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Low Cost Wireless Sensor Networks for Continuous Bridge Monitoring

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ABSTRACT: Continuous monitoring wireless sensor networks (WSN) are considered as one of the most promising means to harvest information from large structures in order to assist in structural health monitoring and management. At the same time, continuous monitoring WSNs suffer from limited network lifetimes, since they need to propagate large amounts of data over regular time intervals towards a single destination in the network. Propagation of information is done through multiple hops, suffering from collisions, retransmissions and therefore high energy consumption. Moreover, since there is a bottleneck effect around the network sink, all routing layer algorithms will always deplete the power of the last tier before the fusion center. Finally, theory shows that in such networks scalability could become an issue since transport capacity per node is severely affected as the number of nodes within the network increases. Therefore, in order for WSNs to be considered as an efficient tool to monitor the health state of large structures, their energy consumption should be reduced to a bare minimum. In this work we consider a couple of novel techniques for increasing the lifetime of the sensor network, related to both node and network architecture. Namely, we consider new node designs that are of low cost, low complexity, and low energy consumption. Moreover, we present a new network architecture for such small nodes, that would enable them to reach a base station at large distances from the network, with minimal energy.

1 INTRODUCTION

Smart management of large structures requires the acquisition of large amounts of data from multiple sensors placed on critical points of the structure, which are sampled continuously over very large periods of time. In order to access the sampled data, a network of sensors is formed, responsible for transferring information from the structure to a fusion centre. The use of wireless sensor networks (WSN) has already been proposed for this task, since the use of wireless links overcomes some significant problems (Bhardwaj & Chandrakasan, 2002) related to the cost of network placement and maintenance.

However, the use of WSNs does not come without problems. Traditional sensor networks (Harms et al. 2010), adopting standard wireless schemes to organize the network topology (e.g. Zigbee), are not optimal in terms of energy efficiency (Liu et al. 2010). Propagation of information is done through multiple hops, suffering from collisions, retransmissions and therefore high energy consumption. Moreover, since there is a bottleneck effect around the network sink, all routing layer algorithms will always deplete the power of the last tier before the fusion center. Finally, theory shows that in such net-

works scalability could become an issue since transport capacity per node is severely affected as the number of nodes within the network increases. Therefore, in order for WSNs to be considered as an efficient tool to monitor the health state of large structures, their energy consumption should be reduced to a bare minimum.

To overcome the aforementioned problems, low cost, energy efficient wireless sensor network techniques are proposed in this work, which can reduce the power consumption significantly. Namely, we propose the use of an energy efficient RF front end circuit on the sensor node, which is composed of an adaptive antenna scheme and an active reflector node architecture, in order to significantly increase network lifetime. In order to take full advantage of the improved sensor node design, a single hop method (Kalis & Kanatas, 2010) is also considered for increasing the energy efficiency of the whole sensor network.

This paper is organized as follows: Section 2 focuses on the sensor node design, which includes the proposed adaptive antenna design, and the active reflector architecture; section 3 presents the wireless sensor network single-hop architecture. The conclusion of the paper is given in Section 4.

2 WIRELESS SENSOR NODE DESIGN

2.1 Adaptive antenna

One of the key elements of sensor nodes, which is often overlooked, is the device that enables electromagnetic signals to be transmitted and received from the sensor node: the antenna. Traditional wireless sensor network implementations often use wire antennas, while only recently more sophisticated printed antennas were considered for wireless sensor nodes (Kounoudes et al. 2010). However, existing antenna designs can be the cause of significant energy waste, regardless of their radiation efficiency characteristics. The reason is that although the antenna itself can be designed to perform in an optimal fashion, when the sensor nodes are deployed in the field, these characteristics are severely affected by the materials and structures in the vicinity of the node. For example, the same antenna that radiates with high efficiency in a wooden structure, it does not radiate next to a concrete structure filled with steel. Therefore, since no one can foresee all the possible environments that a single node will be placed in, the node antenna has to be adaptive in order to adjust its radiation characteristics and achieve optimal radiation efficiency in all possible deployment scenarios.

Recently (Han et al. 2010) a novel reconfigurable antenna design was proposed for enhancing the spectral efficiency characteristics of communication.

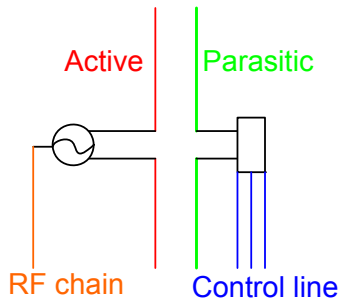


Figure 1. Block diagram of ESPAR antenna with a single active element and single parasitic element

The proposed antenna is a parasitic antenna array (Figure 1) known as electronically steerable passive array radiator (ESPAR), which is capable of reconfiguring its radiation pattern. The control of the radiation pattern is performed by changing the reactive loads of the parasitic elements using baseband control signals. The ESPAR antenna meets both the small size and low-cost requirements of sensor nodes since it allows for inter-element spacing of $\lambda/20$ or less, and requires only a single active front end path to drive the single active antenna of the array. In (Han et al. 2010) the ESPAR antenna concept was extended to increase the control capabilities of the antenna through the use of negative resistance circuits as loads of the parasitic antennas. Extensive

simulation runs showed that reconfigurable complex loads with a negative real part can significantly extend the capabilities of parasitic arrays to incorporate any modulation scheme. Negative resistances, although they are active circuits, they do not require the implementation of full radio-frequency/ intermediate-frequency (RF/IF) paths, thus preserving the low-cost, low complexity nature of parasitic arrays.

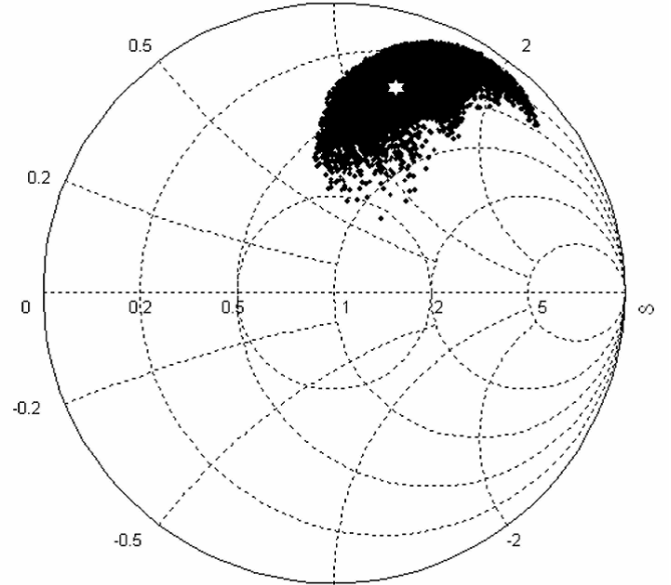


Figure 2. ESPAR antenna port impedance for 5000 loading scenarios.

The same concept is proposed here not only for adjusting the radiation pattern of the antenna for efficient communications, but also for matching the port impedance of the ESPAR to the diverse environment characteristics for achieving maximum energy efficiency. An important consideration noted in (Ohira & Gyoda 2010, Akiyama et al. 2003) is that the port impedance of the ESPAR antenna varies in accordance with the value of reactance employed to load the parasitic elements. Therefore, control of the parasitic results in control of the port impedance. This effect is shown in figure 2, where it is clear that the use of parasitic control can significantly alter the return loss characteristics of the sensor antenna, thus enabling full control of the device and good adaptability to a variety of deployment scenarios.

2.2 Active reflector architecture

In order to further reduce the power consumption of sensor nodes, an active reflector node architecture is adopted (Wehrli et al. 2009, Krishnan et al. 2010). By shifting the main tasks of information fusion and signal processing to the base station, the transmission circuit on the sensor node can be very simple, as shown Figure 3. The main idea in this design is the following: The base station transmits a modulated frequency through its antenna, which serves as

a synchronizing and clocking signal for the nodes. When the sensor node receives this signal, it modulates it with sensed data by a voltage controlled amplifier and frequency selection circuit, in order to send information back to base station.

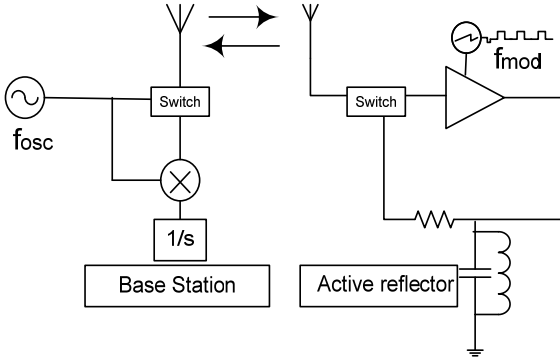


Figure 3. Block diagram of an active reflector in frequency modulated continuous wave (FMCW) communication.

The modulated signal on the sensor node can be formed by one or more frequencies using either OOK or the more power efficient FSK modulation. The sensor node can reproduce the carrier frequency directly from the antenna, without using any additional power hungry oscillator.

An additional advantage of the proposed active reflector architecture is its inherent localization ability. By processing the phase information of the reflected signal format the base station (Bousquet et al. 2009), the distance of the sensor node can be measured. Therefore, when multiple base stations are present, we can retrieve location information of the sensor nodes without any additional cost.

The main challenge of the active reflector design is the frequency regeneration circuit called ‘injection locked oscillator’, which is actually composed of a tunable amplifier. Usually the antenna on the sensor node is single ended, while for the reliability consideration, the symmetric designed amplifier is usually full-differential, calling for a low-return loss balloon design.

Another challenge is the switch design on the active reflector. Usually the switch is controlled by the baseband to determine the transmission period and receiving period. However, for a low cost reflector of a sensor node, the complexity of the baseband circuitry should be minimized. In order to switch the antenna directly on the front end, a high accuracy delay circuit is necessary, which is hard to implement with the traditional shift-register (Lan et al. 2010, Han et al. 2010) design approach. Instead, the charge capacitor array is a good candidate approach for the delay circuit. Moreover, since the sensor cost is directly related to the silicon area required for the integrated design, and the capacitor array consumes lot of area in CMOS, the in-saturation biased MOS-

FET switch capacitor (Lee et al, 2010) will be adopted.

3 NETWORK ARCHITECTURE

3.1 Energy efficient wireless sensor networks

In addition to the novel sensor node architecture, energy saving techniques are also implemented at the network level, using the appropriate network topology and network coding design. There are many existing schemes for sensor communications, including Zigbee, Bluetooth and Mesh network (Jiang et al. 2009, Li et al. 2010), etc. but none of those techniques meets the requirements of energy efficiency. New techniques that reduce the power consumption of the whole network are therefore investigated.

Broadcasting is a good approach to implementing energy efficient communications, because most of the time all the sensor nodes work at a ‘listening’ mode. When the sensor nodes receive a predefined signal from the base station, they switch to ‘active’ mode and lock their carrier frequency according to the pilot signal. All the sensor data are collected at the fusion center (Whelan et al, 2009). In a common structural monitoring scenario, such as that of bridge monitoring, base stations can be installed on the bridge pier or the riparian, as shown in Figure 4; a relay station is put in the middle, depending on the topology and the dimensions of the bridge.

Although the power consumption of this model is low since the transmission circuit on the sensor is switched off most of the time. There are some problems for this broadcasting method. It needs intelligent techniques for smart utilization of the spectrum and synchronization of the sensor nodes.

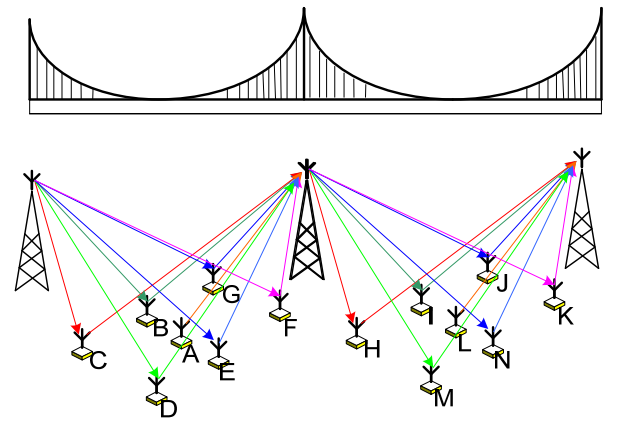


Figure 4. Picture of the bridge model(top) and the sensor network topology (bottom).

Furthermore, many sensor nodes send signals at the same time, making it very difficult for the fusion station to distinguish the received signals. We therefore propose that sensors use a code division multiple access (CDMA) scheme for sharing the link. CDMA is implemented using pseudo-random or-

thogonal sequences for sharing the interference spectrum. This approach has the following advantages: Using synchronized sensors that transmit at the same time a PN-code can be exploited for cooperative beam forming applications as in (Ochiai et al,2005), thus extending the range of sensors and reducing the overall power consumption. Furthermore, for sensors having a direct line of sight to the base station, their position can be obtained by means of time-of-flight measurements.

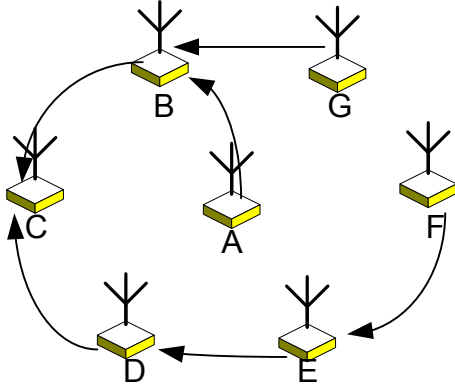


Figure 5. Picture of the multi hop communication method.

3.2 Multi hop VS single hop

Another widely used method for propagating data within in wireless sensor networks is the multi-hop communication method (Li, et al, 2010), where a set of self-organized nodes propagate information by talking with their direct neighbors. This scheme does not require long distance transmissions, which could reduce the energy efficiency per transmission.

The multi hop network has its inherent self-organization ability which could increase the reliability of the network dramatically. As shown in Figure 5, assuming that a sensor node A needs to communicate with node C in a bridge monitoring sensor network, when a car passes through and breaks the link between A and C, then node A will send the signal to node C through the nearest node B. With this message forwarding principle, all the sensor nodes can form a realizable ad-hoc network where all the sensor nodes are connected together. The far node F could reach to node C in 3 hops through node E and node D.

However, a significant drawback of this transmission scheme is the low energy efficiency of the total network. Each sensor node must have the capacity to work as both a repeater and a client. The data from node F to node C needs four sensor nodes to work together in order to form a link; two of them just consume energy and repeat the message, which is not an energy efficient approach. Assuming a sensor network has the capacity of N sensor nodes, in the worst situation, the farthest sensor node needs

$(N-2)$ repeaters to the fusion center, so the maximum message of the whole network is:

$$C_N^1 \times \frac{N \times (N+1)}{2} \quad (1)$$

Assuming the average power efficiency of the single hop method described in the previous paragraph, compare to the multi hop method described here, the efficiency ratio for each signal is:

$$\frac{2}{N \times (N+1)} \approx \frac{1}{N^2} \quad (2)$$

which is much lower than (1). This means that at the system level, the multi hop transmission method consumes more power than the single hop, although the communication distance between each node is small, but the whole network needs more nodes to cooperate per single packet transmission. According to this comparison, the geography dimension of the practical sensor network has great influence on the energy efficiency. In the bridge monitoring example, the fusion center is located at the bridge pier or the riparian; therefore the distance between the fusion center and the farthest sensor node is big. Since the energy efficiency per message satisfies formula (2), the multi-hop scheme is not the best approach to energy efficient communication. Moreover, in the same example we should also take into account that the sensor node working closer to the fusion centre will act most of the time as a repeater, just forwarding messages from other nodes. As a consequence, this node will die more quickly than others, leading to a quick network partitioning.

3.3 Cooperative beam forming

Recently, a novel sensor network topology for energy efficient communications has been proposed, based on the concept of cooperative beam forming (Kung, 1998). The main idea behind cooperative beam forming is that the following: assuming N nodes are randomly placed within an area, sharing the same data information, they can be configured to act as a random antenna array and produce a directional beam toward a desired direction (Dong et al, 2008), as shown in Figure 6.

The beacon station sends a cooperative pilot signal to the sensor nodes, which synchronizes the nodes in such a way that forces the entire sensor array to work as a random antenna array pointing towards the fusion center. The power consumption for each sensor node is low since it exploits the array gain to reach large distances. But the overall transmission power will in this case be N times greater than that of a single node. According to the comparison as it shown in formula (2), the energy efficiency ratio in the cooperative beam forming is N , which is higher than 1. Therefore, when nodes cooperate, they can support transmissions over large distances, enabling

direct access to a distant fusion center without burdening the network with extra relaying tasks.

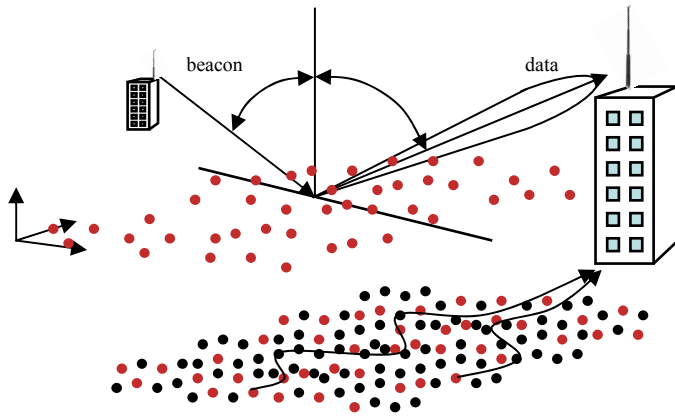


Figure 6. Picture of the cooperative beam forming method.

The challenge in cooperative beam forming is the accurate synchronization among sensor nodes. All nodes in the beam forming network have to share information. So careful sensor node design is a critical rule in this method, the adaptive antenna mentioned in section 2.1 and active reflector mentioned in section 2.2 are key elements for the sensor node in this proposed cooperative beam forming network architecture.

4 CONCLUSIONS

Continuous bridge health monitoring is a widely discussed topic in civil engineering, while wireless sensor network is a widely discussed topic in electrical engineering. In order to build a connection between these two topics, low-cost, low-complexity wireless sensor network solutions for continuous bridge monitoring are proposed. There are a number of critical issues for wireless sensor networks to be used in practical bridge health monitoring. Power management and energy efficient design is a critical rule for the long-time, durable sensor node. As a result, adaptive antenna designs, low-energy transceivers and energy harvesting is proposed at the node level, while a simple cooperative scheme at the network level is shown to significantly reduce the energy dissipation and limited lifetime problems of continuous monitoring systems. Therefore, we foresee that future research will focus on the aforementioned techniques to provide reliable and enduring WSN systems for structural monitoring applications.

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