Event Driven Persistent Sensing:

Overcoming the Energy and Lifetime Limitations in

Unattended Wireless Sensors

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Abstract—**The DARPA Near Zero Power RF and Sensor Operations (N-ZERO) program seeks to overcome the power limitations of persistent sensing by developing wireless, event-driven sensing capabilities that allow physical, electromagnetic and other sensors to remain dormant—effectively asleep yet aware—until an event of interest awakens them. State-of-the-art sensors use active electronics to monitor the environment for such external triggers. The power consumed by these electronic circuits limits the sensor lifetime to durations of weeks to months. In contrast, N-ZERO seeks to exploit the energy in signal signatures to detect and recognize attention-worthy events, such as the presence of a particular machinery type or radio communications protocol, while rejecting noise and interference. This paper will discuss the new architectural approaches and component technologies being developed under the N-ZERO program, which are predicted to extend the lifetime of wireless sensors to several years under many operational scenarios.**

Keywords—wireless sensor networks; remote monitoring; detectors; signal processing; RF signals; low-power electronics

I. INTRODUCTION

Battery powered unattended systems have numerous uses in security applications, infrastructure monitoring and the Internet of Things. For example, deployed sensors can monitor an area and provide pertinent information such as the presence of an intruder, formation of cracks in infrastructure, or a remote radio signal. The life of unattended sensing systems is generally limited to a few months when using a typical compact battery source. In many cases, retrieval or replacement of the devices or their batteries is impractical. At the system level, the large cost for maintenance limits scalability. For example, if the battery replacement cycle is on the order of months, wide coverage systems with thousands or more devices become impractical. The DARPA's Near Zero Power RF and Sensor Operations (N-ZERO) program aims to overcome these limitations by significantly increasing the lifetime of the deployed sensors from months to many years.

Infrequent device activity causes the battery source to be drained by the active wake-up circuitry (solid line), which is substantial even in state-of-the-art (SOA) wake-up stages, as illustrated in Fig. 1. In a system consuming near zero power in the standby state, the lifetime is limited by active processing of useful activity/information or the battery self-discharge (dashed line). The goal of the N-ZERO program is to develop a wake-up

capability with power consumption lower than the battery leakage rate, which for typical small primary batteries is on the order of 10-100 nW. Such improved efficiency allows battery powered unattended systems to potentially last as long as the shelf-life of a battery, which in some cases can exceed 10 years.
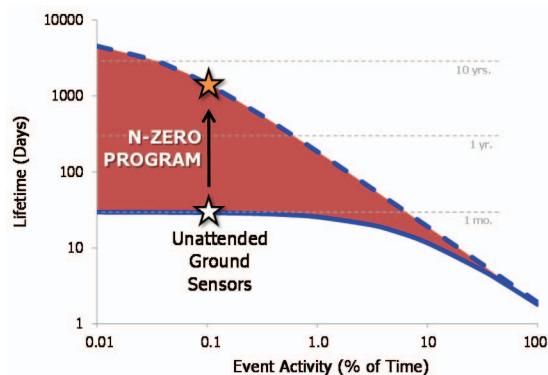

Fig. 1. The N-ZERO vision.

II. BACKGROUND

An effective sensor wake-up system must be simultaneously sensitive and selective. High sensitivity is required for detecting weak signals with a high probability of detection (POD) while high selectivity is required for operation in difficult signal to interference and noise environments with low false alarm rates (FAR). Low FAR is essential to prevent the power consuming stages that follow N-ZERO from false wake-up, which in turn will negate the benefits from the wake-up stage. Wake-up FARs of one per hour or lower are required to obtain the expected improvement in lifetime.

The technical challenge is illustrated in Fig. 2, where typical radio frequency (RF) or environmental input signals can be separated from the SOA detector threshold by as much as a factor of 10^6 on a voltage scale. N-ZERO must apply a combination of passive voltage amplification, processing gain, rectification and low-threshold detection in order to bridge this significant gap. To address these challenges the N-ZERO program has two primary technical areas, RF wake-up and physical sensors. The physical sensors encompass acoustic, vibrational, magnetic, infrared and chemical sensing modalities.
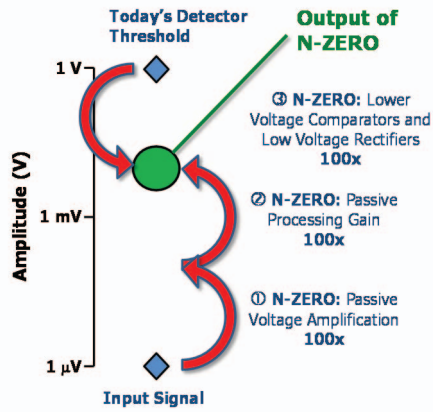
Fig. 2. A notional approach to near zero power sensing.

III. RF WAKE-UP SENSORS

The RF wake-up technical area aims to produce RF receivers with -100 dBm sensitivity. While the RF wake-up signal in this case can be engineered to maximize its effectiveness, the unique challenge is in the cluttered RF background with possible in-band and out-of-band RF interferers. Therefore, signal amplification as well as effective signal processing in a low SNR condition are most critical. Fig. 3 illustrates how the N-ZERO RF wake-up metrics compare to SOA radio receivers [1].
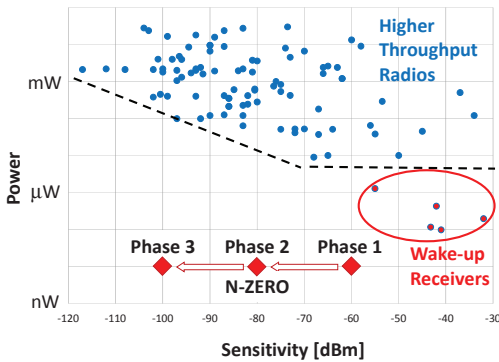

Fig. 3. Survey of low-power radios.

One of the possible approaches taken in the program is to apply a passive voltage amplification by a resonant MEMS transformer, followed by a passive rectification and threshold detection through a resonant MEMS switch (Fig. 4). The advantage of this approach is that frequency selective signal processing is accomplished in the physical domain by high quality factor (high-Q) resonant devices with zero power consumption in the quiescent state of the sensor. For example, in a frequency modulated (FM) wake-up waveform, the resonant transformer responds to the carrier frequency, while the resonant switch is tuned to the modulation frequency. The system successfully demodulates and rectifies the received RF signal. It is noted that rectification in the electronic domain is highly inefficient for low voltage signals due to the thermal voltage (V_T) that must be overcome in electronic circuits. In contrast, the MEMS switch does not suffer from thermal voltage limitations and can perform efficient rectification at very low voltage levels. MEMS switches also possess very steep subthreshold swing, < 1mV/Dec, enabling low threshold comparators with extremely low quiescent power [5].

IV. PHYSICAL SENSORS

In contrast to the RF wake-up, where the detected signal is known and can be optimally designed, in the case of physical sensing the input signals are outside of the designer's control and depend on the nature of the detected event. In order to maximize the POD and minimize FAR, often the best strategy is to employ sensor fusion where multiple modalities are sensed and processed in a decision-forming detection/classification logic (Fig. 5). To that end, N-ZERO aims to develop a suite of highly-sensitive sensors for acoustic, vibrational, magnetic, infrared and chemical modalities as well as the accompanying signal processing capabilities. Furthermore, the sensors themselves can be used to perform signal processing functions such as frequency decomposition.

An example physical sensor architecture is shown in Fig. 6. Multiple physical modalities are sensed by devices such as accelerometers and microphones. Initial processing can be performed with the physical properties of the sensors (e.g. the accelerometers' resonant frequencies). This information can then be reduced to a lower order representation using rectification or quantization and fused using signal processors such as correlators and classifiers. Finally, the processed information can produce a digital output based upon the class identified. Thus, a number of frequency selective sensors are
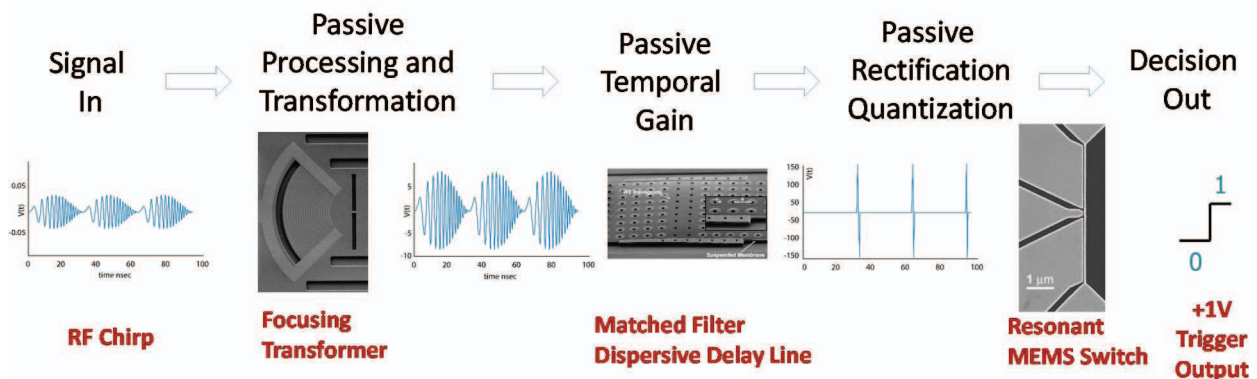

Fig. 4. Example RF sensor architecture and signal flow. SEM images from [2-4].

combined via low-power processing circuits in an effective multimodal sensor system with near zero power consumption.
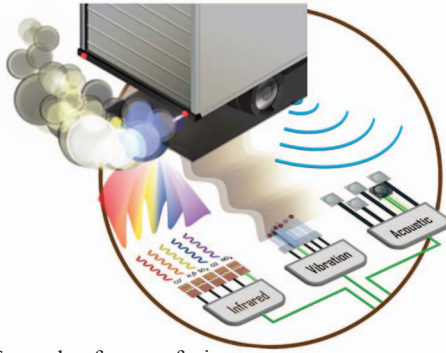

Fig. 5. Example of sensor fusion.

V. SIGNAL PROCESSING

The decision making function in a physical sensor is non-trivial, as illustrated in Figs. 6. Advances in signal processing methods and CMOS technology have allowed digital signal processors (DSPs) to operate under lower power constraints. However, typical processors do not have the ability to achieve the processing gain required in the N-ZERO program of 10 nW.

Analog signal processing can perform many similar functions of DSPs, such as frequency decomposition, with near zero computational cost. The improved efficiency in analog signal processing has been leveraged in the N-ZERO program. Two examples are correlators and classifiers.

A correlator may use a matched filtering approach where the collected signature is correlated with a template corresponding to the targeted signal. One advantage of this approach is that correlation processing in the frequency and time domain can be achieved by analog devices with very little power consumed.

A more robust approach for near zero power classification implements a classifier with greatly improved POD and reduced FAR. In these cases, feature vectors are formed by the inputs from different physical domains. The classifier is trained offline on target signatures previously collected in various interfering environments. Currently, the program manually trains the classifiers and in the future this aspect will be automated. The output of the classifier is a wake-up signal based on the correct classification of the triggering event. Additional advantages of this approach are that it scales to a large number of signatures, the feature vectors can be iteratively refined and optimized based on the training results, and the classification accuracy can be improved as more training data becomes available. In an ideal implementation, the classifier can be trained in the field with data closely matching the exact operating conditions and environmental background.

VI. CONCLUSION

The DARPA N-ZERO program is developing a suite of sensors and signal processing capabilities capable of sensing an event in a noisy environment, classifying it against a set of predefined signatures of interest and triggering a higher order system upon a positive detection. All N-ZERO functions are accomplished with power consumption under 10 nW which is on the order of the self-discharge rates of typical compact battery sources. Therefore, a sensor system equipped with an N-ZERO wake-up capability will be able to function without battery replacement for many years in the field. During that extended lifetime, the N-ZERO system continuously monitors for triggering events. High POD (>95%) ensures that important events are not missed by the sensor system while a very low FAR ensures that the power consuming secondary system does not power up unnecessarily during long deployments. The outcome of the N-ZERO program will enable multiple applications that are currently infeasible or impossible, such as infrastructure-scale sensor networks with decade-long lifetimes.

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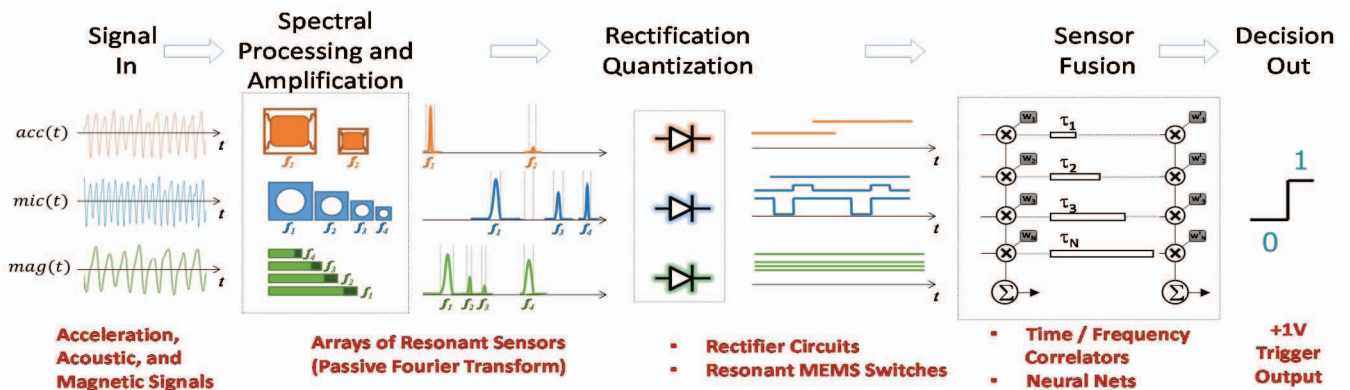
Fig. 6. Example physical sensor architecture and signal flows.