Zero and Near Zero Power Intelligent Microsystems

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Abstract. The Near Zero Power RF and Sensor Operations (N-ZERO) program from DARPA has created a new, nanowatt class of intelligent sensors and RF receivers enabling systems that are passive or nearly passive while operating in an intelligent standby mode. Such systems can be persistently powered by small batteries for many years or perpetually via miniature energy harvesters. The program sought wake-up receivers with a sensitivity of -100dBm and physical sensors that could classify vehicles at a range of 10 m, with power consumption on order of the self-discharge rate of a small battery. Furthermore, researchers with designs that fit other applications, such as chemical and IR sensors, were open to participate as well. From the program multiple approaches have emerged featuring passive and active MEMS devices and subthreshold CMOS circuits. The overall goals of the program have helped to redefine the state-of-the-art in ultra-low power receivers, machine learning processors, and passive physical sensors.

1. Introduction

Recently, with the advent of the Internet of Things (IoT), the commercial sector has established persistent sensing needs for industrial perimeter monitoring, monitoring of engines and industrial equipment, sensing pending infrastructure failures, sensing for smart farming, and early detection of environmental hazards and disasters. While it is currently possible to implement many of these applications in locations with abundant access to electrical energy, nearly all of these applications fail on lifetime, battery replacement frequency and maintenance costs when applied in locations without tethered power access.

The Near Zero Power RF and Sensor Operations (N-ZERO) program was founded to establish an off-but-alert sensing capability to allow intelligent sleeping of sensor nodes that could be awoken by a specific physical, chemical or radio frequency (RF) signature. A node must continuously sense a particular modality, be successfully triggered when a signature of interest is sensed, and ignore all other unimportant inputs. The goal was to consume less than 10 nW in this intelligent standby mode, a power commiserate with the leakage of small batteries or the capabilities of miniature energy harvesters. Sensing infrequent yet time critical events can cause a traditional system to rapidly drain a small battery, as figure 1 illustrates. The goal of the N-ZERO program was to extend the lifetime of persistent unattended sensors to years, enabling cost effective and safe deployment in areas lacking fixed energy infrastructure.
Figure 1. Estimated lifetime for a reference battery-powered, unattended system without (solid line) and with an N-ZERO wake-up (dotted line).

An example application driving the development of N-ZERO technology is perimeter protection. Certain triggers, such as the presence of an unauthorized vehicle, can occur very infrequently, but must be accurately and quickly detected and communicated. The modalities that are often needed for these sensor nodes are seismic, acoustic, and magnetic signatures. Additionally, an RF wakeup can be used to remotely trigger other nodes in the network at will, allowing hopping of information through the sensor network over long distances. Therefore, the N-ZERO program sought physical sensors and RF wake-up receivers that were driven by the metrics in table 1. The program was also opened to other modalities that were performer defined resulting in the development of passive chemical and infrared (IR) sensors.

Table 1. N-ZERO Final Program Goals.

| Detected signature | RF Sensors | Physical Sensors |
|--------------------|------------|------------------|
| RF level at sensor input | ≤ -100 dBm | ≥ 10 m |
| Environment | High interference background | Urban |
| Probability of detection | 95% | |
| False alarm rate | < 1 per hour | |
| Power Consumption | < 10 nW | |

2. Near Zero Power RF Wake-up

Lifetimes of sensor nodes operating in a mesh network are often bounded by receiver power. Traditional nodes must be on and waiting for communication signals since they cannot know when an event will be detected that needs to be relayed through the network. Synchronization of nodes for long sleep durations consumes more power than a typical RF receiver [1]. Thus, the lifetime of mesh network sensor nodes is improved dramatically when the receiver power is reduced, as seen in figure 2.
2.1. Motivation

While the idea of passive RF receivers is not new, inefficient conversion of RF signals to lower, baseband frequencies has limited receiver sensitivities to levels many orders of magnitude away from the performance needed for unattended sensor nodes. The goal of the N-ZERO program was to see if recent advances in piezoelectric materials, steep subthreshold slope switches, and subthreshold CMOS circuit design could enable orders of magnitude improvement in the sensitivity of low power RF receivers. In particular, it was envisioned that recent advances in piezoelectric materials, such as thin film lithium niobate, could realize high gain transformers that improve the conversion efficiency when placed in front of passive rectifiers in the receiver chain [2]. The high gain piezoelectric transformers could dovetail with steep threshold slope MEMS switches that could be used to more efficiently convert low voltage RF signals to baseband frequencies [3]. Once converted to a lower frequency, low power subthreshold CMOS circuits could further process the signal, improving the sensitivity and mitigating interference.

2.2. Implementations and Measured Performance

The N-ZERO program studied a variety of wake-up radio architectures, varying from fully passive receivers than consume zero power to implementations heavily leveraging low power CMOS. The measured performance of various N-ZERO wake-up receives is illustrated in figure 2. Currently, the performance exceeds the Phase 2 goals and is expected to reach the Phase 3 goals by the end of the program. A combination of innovations in CMOS rectifiers, LC-based transformers, ultra-low power digital correlators and waveform design has achieved the best performance to date of a -76 dBm sensitivity at 7.4 nW power consumption, a nearly 1000 fold improvement in performance when compared to state-of-the-art at the outset of the program [4]. Furthermore, completely passive receivers emerging from the program have achieved a sensitivity of -60 dBm [5]. Recently, the figure of merit of piezoelectric RF devices created on the program has been increased to > 1500, a result that promises even higher gain transformers that will further improve receiver sensitivity [6]. An additional 4x gain can be earned through innovative architectural optimization [7]. The final expected performance at the end of Phase 3 and the current performance of the wake-up receivers are plotted in figure 3. A more detailed analysis on the challenges and approaches in nW wake-up receivers can be found in [8].
3. Physical sensing

The N-ZERO physical sensing technical area set out to determine if the complex sounds, vibrations, and electromagnetic fields emitted from different machines could be robustly classified in the presence of noise and interference, all while consuming only 10 nW of power. The strict power budget mandated that the features used to classify the targets be efficiently extracted and that little energy be wasted on information irrelevant to the classification problem at hand. Sparse frequency decomposition was utilized to extract the features for all of the technical approaches. Only the acoustic and seismic modalities were determined to contain information allowing the targets to be distinguished from one another and from the background clutter environments.

The lowest power consumption, zero, was obtained using microsystems comprised of fully-passive resonant MEMS structures. A small number of these frequency selective sensors could extract the key frequency features associated with stable signatures, such as those from a generator, and accurately classify these time invariant targets using simple thresholding in each frequency bin followed by simple logic circuits. The resonant nature and high quality factors of the devices made them highly sensitive and quite effective at rejecting out-of-band interference. These fully passive solutions, however, could not be scaled to the more challenging and time varying targets, such as cars and trucks. The variance of these targets required many more frequency features than could be obtained in a reasonable size using resonant MEMS devices. Furthermore, the classification of these targets required much more sophisticated techniques than thresholding to capture and process the much richer feature space. Nanowatt-class machine learning processors were developed to classify time varying targets with both high specificity and selectivity. In the end, N-ZERO physical sensor systems consuming zero to 20 nW of power were demonstrated and are predicted to result in significant lifetime improvements for unattended sensors, with a particular reference microphone example shown in figure 4.
3.1. Passive Physical Sensing

Several teams set out to perform passive frequency decomposition using both metal contacting [10] and piezoelectric [11] resonant MEMS sensors. The targets exhibited frequency features in the 20 Hz to 300 Hz range and resonant microphones and accelerometers were developed at frequencies as low as 40 Hz [10]. Resonant piezoelectric MEMS sensors with sensitivities as high as 490 V/G and 0.6 V/Pa were demonstrated [11, 12]. The high voltages produced passively by the piezoelectric sensors could be directly rectified and used to drive nW digital CMOS logic circuits. Resonant metal contacting switches driven both acoustically and using vibration were also demonstrated with high sensitivity. These switches could be combined into simple AND, OR, and NOT logic circuits all in the passive mechanical domain to improve the resilience to false alarms while maintaining zero stand-by power [10]. This was particularly important for rejecting non-stationary signals, such as those from airplanes, which would transit through the stable frequency features of targets such as generators. Completely passive microphones were shown to accurately classify generators at ranges in excess of 5 m [10]. These completely passive systems, however, could not classify the car and the truck targets over all of the measured backgrounds and environments. For that task, much more sophisticated signal processing algorithms were needed, but it was unclear if these approaches could be implemented at the required ultra-low power levels.

3.2. Near zero power machine learning processing

The complex processing, such as what is required to classify cars and trucks with a high probability of detection and low false alarm rate, was achieved on the program via ultra-low power machine learning processors applied to audio signals. The first challenge here was how to sense, amplify, and digitize the audio signal to even present it to a machine learning processor. Nanowatt amplifiers, analog-to-digital converters, clocks, and charge pumps used to produce the high voltages needed by a commercial MEMS microphone were all developed on the program. Once digitized, the signal was sparsely and sequentially decomposed by frequency, only extracting the acoustic power at frequencies relevant to the classification problem. While only a subset of frequencies were used, the 8-32 frequencies were far more than what could be supported using reasonably sized passive MEMS devices. A support vector machine was then used to classify the targets based on the frequency features with coefficients for the machine learning processor derived from offline training with a priori data recorded for each target in a number of different background settings. To achieve the low power consumption required innovations in the digital circuits such as low leakage and low read energy memory and heavy duty cycling of the classifier, which would only be powered on once all of the frequency features were sequentially extracted. Although the program goals set targets of a generator, car, and truck, the machine learning processors could be rapidly updated to classify other targets. The processor is also agnostic to the particular sensing modality and can be adapted to other sensor
modalities besides acoustic. To date, a car, truck, and generator have been classified at 5 m range using a 12 nW microsystem that achieves both a high probability of detection and a low false alarm rate [13].

3.3. Sensing and processing in other modalities

Passive IR and chemical sensors were also developed under the program. Like the passive seismic and acoustic sensors, these sensors rely upon the physical architecture of the device to perform the sensing and processing of the desired signatures.

The IR sensor was implemented using a plasmonic MEMS switch that is patterned so that only energy within a particular IR wavelength band causes the switch to mechanically close. Switches patterned for multiple bands can be combined to form simple mechanical logic circuits [14]. This logical combination of switches forms a passive IR spectrometer that while initially targeted for the classification of hot vehicle exhaust also finds application in human occupancy sensing. Currently, the switches consume zero standby power and can detect sub-μWatt levels of IR power residing in a narrow wavelength band that can be designed with an absorption bandwidth of full width at half maximum of ~225 nm mapping to 4.29% at λ=5.23μm [15].

Passive chemical sensing was achieved on the N-ZERO program using a percolation matrix of gold posts coated with a special chemical linker. The spacing between the posts and the particular linker type select for a particular chemical while rejecting other species. When a chemical binds to the linker and links two posts, a conductive path between the posts is formed. When the concentration of the chemical has reached a particular threshold, probability dictates that many of the posts will have conductive chemical paths between them and the overall resistivity of the matrix sharply drops and effectively closes the switch. Resistance changes of >10⁴ are commonly measured for these devices [16]. More testing is required to determine the limits of the sensitivity and selectivity of this sensor. Currently, this sensor has demonstrated selectivity to cadaverine at a concentration of <100 ppm [16].

4. Conclusion

Passive accelerometers, microphones, IR switches, and chemical sensors have been developed to specifications which define the modality and processing necessary to successfully characterize signals using the energy contained in those signals. Passive systems excel when well-defined signatures are known, such as IR energy within a specific band. By expending power that is equivalent to the leakage of a small battery, signal processing can be used to further classify more complex signals. A nanowatt-class machine learning processor has illustrated that it is possible to classify states based upon training. Passive and nanowatt wake-up receivers take advantage of engineered signals to require less than -60 dBm of sensitivity to turn on [4, 5, 17]. The path towards persistent intelligent microsystems was forged by these breakthroughs from DARPA’s N-ZERO program, as summarized in the measured performance metrics in table 2. Future systems can continue along this path towards perpetual sensing nodes enabling a realistically scalable Internet-of-Things.

| Sensor Type         | Signature Detected | Interference w/ Specificity | Standby Power |
|---------------------|---------------------|----------------------------|---------------|
| Acoustic [13]       | Car, truck, and generator @ 5 m | Urban | 12 nW |
| Acoustic [10]       | Generator @ 5 m     | Urban | passive |
| Acceleration [12]   | Vehicle (a < 1 m)   | Urban | 5.25 nW |
| Infrared [14]       | Wavelength-specific IR | Broadband thermal & other wavelengths | passive |
| Chemical [16]       | <100 ppm of cadaverine | Ambient | passive |
| RF [5]              | -60 dBm @ 760 MHz   | N/A | passive |
| RF [4]              | -76 dBm coded waveform | Urban | 7.4 nW |
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