, all of these benefits are not obtained simultaneously, but instead must be extracted depending on design emphasis. As will be described, low power sensor interface and signal processing architecture and circuits enable continuous low power monitoring.

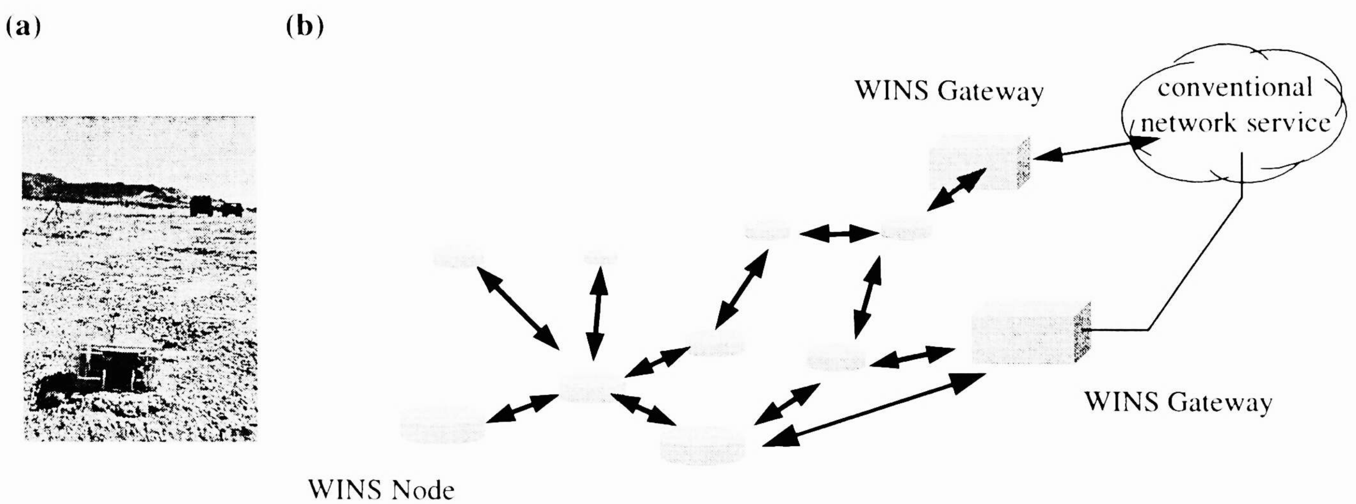


Figure 1. WINS nodes are distributed at in an environment to be monitored or controlled. Panel (a) shows a WINS node in a field test environment. Panel (b) displays the WINS network architecture. Multihop communication permits low power operation of dense WINS sensor networks. Redundant pathways provide robust access in complex operating environments. WINS node data is transferred over the asymmetric wireless link to an end user or to a conventional wireline or wireless (IP) network service through a WINS Gateway, a network bridge. Multiple WINS Gateways support the WINS network and provide redundant access to conventional network services through wireless or wireline high bit rate links.

In contrast to conventional wireless networks, the WINS network must support large numbers of sensors in a local area with short range and low average bit rate communication (less than 1 - 100 kbps). The network design must consider the requirement to service dense sensor distributions with an emphasis on recovering environment information. The WINS architecture, therefore, exploits the small separation between WINS nodes to provide multihop communication. Conventional wireless networks are supported by complex protocols that are developed for voice and data transmission for handhelds and mobile terminals. These networks are also developed to support communication over long range (up to 1km or more) with link bit rate over 100kbps.

Multihop communication yields large power and scalability advantages for WINS networks. First, RF communication path loss has been a primary limitation for wireless networking, with received power, P_{REC}, decaying as transmission range, R, as $P_{REC} \propto R^{-\alpha}$ (where α varies from 3 – 5 in typical indoor and outdoor environments). However, in a dense WINS network, multihop architectures may permit N communication link hops between N+1 nodes. In the limit where communication system power dissipation (receiver and transceiver power) exceeds that of other systems within the WINS node, the introduction of N equal range hops between any node pair reduces power by a factor of $N^{\alpha-1}$ in comparison to a single hop system. Multihop communication, therefore, provides an immediate advance in capability for the WINS narrow bandwidth devices. Clearly, multihop communication raises system complexity. However, WINS multihop communication networks permit large power reduction and the implementation of dense node distribution.

3. WINS NODE ARCHITECTURE

The WINS node architecture (Figure 2) is developed to enable continuous sensing, signal processing for event detection and local control of actuators, event identification, and communication at low power. Since the event detection process must occur continuously, the sensor, data converter, data buffer, and signal processing must all operate at micropower levels. In the circumstance that an event is detected, a process may be alerted for identification of the event. Protocols for node operation then determine whether energy should be expended for further processing and whether a remote user or neighboring WINS node should be alerted. The WINS node then communicates an attribute of the identified event, for example, the address of the event in an event look-up-table stored in all network nodes.

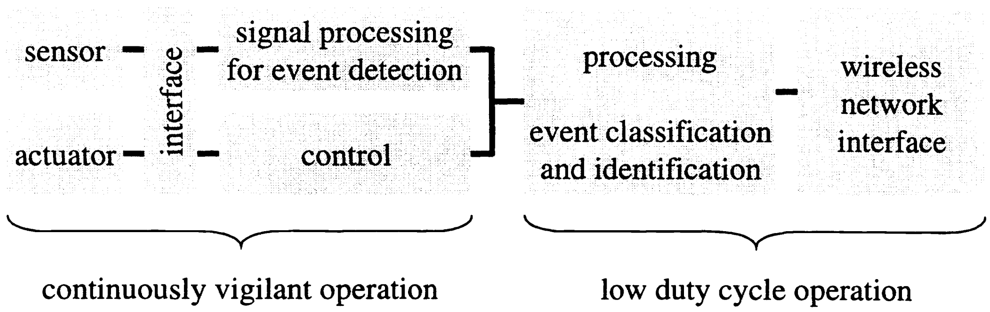


Figure 2. The wireless integrated network sensor (WINS) architecture includes sensor, actuator, interface, signal processing, and control functions. Processing supports functions including event classification and identification. A wireless network interface may support a wide range of physical layers that are adapted to the specific WINS application. For short range, local area systems, micropower RF communication provides bidirectional network access for low bit rate, short range communication. The architecture is partitioned between micropower components operating continuously for event recognition, while the network interface operates at low duty cycle.

Many primary LWIM applications require sensor nodes powered by compact battery cells. Total average system supply currents must be less than 30μA to provide long operating life from typical compact Li coin cells. Low power, reliable, and efficient network operation is obtained with intelligent sensor nodes that include sensor signal processing, control, and a wireless network interface[1]. The signal processors developer here can supply a hierarchy of information to the user ranging from a single-bit event detection, to power spectral density (PSD) values, to buffered, real time data.[4] This programmable system matches its response to the power and information requirements.

Unique requirements for the WINS node appear for sensors and micropower sensor interfaces. For the particular applications of military security, the WINS sensor systems must operate at low power, sampling at low frequency, and with environmental background limited sensitivity. The micropower interface circuits, implemented in low cost CMOS technology, must sample at dc or low frequency where "1/f" noise limits input noise at the interface.

While unique requirements exist for low power node operation, there is a balancing set of unique operational characteristics that permit low power operation if properly exploited. In particular, WINS applications are generally tolerant to latency. Specifically, in contrast to conventional wireless network applications where latency is not tolerated, the WINS node event recognition may be delayed by 10 – 100 msec, or longer. This permits low clock rate signal processing and architecture design that minimizes computation and communication power at the expense of latency. For example, in the latency-tolerant WINS system, time division multiple access protocols may be implemented to reduce communication power. Also, it is important to note that sensor signals are generally narrowband signals (bandwidth less than 10kHz) that require only low sample and processing rates.[4]

4. WINS MICROSENSORS AND INTERFACE CIRCUITS

The WINS microsensor systems include accelerometer and infrared sensor systems.[1-3] As was noted above, the WINS microsensor systems must be monitored continuously by interface and signal processing systems. A CMOS micropower analog-to-digital converter (ADC) has been developed for this critical interface application. Power requirements constrain the ADC design to power levels of 30μW or less. Sensor sample rate for typical microsensor applications is less than 1kHz (for example the infrared microsensor bandwidth is 50Hz, thus limiting required sample rate to 100 Hz). Also, it is important to note that the signal frequency is low. Specifically, the themopile infrared sensor may be employed to detect temperature, presence, of motion at near dc signal frequencies. Therefore, the ADC must show high stability (low input-referred noise at low frequency). For the WINS ADC application, a first order Sigma-Delta (Σ-Δ) converter is chosen over other architectures due to power constraints. The Σ-Δ architecture is also compatible with the limitations of low cost digital CMOS technologies.

(a) **(b)** **(c)**

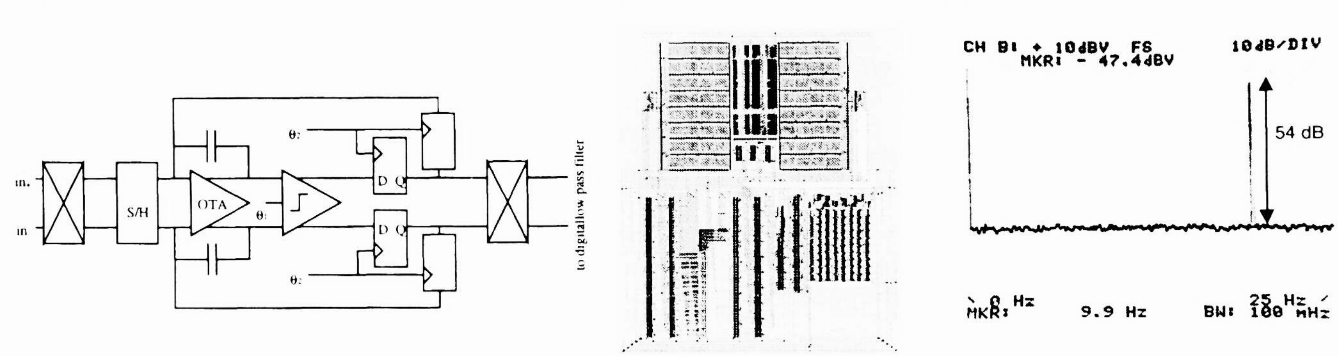


Figure 3. (a) The WINS Σ-Δ ADC. The chopper architecture suppresses "1/f" input noise and preserves 9-bit resolution through the low frequency region of the spectrum to below 0.1 Hz. (b) The WINS Σ-Δ ADC chip layout. (c) The WINS Σ-Δ ADC response to a 20 Hz full-scale (0.5 V p-p) sinusoid input signal.

The analog components of the ADC operate in deep subthreshold to meet the goal of micropower operation [2]. This imposes severe bandwidth restrictions on the performance of the circuits within the loop. A high oversampling ratio of 1024 is thus chosen to overcome the problems associated with low performance circuits. The possible increased power consumption of digital components in the signal path including the low pass filter is minimized with the use of low power cell libraries and architecture.

Implementation of low noise ADC systems in CMOS encounters severe "1/f" input noise with input noise corner frequencies exceeding 100 kHz. The WINS ADC applications are addressed by a first-order converter architecture combined with input signal switching (or chopping). The chopper ADC heterodynes the input signal to an intermediate frequency (IF) before delivery to the Σ-Δ loop. An IF frequency of $1/8^{th}$ of the ADC sampling frequency is chosen. The required demodulation of the IF signal to the desired baseband is accomplished on the digital code modulated signal, rather than on the analog signals. This both simplifies architecture and avoids additional injected switching noise. The architecture of the chopped Σ-Δ ADC is shown in Figure 3.

The first order Σ-Δ ADC has been fabricated in the HPCMOS 0.8μ process (Figure 3). Direct measurement shows that the converter achieve greater than 9 bit resolution for a 100 Hz band limited signal with a power consumption of only 30μW on a single 3V rail. This chopper ADC has been demonstrated to have a frequency-independent SNR from 0.1 – 100Hz (Figure 3). This resolution is adequate for seismic and infrared sensor motion detection applications.

5. WINS SIGNAL PROCESSING AND EVENT RECOGNITION

WINS networks have been developed and have been demonstrated in multiple battlefield and condition based maintenance applications. These applications have the primary requirement of event recognition. WINS network distribution enhances the accuracy and sensitivity of event recognition. For example, it has been shown that WINS enable network signal processing where the aggregation of information from multiple, distributed sensors can be applied to identifying threats. Also, the dense distribution of WINS increases the probability that nodes are located near the signal sources creating events of interest (whether the signals are seismic signals due to threat motion or vibration signals due to an event associated with equipment operation). Thus, WINS networks of low cost sensors, operate at an advantage over conventional sensor networks operating with sparse, large scale nodes. Specifically, densely distributed WINS nodes receive the signals emanating from threat sources at relatively short range, and enhanced signal-to-noise ratio. The following discussion is directed largely to battlefield surveillance applications, but, is applicable in most WINS event detection problems.

Operation of distributed seismic and acoustic threat detection sensors in field conditions reveal a number of challenges for signal classification and identification. Specifically, variation in the node deployment environment yields distortion of threat signals. Also, variation in threat motion yields rich variation in signal characteristics. Finally, many important threat events produce complex and short impulse signals. These characteristics have guided the development of a signal processing method that is adapted for identifying events in the midst of widely varying environmental influences on signal source and signal propagation. This new method, the Signal Search Engine (SSE) is developed to permit direct comparison of unknown threat signals to a large library of stored threat templates. While the SSE may provide frequency and time domain signal processing functions for event identification, time domain signal processing methods are emphasized here to accommodate analysis of short impulse signals.

The SSE architecture is shown in Figure 4. The SSE compares unknown event records with stored library signals using a low power correlator. Operation of the SSE begins with the selection of a set of signal library elements (correlators). These correlators are short data packets (length of 10 – 100ms) selected *directly* from field records. (The SSE results for tracked and wheeled vehicle seismic records will be discussed here.) The correlation between the signal correlator packet and unknown signals is computed over the full length of the unknown signal data series (typical length of 10 – 20s). The correlation process yields a new oscillatory signal. A short term average rms value of this signal is then computed over an adjustable time window (100 – 1000 ms).

SSE analysis continues with an examination of the rms value of each inner product result. As shown in Figure 5, the SSE operating on a set of seismic records (obtained in WINS seismic sensor field tests) favors a single seismic record and accurately classifies an event as resulting from a particular vehicle. The SSE operation may be optimized for signal identification through selection of: 1) the correlator time series segment, 2) the correlator segment length, 3) the window period for rms averaging, 4) filtering and subsampling of the correlator and data series. The optimization of these parameters may be completed prior to the initial configuring of the WINS node.

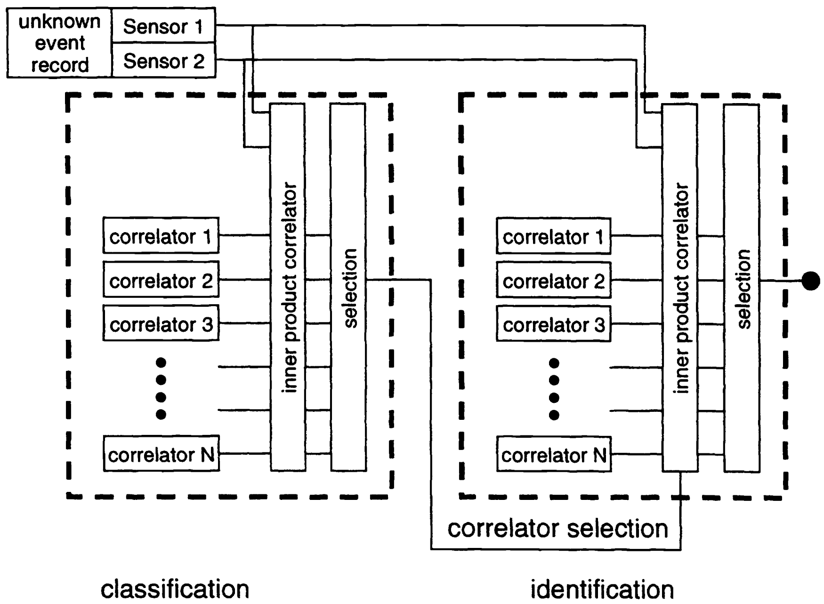


Figure 4. A schematic view of the Signal Search Engine (SSE) architecture is shown. The SSE compares unknown event records with stored library signals using a low power correlator engine. Two stages of inner product correlators are shown above. The first stage correlator classifies unknown event records into classes. The second stage correlator Multiple sensor data streams may be employed, while two are shown here. A hierarchy of signals may allow signals to be first classified, then identified. The hierarchical search minimizes the number of computations required to arrive at identification. In addition, the benefits of energy expenditure as a function of improved identification accuracy may be estimated and used to manage node energy

The SSE offers scalability capabilities for multiple sensor data streams. In addition, SSE operation has also been demonstrated for the identification of events using information derived from the time evolution of a signal. Specifically, the SSE operates on data obtained during the approach, departure periods of a vehicle traveling past a seismic WINS sensor.

Clearly, selection of the correlator library elements, shown in Figure 4, is critical in obtaining successful identification. Correlator selection may focus on two goals: 1) capability for hierarchical event classification (where classification is a process that identifies an event as being a member of a class of event types), and 2) capability for event identification (where identification is process that identifies an event as being a member of specific event type). For example, the correlator engine may *classify* a battlefield seismic event as being due to a vehicle in the wheeled or tracked classes. A subsequent correlator engine operation may refine this classification into a further library subclass. Finally, continued operation leads to identification of the event type. This hierarchical search method may yield robust operation, metrics for identification confidence, and minimizes the required total number of correlation operations.

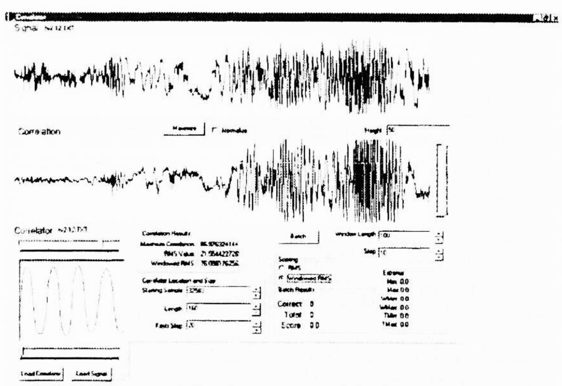
The SSE offers low power operation through its hierarchical search method. The hierarchical search may allow signals to be first classified, then identified. Here, an unknown event signal is first tested against a limited family of correlators with the intention of identifying the class of origin of the event. The identification of the signal class may itself be a valuable result. However, as called for by the node protocols, a more intensive search may be executed on the family members in the derived class. The hierarchical search minimizes the number of computations required to arrive at an identification decision. In addition, the benefits of energy expenditure as a function of improved identification accuracy may be estimated and used to manage node energy.

Correlator packet selection is made *directly from data time series acquired in the field.* This provides confidence that signal source and environmental conditions may be properly addressed in the signal identification problem. It is recognized that the SSE library may be massive for systems that are generally useful. However, large memories, required for the SSE, do not require large energy and are compatible with WINS technology. Correlator selection may be made through decisions including: 1) selection of the highest signal-to-noise ratio portions of a data time series, 2) selection of particular segments of the time series corresponding to the evolution of an event (for example, the approach or departure of a vehicle), and 3) methods that are based on training of the SSE. In this latter case, the SSE, along with supporting processes, may be employed to search and identify optimal packets for detection of large vehicle populations in diverse environmental and source signal conditions.

The SSE architecture may be extended to multiple sensor data streams, each providing additional threat detection capability and robust operation in the presence of diverse field conditions.

Distributed sensor signal processing can exploit network communication to enhance the performance of local node signal processing. In particular, the network can offer programmability. The benefit of this feature is illustrated here: In the event that a node (or a collective group of nodes) is unable to identify a threat among a library, it will be required that the time series data, associated with the threat, be propagated through the network to the remote user (for analysis by a more powerful system). To avoid the high energy dissipation associated with such an error, remote reconfigurability must be applied. The network is exploited, in this event, to marshal new signal processing code and data to enable future detection of this event.

(a)



(b)

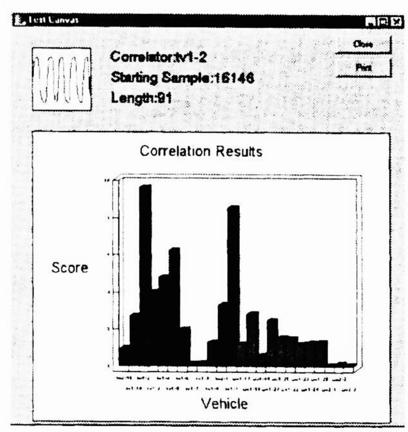


Figure 5. The Signal Search Engine has been implemented on a conventional processor. Panel (a) shows the Signal Search Engine (SSE) application window. Unknown and template data sets are displayed along with scoring values for the search. Matching success may be measured against template type, template origin, template vector length, and various windowing methods. The prototype SSE software platform serves as a testbed and engine for identifying the proper templates for later incorporation into the WINS node. Operation on a set of seismic field records for tracked and wheeled vehicles is shown here. A template derived from a tracked vehicle record is used to search for a seismic record of this vehicle in a large set of unknown signals. These results are those of a typical test including unknown signals obtained from testing on two tracked vehicles and two wheeled vehicles. Panel (b) displays the averaged rms amplitude of the correlator output for each record. The correlator itself, is a record taken from one of the tracked vehicle data sets. The results correctly identify the signal classification (tracked) and the signal identification to a specific vehicle record from which the correlator was derived. The SSE results are dependent, as expected, on the selection of the proper correlator.

6. SUMMARY

Wireless Integrated Network Sensor (WINS) technology now includes microsensors, micropower interface, signal processing, and wireless communication. The WINS network architecture provides multihop, redundant access to WINS nodes and direct interoperability with large area networks and the Internet. WINS networks rely on event detection computation at the WINS nodes. This paper has described recent developments in signal processing and event recognition for WINS. The Signal Search Engine (SSE) employs an inner product correlation engine to hierarchically search a signal database and classify and identify event signals. The SSE is scalable and may be extended to multiple sensor identification applications. Applications of the SSE are being explored in structure control and condition based maintenance. Examples, of WINS smart structure applications under current development include monitoring of large structures for diagnostics of seismically induced damage and condition monitoring of powerplant systems and vehicles. WINS smart materials applications include monitoring of structural materials with embedded, networked, WINS nodes.

7. ACKNOWLEDGEMENTS

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