Conceptual Design of a Wireless Strain Monitoring System for Space Applications

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Abstract. The conceptual design of the architecture of a wireless strain monitoring network suitable for space applications is presented. The system is a heterogeneous wireless network that consists of battery powered nodes and batteryless nodes that are able to harvest energy from an incident RF field. Battery powered nodes are based on the Zigbee standard. Both battery and batteryless nodes are envisioned to include sensors but some battery powered nodes could simply serve as relaying points to transfer data to the central computer. The structure of the batteryless nodes as well as remote powering and data transmission are analyzed.

Keywords: Wireless sensor networks, remote powering, structural health monitoring.

1 Introduction

Health monitoring of structures is a major concern in the space and aviation community, where the need for more sophisticated structural health monitoring (SHM) systems has been recognized [1]. The core of SHM technology is the development of self-sufficient systems that use built-in, distributed sensor/actuator networks not only to detect structural discrepancies and determine the extent of damage but also to monitor the effects of structural usage. SHM can provide early warnings of physical damage, which can be used to define remedial strategies before the damage compromises the spacecraft. Furthermore, it may be possible to quickly, routinely and remotely monitor the integrity of an air/spacecraft structure while in service.

Wireless SHM systems have many advantages over cabled systems because they are characterized by local computational ability, low cost of deployment and wireless networking functionality. In addition, massive interconnections between sensors and a central computer are avoided.

2 SHM System Architecture

The system under development is a heterogeneous wireless network of strain sensors which may be deployed to air or space vehicles. The system is envisaged to consist of

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both battery powered and batteryless nodes interoperating and communicating together and with a central computer which gathers, logs and evaluates data. Both battery and batteryless nodes may include sensors but some battery powered nodes could simply serve as relaying points to transfer data to the central computer. Batteryless nodes will harvest energy from incident RF waves.

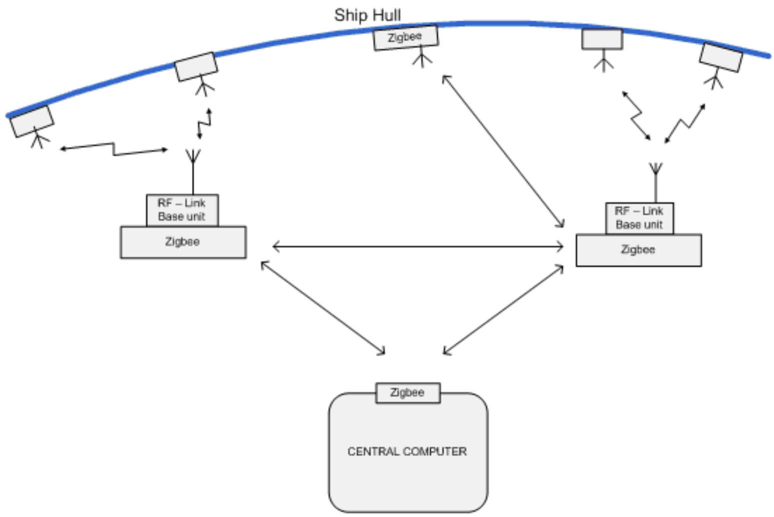

Fig. 1. Concept of the system which will demonstrate a short-range RF wireless system for Structural Health Monitoring

The general structure of the sensor network is depicted in Figure 1. Two different types of battery powered nodes will be built using Zigbee compliant transceivers [2]; nodes that will incorporate sensors and will have the capability to be used either as network coordinator or end device and nodes that will be connected to an application specific board incorporating the RF reader of the batteryless node and will be configured as an end device only.

In such a network the most crucial point is to collect and accumulate power from the reader RF field and then making it available to the batteryless sensor tag electronics. The block diagram of the batteryless sensor tag is depicted in Figure 2. It will consist of the tag antenna, an impedance matching circuit, the power harvester, a microcontroller (MCU), the sensor and an ASK modulator. In order to power the tag the reader will have to emit continuously until enough energy is accumulated to power the tag electronic circuitry, collect the sensor data and transmit them back to the base unit/reader.

The RF reader will comprise two basic subsystems: one for transmitting power to the remote sensor tag and one for reading backscattered data coming out of the tag (Figure 3). The reader functions will be controlled and coordinated by a dedicated low power microcontroller which will also be responsible for communicating with a corresponding Zigbee compliant node through its serial port. The subsystem which will be responsible for transmitting the power to the remote tag will comprise a frequency generator and an amplification unit, while the receiver will be a standard ASK receiver.

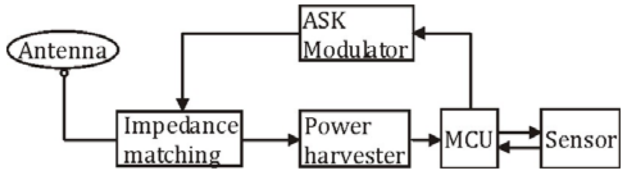

Fig. 2. Tag architecture

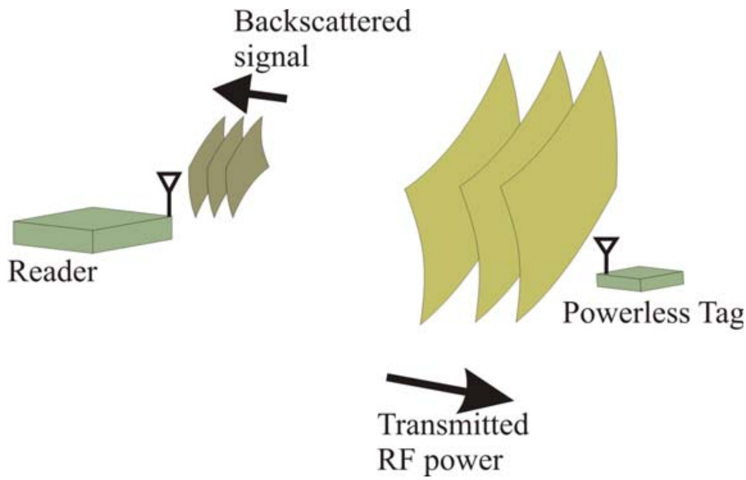

Fig. 3. The basic scheme of the passive link between the reader and the sensor tag is shown. The tag receives power from the remote reader and uses it to power its circuitry, perform the sensor measurement and modulate the backscattered signal with the sensor data.

2.1 Remote Powering

The balance between the available power at the tag and the power required to operate its electronic circuitry is the most important problem of the proposed RF wireless sensor network. According to Friis equation (1) tags receive only a portion P_{tag} of the power P_r emitted by the reader.

$$P_{tag} = A_{er}A_{etag} / (r^2\lambda^2P_r) . \quad (1)$$

where lossless matched dipole antennas are assumed; A_{etag} is the effective aperture of the tag antenna at distance r and A_{er} is the effective aperture of the reader antenna, while the radiation wavelength is denoted by λ. In a practical circuit the voltage generated at the antenna terminals is of the order of only a few millivolts and has to be raised to such a level so as it would be possible to power practical circuits. This task implies that a voltage multiplication circuit follows the antenna and matching circuits (Figure 4). Insertion of the voltage multiplier in the tag circuitry comes however with an extra power loss, as the efficiency n of a six stage multiplier is approximately 30%.

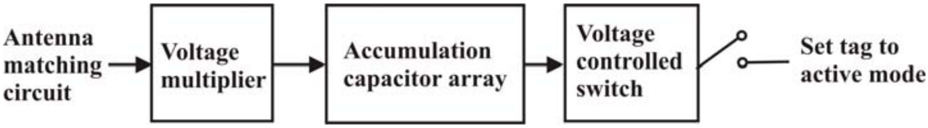

Fig. 4. Block diagram of the power harvesting unit architecture

Thus, the only way to power the tag circuitry is to accumulate enough energy over time by storing it in an accumulation capacitor array, and then making it available to the microcontroller to perform the required tasks.

The whole process will have to be controlled via a low power control circuit which has to be continuously on to perform its task. The power consumption of the control circuit equals the power consumption at standby mode. It should be noted that in order to charge the capacitors the minimum power available at the voltage multiplier input $P_{ant,min}$ must be higher than the power consumption in standby mode (formula (2)).

$$P_{ant,min} \geq P_{tag}/n \; . \tag{2}$$

As a result, the use of the capacitor array adds a limitation on the minimum amount of power that must be harvested by the antenna.

The time interval t_{charge} required to charge the capacitor array between operation cycles (the capacitor array has been fully charged once) is calculated by formula (3).

$$t_{charge} = t_{on} \,/\, (P_{load} - P_{standby}) \; . \tag{3}$$

Where t_{on} is the time interval required for measurement and data transmission of the remote tag and in the current implementation is equal to 125.1 msec. P_{load} is the power available at the terminals of the accumulation capacitor and is determined by the power emitted by a reader antenna and the power efficiency of the harvesting unit. The charging time versus distance for different levels of power emitted by the reader antenna is presented in Figure 5. From this figure it is evident that the charging time increases with distance and poses a severe limitation on the reader – sensor tag range that can be achieved. For example for 100mW of reader transmitted power less than 2m may be achieved even with long charging time.

2.2 Data Transmission and Backscattering Modulation

Tag is designed so as each tag of the network transmits data as soon as one measurement cycle is complete. Furthermore, in order to minimize the power required by the tag backscattering modulation is used. In addition, a simple anti-collision algorithm is employed, whereas in order to minimize the possibility of data collision each tag waits for a predefined time interval before transmission. The proposed transmission algorithm further reduces power consumption as the tags do not have to listen to the channel.

To calculate the minimum bits required to be transmitted by the tag we should take into account that at least two bytes must be initially transmitted in order to lock the

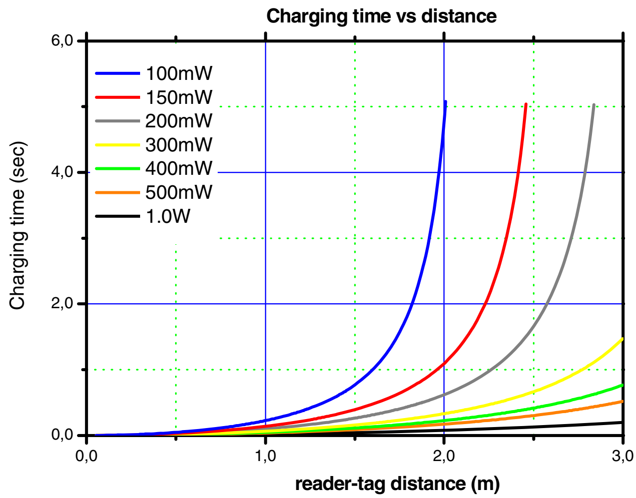

Fig. 5. Charging time versus distance for different reader antenna power (ERP). Perfectly matched dipole antennas have been considered for the reader and the tag. Operating frequency is 900MHz. The maximum power consumption of the tag is approximately P_{tag} = 80μW, while the estimated consumption in standby mode is about $P_{standby}$ = 12μW.

PLL circuit of the reader. In order to minimize the data to be transmitted, the last 4 bits of this sequence of bits are also used as tag ID numbers. This way the system will be able to support up to 16 tags. The next two bytes will contain the actual sensor measurement. The tag transmission finally ends, with a checksum in order to ensure that the received data is not corrupt. The checksum algorithm is based on the addition of the assorted bits with the resulting byte appended to the transmitted data. Overall 5 bytes have to be transmitted in each reader-tag communication.

In backscattering modulation the tag modifies the amount of the incident radiation that it backscatters. According to [3] the actual backscattered power of the tag is approximately 1/3 of the absorbed power (that is -5dB). Thus, according to Friis equation the power P_{bsc} that is backscattered by the tag is given by formula (4), where P_r is the power transmitted by the reader, and G_r and G_t are the gain of the reader and the tag respectively. The wavelength is denoted by λ and the backscattering transmission loss by T_b.

$$P_{bcs} = P_r G_r G_t T_b (\lambda/(4\pi r))^2 . \quad (4)$$

Using again the Friis equation the backscattered power received by the reader P_{rbsc} is given by formula (5).

$$P_{rbcs} = Pr(G_r G_t)^2 T_b (\lambda/(4\pi r))^4 . \quad (5)$$

If a reader that emits 1mW of power ERP, and dipole antennas of gain 2.2 for the reader and the tag are considered, then the values of the backscattered signal power for different distances are presented in Figure 6. In order to decipher the maximum range between reader and sensor tag that may be achieved one should take into

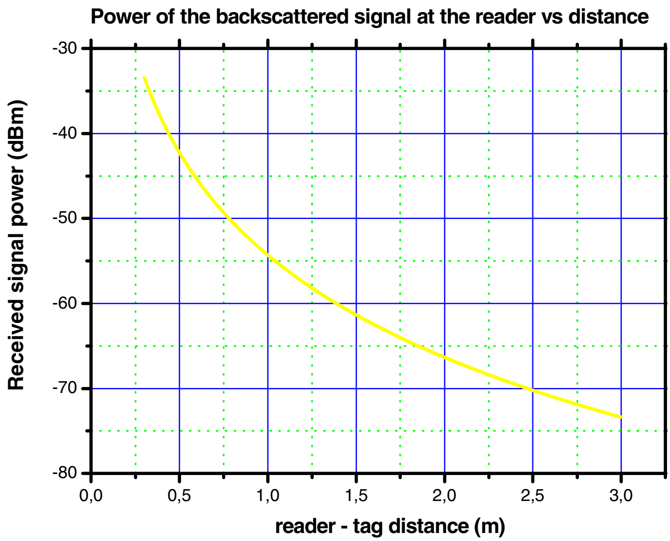

Fig. 6. Power of the backscattered signal received by the reader as a function of reader – tag distance. Operating frequency 900MHz. Dipole antennas have been considered for the reader and the tag (Reader transmitted power: 0dBm).

account that commercial readers are able to demodulate signals down to -80dBm, yields a range of more than 3m. Thus, in this implementation, the main limitation comes from the maximum distance at which the sensor tag may be powered, while the data transmission link does not impose any additional range limitation.

3 Conclusions

The basic considerations behind the design of a passive reader – sensor tag link for use in a wireless strain monitoring network suitable for space applications has been presented and major limitations explored. The system is a heterogeneous wireless network consisting of battery powered, Zigbee compliant, and batteryless nodes that are able to harvest energy from the incident RF field generated by reader. It has been found that it is possible to provide enough power to operate the sensor tag circuitry at a distance of up to 2m with 100mW transmitter power, while reading the sensor tag data does not pose any additional limitation when using backscattering.

References

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