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Towards packet-less ultrasonic sensor networks for energy-harvesting structures

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ABSTRACT

This paper proposes and evaluates an energy-aware pulse switching architecture for a through-substrate ultrasonic sensor network. The network is run from vibration energy harvested on an airplane stabilizer structure, whose health is monitored using the through-substrate network. Pulse- switching-based protocols use single pulses instead of multi-bit packets for information delivery with ultra-high energy-efficiency. Pulse switching using ultrasound is particularly well suited for event reporting through metal / composite substrates used in structures such as bridges, aircraft wings, etc. This can eliminate the need for out-of-substrate radio or wired links. This paper presents a large-scale simulation model in which structural vibration modeling using finite element methods, energy harvesting modeling from such vibrations, and energy-aware pulse networking models are integrated for end-to-end architecture level performance evaluation. Simulation results are used for demonstrating the sensitivity of network performance to key system parameters, namely, structural vibration intensity, energy harvesting efficiency of the used piezoelectric material, and the energy storage capacity at the pulse switching sensor nodes. In addition to event reporting delay, the impacts of pulse loss have been thoroughly characterized using the integrated simulator.

1. Introduction

The core objectives in structural health monitoring (SHM) [1] are to collate information such as unusual stress, faults and cracks from a large number of strategically positioned sensors over a target structure, and infer the health of the structure using such information [2]. Energy-efficient wireless sensor networks ([3,4]) are often deployed for multi-hop data collection from such sensors to an access-point or a sink, where the collective data processing functions can be placed.

It is noted that many such structures are made of a substrate material such as metal or composites, which itself can be used as communication medium for signals such as ultrasound. This has motivated the idea of developing a through-substrate sensor network. Tiny sensors, when embedded or affixed on a bridge or an aircraft wing, can communicate with each other using ultrasonic pulses propagating through the structure's solid substrate. This can eliminate the need for out-of-substrate radio or wired links. A prototype modem as described in [5], which deals with the various challenges in such a design, had been developed in our laboratory to demonstrate the feasibility of this approach.

Moreover, opportunities exist in harvesting energy from ambient vibrations in several structures such as airplane wings, stabilizers, and bridge beams. Such harvesting can provide energy for sensing and communication of collected sensor information. Self-powered sensors have already been demonstrated which can use the energy from the signal being sensed to power the sensing, computation and non-volatile storage operation [6]. Work is under way on a collaborative project to design a piezoelectric-based transducer that can use vibrations inside a structure to power communications in addition to sensing and buffering needs. The notable fact here is that the same transducer (i.e., a substrate-embedded piezoelectric module) can be used for sensing (ultrasonic fault signatures), communication (ultrasonic link), as well as energy harvesting (ultrasonic vibration harvesting) to power all operations. Such convergence of functionality in a through-substrate approach leads to a cleaner design by removing the need for separate retro-fitted components for sensing, communication and, energy generation.

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Another notable observation is that after a certain amount of local processing at a sensor, often the transportable information from the sensor to an access-point is merely an event. This can be a threshold crossing of local stress, detection of a pre-defined temporal stress pattern, or even a crack in the extreme case. Since the event information is binary (yes or no), a single pulse can be used to communicate this, thus eliminating the needs for packets and their associated overheads such as synchronization preambles. This would lead to significant benefits in energy-starved environments. The low energy usage can also improve reliability of operation in systems powered by energy harvesting, by keeping the consumption rate lower than the energy generation rate. The primary design questions here are how to: 1) transport event localization information using a single pulse, 2) route a pulse multi-hop without explicit node addressing, and 3) reliable event delivery under energy constraints. These problems are architecturally addressed by integrating a pulse's (i.e., event's) area of origin within a MAC-routing protocol framework, and incorporating several energy-awareness syntaxes within the same framework as demonstrated in the Energy-Aware Pulse Switching Protocol for Through-Substrate Event Reporting developed in our previous work [5].

It is to be noted that the pulse-based networking approach has been shown to have significantly less energy consumption compared to the most energy-efficient packet-based protocols (TDMA-based) when the information to be transmitted is binary and network event rate is not very high. For example, it was established in [7] that the cellular pulse switching approach can operate with a total energy expenditure (considering transmission, reception and idling) that is about half of that for a comparative packet based approach (sink-rooted TDMA) when the event rates are lower than 1 event/node/sec. When the idling costs are removed (e.g. when the receiver is not energy limited), the gains can go up to 4 times in comparison to the packet based approach. These results motivate the use of the pulse based networking architecture compared to a packet-based one when the network is energy-starved and the data is essentially binary in nature.

The prior work [5] evaluated the pulse protocol performance in an energy-harvesting environment using a simulated structural energy harvesting profile. A storage capacitor in each sensor was assumed to follow a charging profile based on exponentially-distributed ON and OFF cycles. A perfect synchrony in charging cycles among different sensor nodes in the through-substrate network was assumed. In this paper, we develop a practical harvesting scenario that uses a Finite Element Modeling (FEM) based realistic vibration model for an airplane stabilizer. Thereafter, the vibration profiles are translated into harvested energy profiles using a piezoelectric harvester circuit simulation. The harvested energy profiles are essentially asynchronous because the node vibration profiles over time are independent of each other. Finally, we evaluate the performance of the energy-aware pulse network protocol in such a realistic event-monitoring scenario and derive conclusions about its scope of application.

The contributions of this paper are as follows. First, a realistic acceleration profile across an airplane stabilizer is developed using dynamic response simulation based on Finite Element Modeling. Thereafter a simulated model of harvested energy is obtained from the spatio-temporal vibration profiles on the stabilizer. Finally, network simulation is performed on an array of nodes distributed over the stabilizer to demonstrate the performance advantages of the Energy-Aware Pulse Protocol in such a scenario.

2. System architecture

The high-level system architecture envisioned for the Structural Health Monitoring application is demonstrated in Fig. 1.

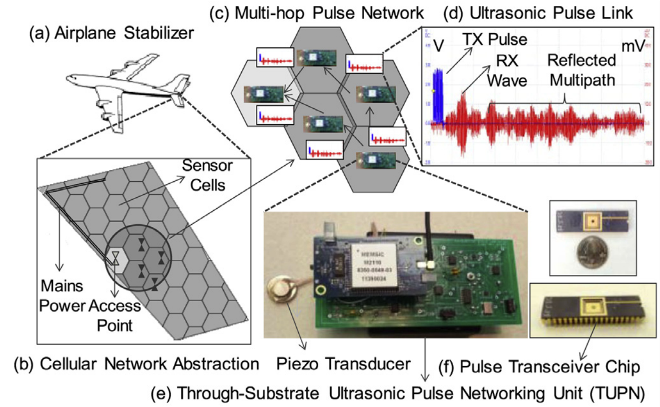

Fig. 1. Event monitoring using a through-substrate sensor network.

Table 1
PLR/FPPR for ultrasonic communication over Al 2024 alloy plate using prototype TUPN module.

Pulse Link Length (meters)	Pulse Voltage (80 µs pulses)	Pulse Loss Rate (PLR)	False Positive Pulse Rate (FPPR)
0.5	3	2.16×10^{-6}	4.02×10^{-6}
0.75	3	2.89×10^{-6}	5.77×10^{-6}
1.00	3	3.02×10^{-6}	7.21×10^{-6}
4.00	6	1.62×10^{-6}	3.4×10^{-6}

The broad idea is to use a through-substrate sensor network as shown in the figure, where a collection of Through-Substrate Ultrasonic Pulse Networking (TUPN) units are mounted / embedded on the structure being monitored. The example in Fig. 1(a) and 1(b) demonstrates how an event transportation network can be formed on an airplane stabilizer through the stabilizer substrate itself. As shown in Fig. 1(c), neighboring TUPNs can form short ultrasonic communication links through the substrate (e.g., aluminum alloy or composite). A TUPN detected event (i.e., strain, fatigue etc.) results in an ultrasonic pulse, which is transported multi-hop to a data logger or sink node in such a manner that the latter can indicate: 1) the very occurrence of the corresponding event, and 2) its location of origin with a pre-defined resolution. Resolution is based on a cellular abstraction (Fig. 1(b)) in which the TUPNs are addressed not individually but on the basis of the cell IDs in which they reside. Even with such limited information, several application level conclusions can be derived at the sink by correlating multiple event pulses [2].

3. Prototype ultrasonic transceiver and link characterization

A prototype TUPN, as shown in Fig. 1(e), was developed in our prior work [5]. It was used for characterizing pulse-based ultrasonic data links (Fig. 1(d)) through metal substrates. Each TUPN can both transmit and receive using an ultrasonic piezoelectric attached. An integrated circuit version of the modem, which is currently being developed, is shown in Fig. 1(f). The Pulse Loss Rate (PLR) and False Positive Pulse Rate (FPPR) for communication using the above-mentioned transceiver through a 2024 Aluminum alloy plate (substrate) over a variety of distances and two different source voltages has been listed in Table 1. It is to be noted that the choice of substrate material (Al 2024) was motivated by the fact that this is the most prevalent material used in aircraft stabilizer construction. The two source voltage levels (e.g., 3 V, 6 V) were chosen keeping in mind the different voltage requirements for transmission in two network roles – source (forwarding) and sink (synchronization) as will be discussed further in Section VII.

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