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# Performance testing of a low power consumption wireless sensor communication system integrated with an energy harvesting power source

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*Abstract*— **This paper presents the performance testing results of a wireless sensor communication system with low power consumption integrated with vibration energy harvesting technology. The experiments focus on the system's capability to perform continuous monitoring and to wirelessly transmit the data acquired from the sensors to a user base station completely battery-free. Energy harvesting technologies together with system design optimisation for power consumption minimisation ensure the system's energy autonomous capability demonstrated in this paper by presenting the promising testing results achieved following its integration with Structural Health Monitoring (SHM) and Body Area Network (BAN) systems.**

***Keywords - vibration scavenging, energy harvesting, low power consumption, wireless sensor communication system.***

## I. INTRODUCTION

Technological advances have led to increasing levels of automation, but have also contributed to creating new vulnerabilities to equipment failure, human error, weather conditions and other interfering factors. These vulnerabilities need to be addressed using evolutionary approaches. The continuity and viability of critical infrastructures can be ensured using adaptive approaches that monitor sensory data coming from various sensors situated in vulnerable locations. Such networks of sensors that monitor different physical or environmental conditions, and then communicate this data wirelessly to a base station, are known as wireless sensor networks (WSN).

A wireless sensor network consists of sensor nodes that possess computing power and the ability to transmit and receive messages wirelessly. Each sensor node is typically formed of a sensing unit (i.e. sensors), a processing unit (i.e. microcontroller), a transceiver/receiver unit (i.e. the part that connects the node to the network) and an energy source (i.e. a battery or an energy harvester). The energy source is one of the most important components of a sensor node, as this component determines its life span. The use of a battery as energy source would limit the lifetime of the sensor node, and of the entire sensor network. This shortcoming can be addressed by designing self-powered wireless sensor nodes that harvest energy from the surrounding environment and use this energy efficiently to ensure a potentially unlimited functionality of the sensor node. Energy harvesting from external sources such as ambient vibrations, wind, heat or light could produce sufficient energy for the sensor nodes to be functional indefinitely, as long as the wireless sensor network uses this energy efficiently.

Energy efficiency is a major issue for wireless sensor networks. The most power-consuming activity of a WSN is communication. In our previous work ([1]), this problem was addressed by proposing a novel for the design and implementation of an autonomous wireless sensor communication system with low energy consumption powered from a vibration piezoelectric harvester. The innovative design and implementation technique targeted power consumption minimisation at three different levels: hardware, software and data transmission, in order to reduce the power consumption of the off-the-shelf components included in the system with the aim of ensuring its energy autonomy. The capability of the resulted system to perform continuous monitoring and to wirelessly transmit the data acquired from the sensors to a user base station was then evaluated in the context of SHM and BAN applications. The main motivation underlying this paper is to present the results of laboratory testing for the designed and implemented low power consumption communication sensing system in SHM and for BAN technology.

## II. SYSTEM DESCRIPTION

Fig. 1 illustrates a self-powered autonomous wireless sensor system composed of a power source and a wireless sensing communication system. These two main subsystems are further divided into five functional blocks: vibration

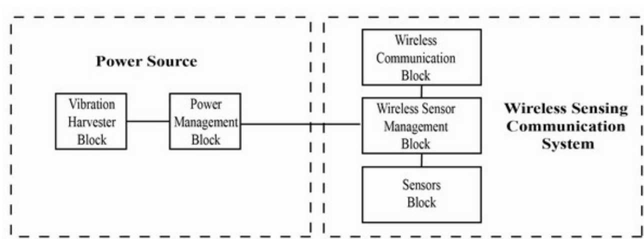


Figure 1. Block diagram of a wireless sensor node powered by a vibration energy harvester

energy harvester block, power management block, wireless communication block, wireless sensor management block and sensors block.

**The vibration energy harvester block** is the power supply. The energy it produces is directly dependent on the vibration provided by the wireless sensor deployment environment.

**The power management block** transforms and stores the energy generated by the vibration harvester.

**The wireless sensor management block** is the link between the sensors block and the wireless communication block. It takes data from the sensors block and processes it in order to be sent to the wireless communication block.

**The sensors block** interacts with the external environment and interprets specific stimuli (e.g. temperature, acceleration, light intensity, pressure, etc.) by transforming them in useful signals for the management block processing.

**The wireless communication block** transmits the data provided by the wireless sensor management block, via air to a base station which can be linked to the internet or directly to the user.

## III. SYSTEM IMPLEMENTATION

This section describes briefly the design and implementation of the system by overcoming the challenges that appeared during the initial design stages presented in our previous article [1]. The novelty of our approach lies in the analysis and implementation of the optimal strategy to reduce the power consumption for all the embedded off-the-shelf subsystems at three different levels: hardware, software and data transmission.

At hardware level, the wireless microcontroller was isolated from the power management module during periods of inactivity by introducing an Energy Aware Interface (EAI) which monitored the amount of energy produced by the harvester stored in a charging element, and interrupted the power supply to the wireless communication module until the minimum level of energy required for the active state was reached. The current consumption of the whole system was reduced to 1.2μA for the disconnected mode – the passive mode of the functioning duty-cycle. This represents a 10-times reduction in current consumption before undertaking any modification of the system module.

At software level, the system was improved in terms of reducing power consumption by choosing the most suitable libraries for the application, the right sensors and by designing a suitable power-saving algorithm to read and transmit data.

The choices concerning data transmission were made with a view towards minimising data consumption, preserving the simplicity of the architecture, avoiding collisions and interferences, and ensuring data security. To this end, a IEEE 802.15.4 star configuration was selected for the data transmission level. The data was wirelessly transmitted using 3 different channels corresponding to the 2.4GHz world-wide free license frequency. This multichannel mode favoured the implementation of a TDMA (Time Division Multiple Access) protocol, thus ensuring better transmission/reception and efficiency due to solving the problem involving the data packets collisions.

The vibration energy harvesting power source is different for each of the applications presented in the following, i.e. SHM and BAN, and it was chosen as the most suitable model for implementation in these two different technologies.

For SHM, the vibration energy harvester is based on the Macro-Fiber Composite (MFC) designed by NASA [2] and glued to an aluminium plate of the same material used in the airplane industry for producing the aircraft fuselage covers. The aluminium plate is mounted inside a tensile testing machine which simulates the airplane wing flying stress levels and vibration conditions.

For BAN, the vibration energy harvester is based on a design created at Cranfield University for a project involving body wearable energy harvesting sources, and described in [3] and [4]. It is composed of four fixed bimorph piezoelectric cantilevers which are fitted in the centre of a wearable rotating wheel. Small plectra are fixed on the interior side of the wheel's outer ring. The wheel is mounted on a stepper motor to simulate the joint-knee movements. When the wheel is rotating, the plectrum is plunking the bimorph piezoelectric material, makes it vibrate, therefore converting the leg simulated movement to vibration, and afterwards to electricity.

The implemented design of the wireless sensing module powered by a vibration piezoelectric energy harvester is presented in Fig.2. In the context of this architecture, the power source is for both applications (SHM and BAN) the vibration harvester which converts the vibration energy to electricity. The power management module then rectifies the voltage and stores it in a 2 x 1mF reservoir capacitors. The energy is discharged when a pre-set threshold is reached. This is triggered by the energy aware interface present on the back of the module. The energy is distributed to each sensor by the wireless microcontroller. The microcontroller, represented by the JN5148 module manufactured by Jennic-NXP is one of the lowest power consumption products currently available on the market. It features a 32 bit CPU (Central Processing Unit), 4 to 32MHz speed, 128Kb RAM (Random Access Memory) [5]. Three sensors were chosen to be included in the system because of their low power consumption, low initialisation time, and also due to the deployed environmental stimuli. The first-one is ADXL 335 3 axes accelerometer [6], the second one is the temperature sensor MCP9700 [7], and the last one is the light intensity sensor GA1A2S100 [8]. All sensors are interrogated by the JN5148 microcontroller, and afterwards the information is sent to the wireless integrated transceiver/receiver (Tx/Rx). The Tx/Rx is compliant with the IEEE 802.15.4 protocol working at 2.4 GHz frequency and allowing the usage of 16 different channels. Out of those 16 channels, three channels were chosen for a multichannel transmission which allows the implementation of a simple TDMA (Time division multiple access) anti-collision algorithm, reduces the possibility of channel overlapping and interference with the existent wireless applications active in the same area, and also provides the user the possibility to calculate the location

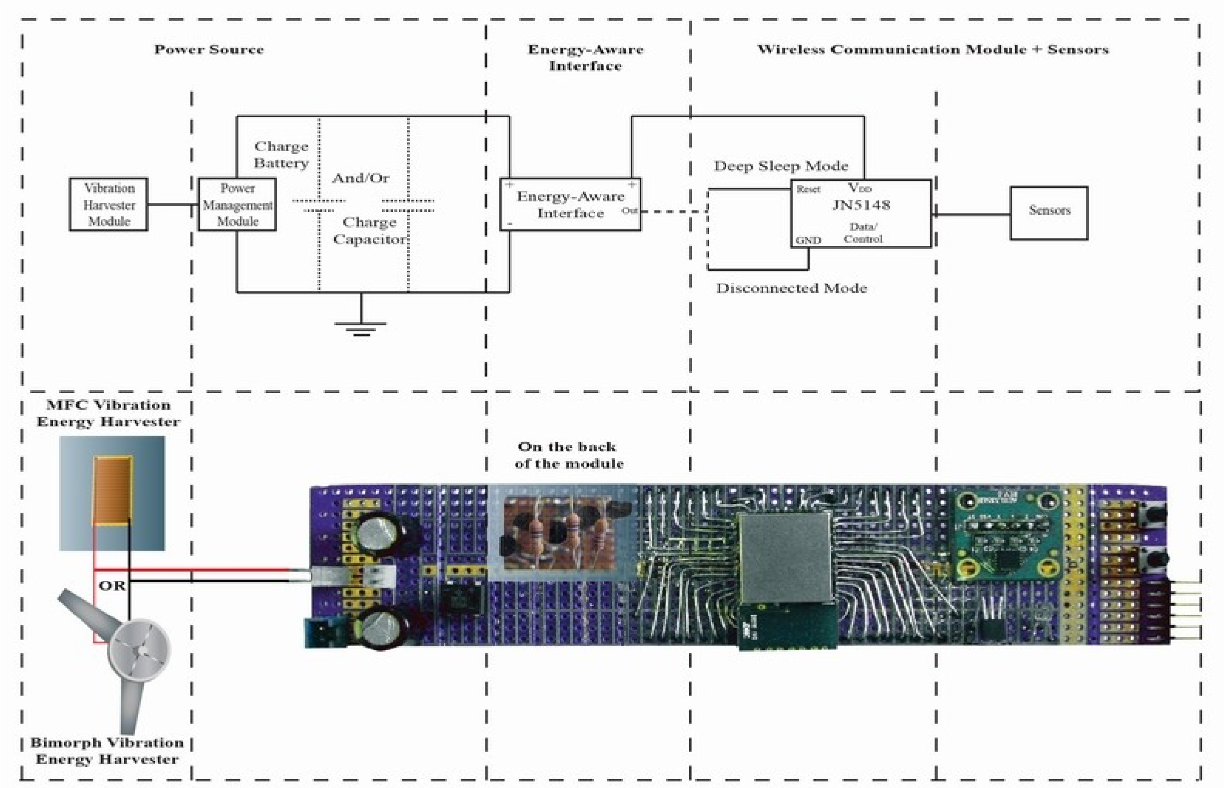


Figure 2. Implemented System Architecture.

of the node using a TOF (Time-of-flight) algorithm. The data is sent wirelessly to the user base station equipped with the same JN5148 wireless microcontroller, powered by a stable power source (battery or DC power source) and linked with a USB cable to a computer. The information is displayed in LabView using a graphical interface especially designed and implemented for this purpose. The signal strength and data from the sensors are monitored and saved for further analysis in two output text files: one containing all the sensors and signal data, and another one counting the number of transmissions/receptions and measuring the time interval between two consecutive ones.

Due to the fact that the module is designed to continuously monitor the vibration, which is its energy source, the system duty cycle is directly related with the energy source: if there is vibration, there is energy to function, to monitor and transmit the data; if there is no vibration, there is no energy and nothing to be monitored.

In order to test the wireless sensing system's ability to provide continuous monitoring, we powered it, in turn, from two different energy harvesting technologies related to SHM and BAN, the main criterion used to illustrate the performance of the system being the dimension of the time gap between two consecutive duty cycle transmissions.

The data is transmitted with the standard IEEE 802.15.4 speed of 250 Kbps, using three different channels, and the total amount of data transmitted during one duty cycle (i.e. data payload, network addresses and correction bytes) containing 100 Bytes.

## IV. TESTING RESULTS FOR SHM

As previously mentioned in Section III, the wireless sensing system integrated with SHM technology is powered by a vibration harvester based on NASA's MFC glued on an aluminium plate which is then mounted into the Istron 8500 tensile testing machine.

The tensile testing machine applies a range of frequencies from 1 to 10 Hz and a force between 11 and 51KN to the aluminium plate, and the material stress generates a proportional strain, varying from 114 to 570με. The tensile testing machine and the aluminium plate are simulating the real flight stress and vibration which are applied to an airplane wing during a flight.

This investigation is motivated by the intention of implementing piezoelectric vibration harvesters in aircraft wings so that they power wireless sensing systems embedded or mounted in the fuselage. The wirelessly transmitted data would be collected by a base station, powered from a regular power source, which can be located inside the airplane body. The piezoelectric harvesters were chosen against electromagnetic ones doe to their light weight, small volume and possibility to be embedded in layered structures or used as patches. The downside of the piezoelectric vibration harvester materials is the small amount of power output and, as a consequence, the power consumption of the wireless sensing system should be reduced at all three levels, hardware, software and data transmission, so that it is able to grant the continuous monitoring capability of the system.

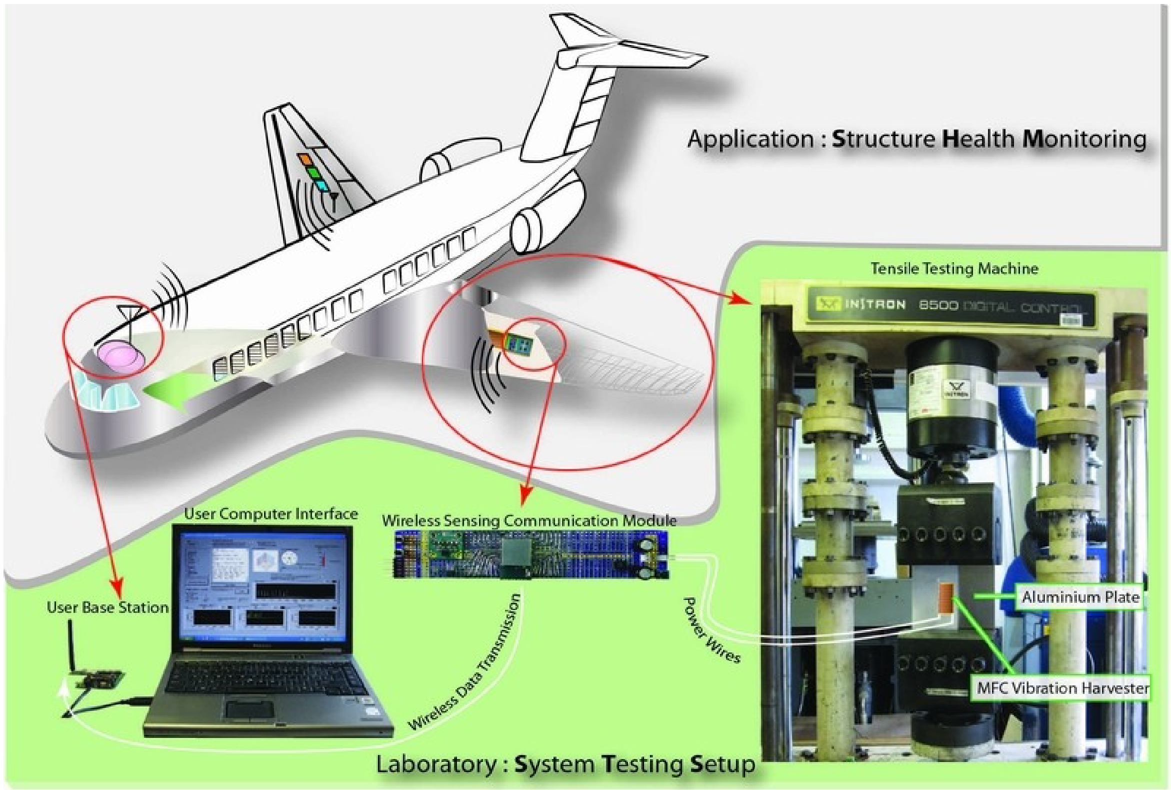


Figure 3. Structural Health Monitoring: application and laboratory testing set-up.

The targeted SHM application and the equivalent laboratory testing set-up are presented in Fig.3.

The continuous monitoring capability can be observed in Fig. 4 obtained by plotting the data stored by the LabView user interface. The data reveals a gap of only 0.4s between two consecutive data transmissions for 10Hz vibration frequency and 51KN (570με) of applied force.

The measured time gap between two consecutive system transmissions (duty cycle) is presented in Table 1, for all frequencies and strain outputs generated when the applied force is present.

As results included in the table below demonstrate the system's continuous monitoring capability not only for higher vibration frequencies like 7.5-10Hz, when it can monitor and transmit new data every 0.4s, but even at a vibration level of 1Hz, when it can transmit the 100 Bytes of information every 3.5s.

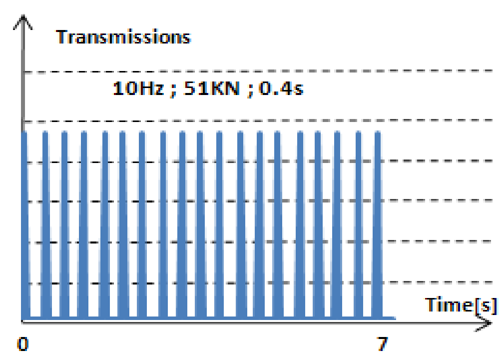


Figure 4. Time gap between transmissions for SHM.

TABLE 1. Experimental Data Transmission for SHM

| Test Conditions | Pause between two consecutive system duty cycle data transmissions [s] | | | | |
|---|---|---|---|---|---|
| Frequency \ Applied Force (Strain) | 11KN (114 με) | 21KN (228 με) | 31KN (342 με) | 41KN (456 με) | 51KN (570με) |
| 1Hz | 39.6 | 12.5 | 7 | 4.9 | 3.5 |
| 2.5Hz | 13.5 | 4.9 | 2.7 | 2 | 1.5 |
| 5Hz | 6.6 | 2.4 | 1.5 | 1 | 0.8 |
| 7.5Hz | 6.2 | 1.7 | 1.1 | 0.7 | 0.6 |
| 10Hz | 5.2 | 1.4 | 0.7 | 0.6 | 0.4 |

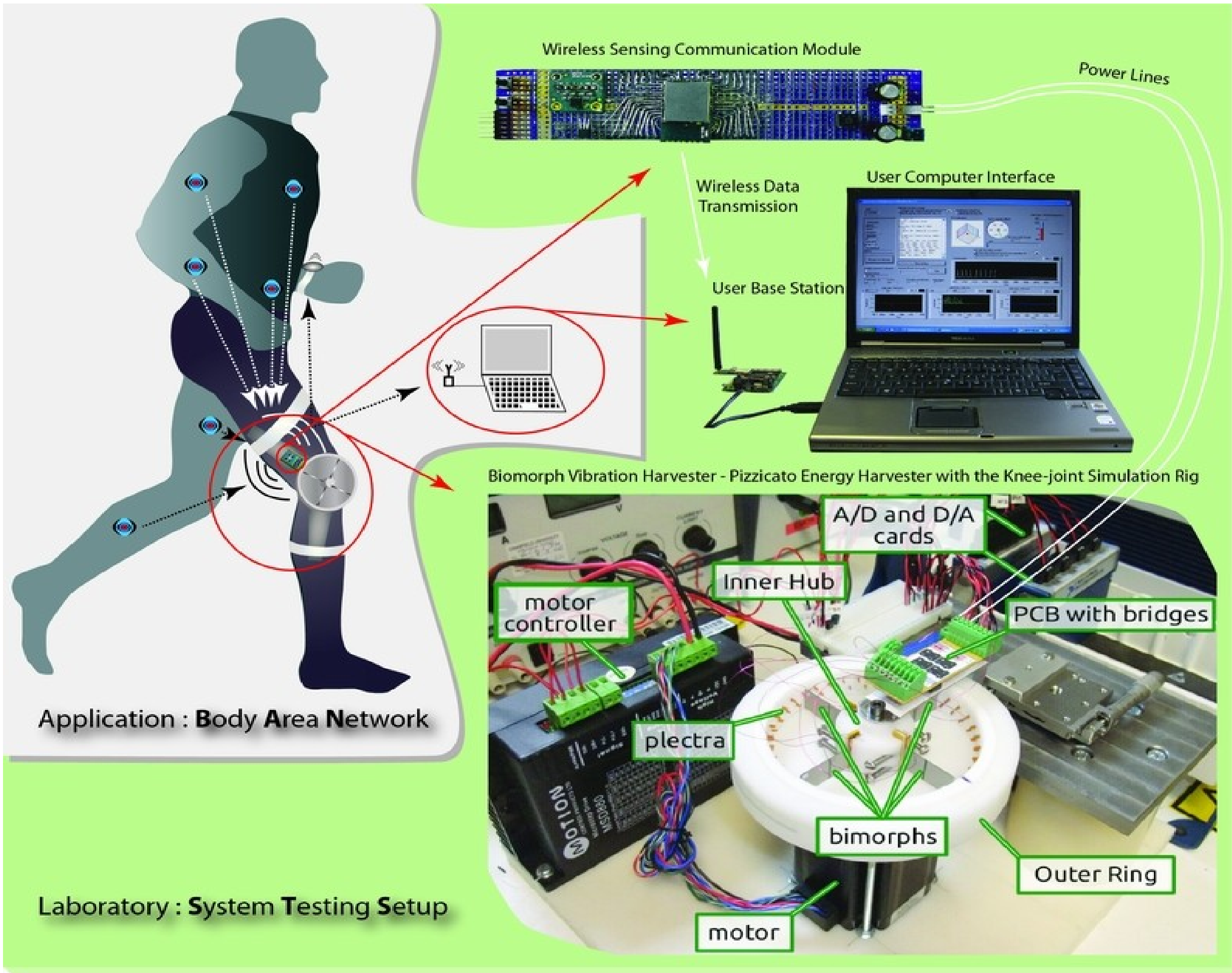


Figure 5. Body Area Network: application and laboratory testing set-up.

## V. TESTING RESULTS FOR BAN

In the case of the BAN technology, the power source is represented by the wearable piezoelectric harvester wheel, which was developed at Cranfield University, and named "Pizzicato energy harvester", [9], [10].

In this case, the piezoelectric energy harvesting system was designed to produce energy by plucking the 4 small piezoelectric bimorphs fixed inside of a wearable wheel whenever the outer ring containing the plectra and the centre are moving due to the knee-joint motion. This system is designed to be fitted externally on the side of a human knee in order to produce energy by harvesting the body movement. For the tests presented in this paper, the harvesting wheel was fitted onto a stepper motor computer controlled via a controller driver interface and a National Instruments data acquisition card (DAQ).

The aim of the application is to monitor and to wirelessly transmit real time data about the bearer, using the three sensors already described, and/or to link future implantable sensors with shorter wireless range, interrogating them and retransmitting the data to the user base station which can be a regular computer or a wearable low power consumption display interface (i.e. wrist watch) (Fig. 5).

Three computer simulated testing scenarios were used for the wheel movement that rely on real data gathered from human behaviour monitoring. The first scenario simulates the movements of a human carrying an empty backpack, the second one simulates a human carrying 12Kg inside the backpack, and the third one a human that has 24Kg inside the backpack. The power from the piezoelectric wheel harvester, after rectification, is transmitted via two wires to the wireless sensing module. The module stores the energy in the 2mF capacitor and it transfers it to sensors and microcontroller when there is enough to perform the duty cycle. Afterwards, it transmits the 100 Bytes to the user base station for further analysis.

A representative example of continuous monitoring capability can be observed in Fig. 6 that was plotted using the data stored by the LabView user interface. The data shows a gap of only 1.1s between any two consecutive data transmissions for the simulated scenario when the backpack contains 0Kg of weight.

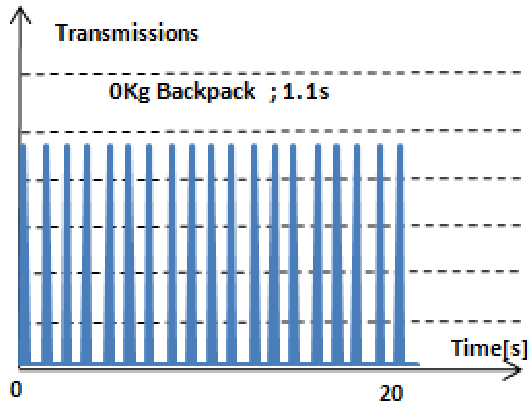

Figure 6. Time gap between transmissions for BAN.

The experimental test results obtained for the all three tests described above are presented in Table 2.

TABLE 2. Experimental Data Transmission BAN.

| **Simulated Situations** | **Pause between two consecutive system duty cycle data transmissions [s]** |
|---|---|
| 0 Kg Backpack | 1.1 |
| 12 Kg Backpack | 1.1 |
| 24 Kg Backpack | 1.1 |

The results of these experiments demonstrate the system's continuous monitoring capability for BAN energy harvesting technology, being able to transmit the 100 Bytes of data every 1.1s for all the three simulated scenarios.

## VI. Conclusions

This work relies on a low power consumption wireless sensor communication system that was designed and implemented so that the power consumption was minimised at three levels: hardware, software and data transmission. This optimisation strategy that guided the system development was directed towards the aim of achieving energy autonomy, while at the same time ensuring the required functionality only with the power provided by a low power vibration energy harvester. The resulted battery-free wireless sensor communication system built using only off-the-shelf components, and powered by a low energy vibration harvester, was employed in two different applications: SHM and BAN monitoring. The successful testing scenarios presented in this paper illustrate the system's ability to not only adapt for usage with two different energy harvesting technologies, but also to continue monitoring and to transmit wirelessly the information gathered for further analysis, at the same time achieving a speed between two transmission duty cycles of 0.4s for SHM and 1.1s for BAN.

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