

Wireless Sensor Communication System with Low Power Consumption for Integration with Energy Harvesting Technology

Vlad Marsic, Meiling Zhu, *Member, IEEE*, and Stewart Williams

Abstract — This paper reports on the design and implementation of a wireless sensor communication system with a low power consumption that allows it to be integrated with the energy harvesting technology. The system design and implementation focus on reducing the power consumption at three levels: hardware, software and data transmission. The reduction in power consumption, at hardware level in particular, is mainly achieved through the introduction of an energy-aware interface (EAI) that ensures a smart inter-correlated management of the energy flow. The resulted system satisfies the requirements of a wireless sensor structure that possesses the energy autonomous capability.

Keywords — Energy harvesting, low power consumption, wireless sensor communication system.

I. INTRODUCTION

Successful high technology manufacturing industries are offering a range of high value products and services. High value products are technology intensive, expensive and reliability critical requiring engineering services (e.g. maintenance and repair) throughout the life cycle, e.g. railway axle bearings, wind turbine rigs, and aircraft engines and wings. These products must be monitored and assessed throughout their lifetime. Currently, the process is often manual, expert dependent and time consuming, and often lacks information on what is going on while in active service. High technology industries are increasingly demanding easy access to information for better decision-making in the maintenance process over the life cycles of their products. The management process typically requires an autonomous monitoring system like the one proposed in this paper research program, that operates as long as possible to collect, elaborate, store and share information within wireless sensor and communication networks powered by energy harvesting technology, rather than powered by mains electricity or batteries.

Energy harvesting means to scavenge ambient energy from human motion, machine vibration, thermal and solar energy, and then convert the scavenged energy into useable electrical energy in order to provide electrical power for small electronic and electrical devices making them self-sufficient in energy supply. Benefits of this

technology include: no need of battery replacement, no need of cabling, easy to retrofit infrastructures, and a “truly fit-and-forget” approach that allows reduction of physical installation, replacement and maintenance costs, and time. The system will become completely autonomous, with minimum or no maintenance. This technology will provide an easy access to up-to-date asset information for better decision making on operations, service and maintenance and improve reliability and safety of industry business. The need for such systems is certainly not unique to any one industry, and currently there are widespread needs for the use of such energy autonomous systems to power sensor networks for structural health monitoring, especially in areas like oil and gas pipeline monitoring, bridge maintenance companies, as well as railway, automotive, aircraft, marine and military industry.

Because of the limited amount of energy harvested by vibrating harvesters, the majority of the actual technology is currently using as energy sources the light, air and water movement to power the Wireless Sensor Networks (WSN). The systems are applicable for those that monitor processes in open spaces, but not applicable inside the buildings or other structures operating in a full enclosure habitat. Because of the growing need to monitor under high stress dynamic structures like industrial machines, vehicles, bridges or pipe systems, the industry is demanding to have self-powered WSNs capable to operate without light, water or air movement in a partially or fully closed environment. One of the best harvesting mechanisms in such conditions is to scavenge the vibration energy [1], [2]. However, the wireless sensor nodes available on the market are characterised by high power consumption, while the energy harvested by vibration harvesters, which can take the form of magnetic, piezoelectric or capacitive transducers, is normally limited to a few hundred mill watts. This paper presents the design and implementation of a wireless sensor communication system that has a low power consumption and can be integrated with energy harvesting technology.

II. DESCRIPTION OF THE SYSTEM

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

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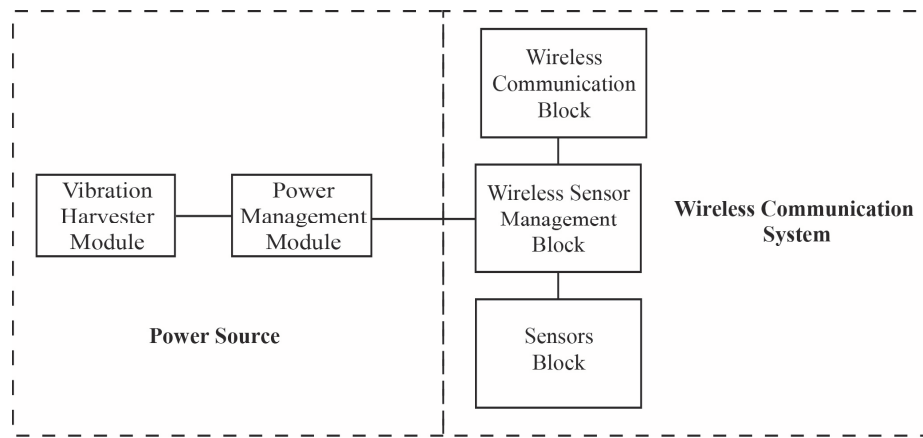


Fig. 1. Block diagram of a wireless sensor node powered by a vibration energy harvester.

wireless communication block, wireless sensor management block and sensors block.

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

The power management block extracts, transforms and stores the energy generated by the vibration harvester, making it useful as a stable DC power source.

The wireless sensor management block 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 into electrical signals.

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.

This paper will discuss the design and implementation of the wireless communication system which must satisfy certain conditions in order to achieve the state of energy autonomy.

Considering the power consumed by the transceiver/receiver (Tx/Rx) in the sleep and active modes, the speed of the Central Processing Unit (CPU), the dimension of Random Access Memory (RAM), and of the Flash Memory (Flash), the Jennic-NXP wireless microcontroller, JN5148, is chosen for the wireless communication system. JN5148 is an ultra-low power, high performance wireless microcontroller. The device features an enhanced 32-bit Reduced Instruction Set Computing (RISC) processor with programmable clock speeds. It also includes a 2.4GHz IEEE802.15.4 compliant transceiver, with a power consumption of 15 mA when transmitting, 17.5 mA when receiving, and 1.25 μ A in sleep mode, 128kB RAM, and a rich mix of analogue and digital peripherals. The 4Mb flash memory footprint allows the device to run both a network stack (e.g. ZigBee PRO) and an embedded application.

Having established the core structure of the wireless communication system, one can focus on the system design and implementation at three levels: hardware, software and data transmission.

At the system design stage, the key-problems to be resolved are:

- Reduce the power consumption in the active mode (while executing the programmed instructions, reading sensors' data, and transmitting wirelessly the information), and in the passive mode (while the device is disconnected from the power source or enters an idle mode known as deep sleep, until the energy storage device regains enough energy for the system to function in active mode);
- Preserve the system's basic functionality and compatibility with standards after reducing the energy consumption (i.e. preserve the main function of transmitting data using a certified protocol like IEEE 802.15.4, and respect the restrictions involving power and license for certain geographic regions).

III. SYSTEM IMPLEMENTATION

The system is implemented at three levels: hardware, software and data transmission and aims to have low power consumption in order to be integrated with energy harvesting technology.

A. Hardware Level

As already mentioned, the system is powered using a vibration harvester which converts the vibration energy from the surrounding environment into alternative current and voltage. This electric output is afterwards transformed by the power management module. The amount of energy is supplied to the wireless communication system. It is known that the output is influenced (e.g. reduced, discontinued) by the type of the harvester and the strength, frequency and period of its vibration. Due to this fact, the system has to conserve its energy in low duty cycles.

When enough energy is available, the system reads the sensors, transmits the data wirelessly to the user (base station), and then enters in a low energy consumption state (sleep mode or disconnected from the power supply).

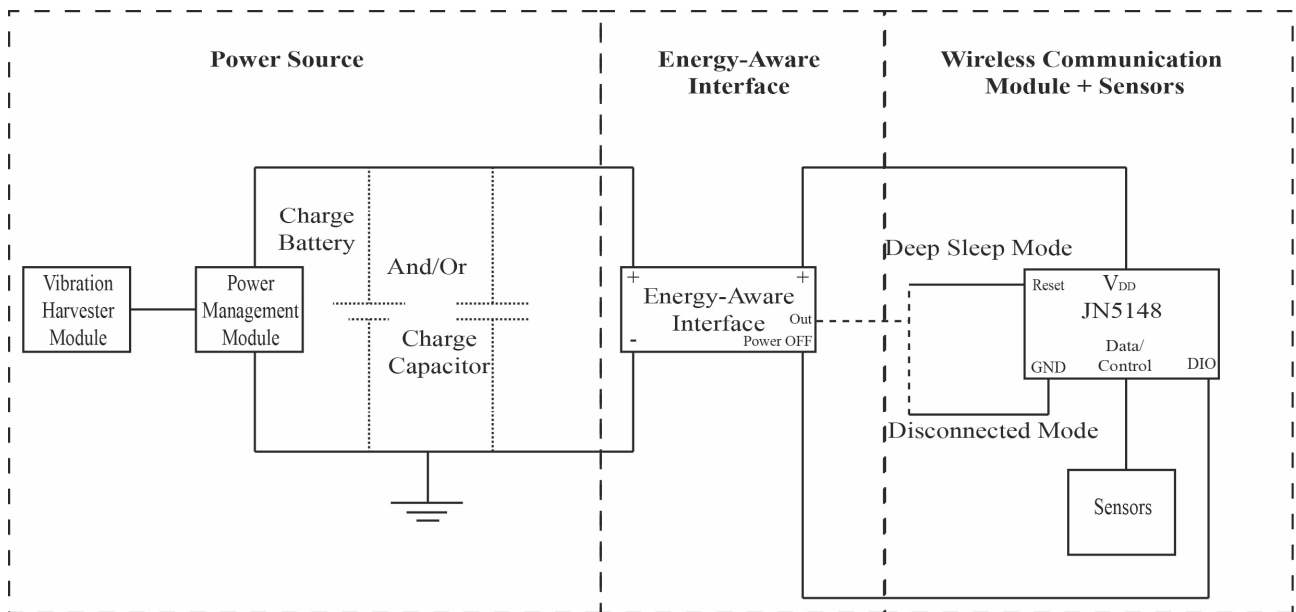


Fig. 2. System design and implementation at hardware level.

The low energy state can be in the period of a few seconds or hours depending on how much energy is available for the harvester to recharge a capacitor up to a certain level (Energy-aware interface Voltage Threshold) to allow the system to function again.

The low energy state can reach the minimum of power consumption in two scenarios: either the system enters in deep sleep mode and can be “woken up” by an external monitoring circuit, or the system is disconnected from the power supply by an external monitoring circuit. In both cases, an energy-aware interface is mandatory needed to be introduced into designed system in order to control and monitor the low energy state of the system until the available energy allows the next active stage: reading sensor and transmitting wirelessly the data (Fig. 2).

The charging element from the power source block can be a capacitor.

The energy-aware interface (EAI) introduced here to ensure the low energy state can be connected for the deep sleep mode to the RESET pin of JN5148, or for the disconnected mode to the gate of the N-MOS transistor used as a switch between JN5148 minus and system ground. The energy-aware interface operates in two stages:

1. When the voltage on the charging element reaches the threshold voltage of the EAI, the OUT pin of the EAI is set to Active, which will open the connection to the ground for JN5148 or will wake up the JN5148 module from the deep sleep mode.
2. Afterwards the wireless microcontroller starts the booting sequence. After waking up, JN5148 sets to Low logic the Digital Input-Output (DIO) connected to the gate of N-MOS transistor placed between the minus of the EAI and the ground of the system, disconnects the EAI, read sensors, transmits the data,

sets to High logic the same DIO as before, and reconnects the EAI. This will detect if the voltage on the charging element is below its threshold voltage, and will give a passive state signal to the gate of N-MOS, placing the transistor in high impedance state, and cutting the power for JN5148 for the disconnected mode.

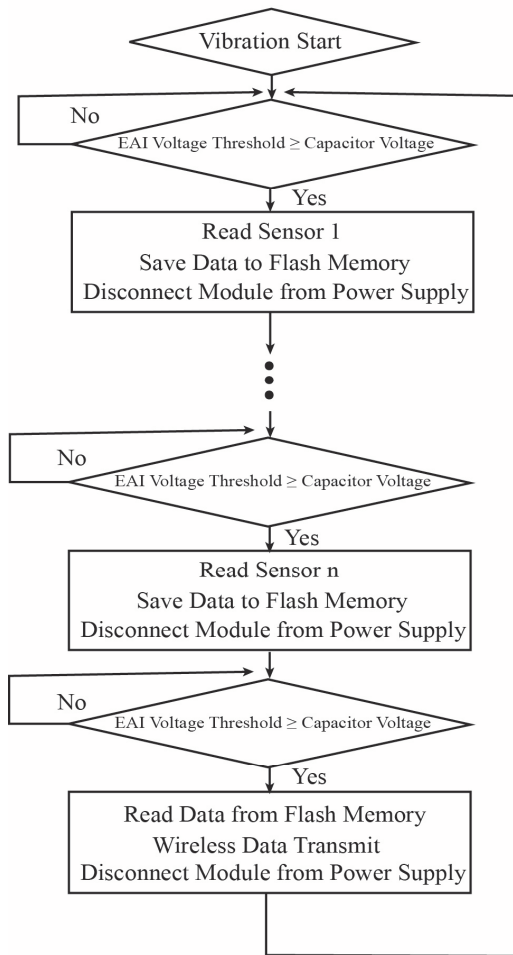
B. Software Level

To reduce the energy consumption at software level, one requires a good practical approximation and calculation of the energy used in order to boot the system, read the sensors and wirelessly transmit the data.

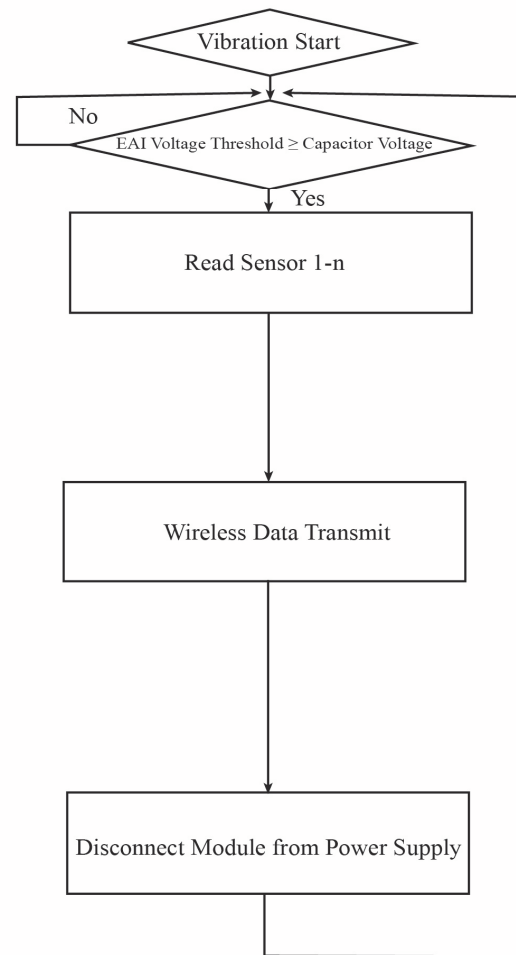
The optimisations that can be addressed at the software level are concerned with reducing to minimum the dimensions of the program, accelerating the operations, eliminating the unnecessary delays, and reducing the time of the active mode.

Considering the worst case scenario in which a charging element of minimum capacity can be filled up in the maximum accepted period of time, and the best case scenario in which a charging element of maximum capacity can be charged in the minimum period of time, we designed two algorithms that capture the system functionality when addressing these scenarios (Fig. 3).

Both algorithms were implemented in application programming. The first one has the advantage to be adaptive when a random minimum power is provided to the charging element, but its main disadvantage is the impossibility of real timing for reading the sensors. The second one has the advantage of transmitting the data immediately after reading the sensors, thus eliminating the problem of real timing, but it does not have the capacity to adapt when the charging element is confronted with random variable power.



Software Device Control – Algorithm 1



Software Device Control – Algorithm 2

Fig. 3. Software algorithms.

Both these disadvantages are corrected and compensated at the software level through the following methods:

- The timing issue is solved at the next stage of system design, data transmission, by associating to each node a time allocation frame in addition to its data frame, so that the timings can be correlated and errors reduced.
- The adaptation problem is addressed by reducing the code size and the start-up time of the application with functions from the Low Power Transmit library (libLPTI.a) for the IEEE 802.15.4 stack (provided by the Jennic programming team).

Nevertheless, a very important factor in reducing the time when the system is in active mode, and at the same time preventing malfunction, is the choice of the sensors used in the application, an issue that needs to be considered very seriously. The sensors are discrete and simple devices which can be accessed only through software and by programming the communication module microcontroller. Due to the large variety of sensors on offer from various electronic sensor manufacturers, one can identify many digital and analogue low power consuming integrated devices that can be used in

applications. In the design of the system presented in this paper, we have chosen as starting point two sensors: acceleration and temperature. In this work, the following sensors are chosen for experiments due to their power consumption and supply voltage range: the digital 3-Axis Accelerometer from VTI, CMA3000-dx; the digital Thermal Sensor from Microchip, TC77; the analogue 3-Axis Accelerometer from Freescale, MMA7361LC, and the analogue Temperature Sensor from Microchip, MCP9700. Their key-features are presented in Table 1.

TABLE 1: SENSORS' VOLTAGE, CURRENT AND TIME CHARACTERISTICS.

Sensor	Type	Supply Voltage [V]	Current Consumption [μ A]	Time to initialise [ms]
CMA3000	Digital	1.7-3.6	70	25
TC77	Digital	2.7-5.5	250	400
MMA7361LC	Analogue	2.2-3.6	400	0.5
MCP9700	Analogue	2.3-5.5	12	0.4

Due to the power source dropping in voltage when used in active mode, the sensors must be accessed in a descending order of their minimum voltage supply.

Both the sensor and the main system that communicates with the sensor consume energy, therefore the overall

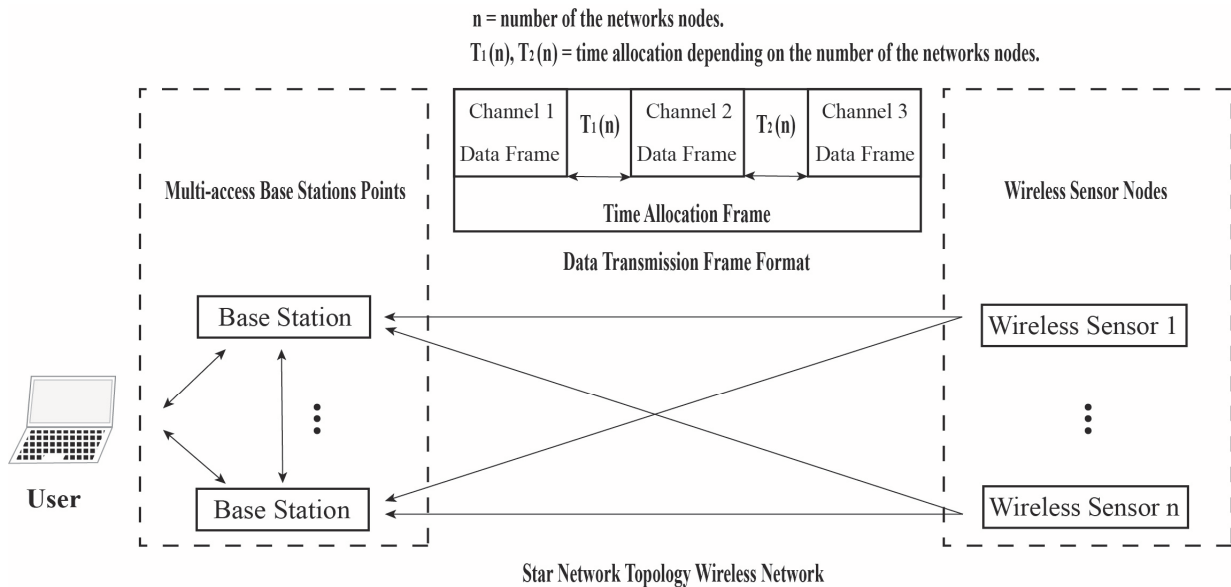


Fig. 4. Modified network topology for the new data frame format.

power consumption is calculated as the sum of the power used by the wireless system and sensor, multiplied by the sum of the initialisation time and the read/write time. Given that the analogue sensors when compared to the digital ones require less initialisation time, the final implemented sensor solution employs the analogue acceleration and temperature sensors.

C. Data Transmission Level

At this level, the ideal scenario offering the lowest power consumption would be the Self-Powered Autonomous Wireless Sensor offering the same functionality as a passive Radio Frequency Identification (RFID) tag. In real life, this functionality implies, except for the low consumption part, only downsides. On the one side, the distance between the RFID tag and the reader would be constrained by the fact that local standards regulate the maximum power level for transmitting, and with such power level one cannot transmit further than a certain short distance. On the other side, given this type of functionality, the power would be very low and insufficient to implement an algorithm for communication and data transmission with multiple sensors.

There are many attempts to combine the IEEE 802.15.4 compliant wireless networks with RFID technology in a hybrid dual transceiver/receiver, but due to the amount of power required this combination is suitable only for battery powered systems. However, at the present moment, mixing two different transceivers/receivers (one for the IEEE 802.15.4/ZigBee protocol, and the other one for the Amplitude Modulation (AM) used by RFID technology [4]) that usually work at different frequencies, into the same product, increases the expenses and complicates the structure of the wireless network.

The ZigBee protocol approach is not yet technologically suitable for this project, because it implies the presence of routers which are devices continuously powered to connect the end device nodes to the base station, without being allowed to have a low power duty cycle.

A ZigBee network without routers could be resembled to a star network configuration, in which every node transmits and receives data to and from the base station. This configuration is identical with the IEEE 802.15.4 star configuration. Therefore, the IEEE 802.2.15.4 protocol suits better the purposes of this work when compared to ZigBee, as it offers a simplification of the software and data transmission levels, thus resulting in less power consumption.

Due to these above considerations, one has chosen for the data transmission level an IEEE 802.15.4 star configuration. The wireless sensors representing the nodes of the network use a IEEE 802.15.4 minimum data frame format, less than 32 bytes per total length, to transmit the data they collect to the base station. The transmission uses 3 communication channels with a dynamic calculated time allocation frame in order to prevent data collision between nodes, given the fact that all nodes only transmit data, without performing Clear Channel Assessment (CCA), Energy Detection (ED), or receiving data from the base station. These limitations were imposed in order to save energy. The type of the base station can be Simple (one station), or Multiple Access (multiple fixed stations interconnected with each other, offering better reception and efficiency) (Fig. 4).

IV. TESTING AND MEASUREMENTS

The measurements were made in three steps using the setting described in Fig. 5, according to [3].

The first board for testing the current consumption for JN5148 was the sensor board DR1048. For the deep sleep mode measurements, the sensor board, which contains the wireless communication module JN5148, was directly connected to the testing set at the points A and B.

The second board for measuring the current consumption carrier also for the wireless module, was built on a single layer cooper prototype board, using the minimum configuration for low power applications

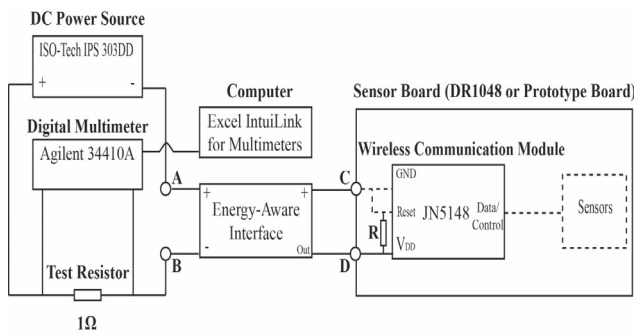


Fig. 5. Setting for measuring the current consumption.

suggested in the following Jennic documentation articles: DR1048_Schematic, JN-AN-1146 and JN-AN-1055.

The last step in measuring the current consumption in deep sleep mode for the JN5148 module was made using the same single layer cooper testing board, but replacing the 18 K Ω resistor (R) between the Reset pin and the V_{DD} with a 10 M Ω pull-up resistor. The same measuring configuration (connected to the points A and B) was used for measuring the current consumption of the prototype board in sleep mode.

The results quantifying JN5148's current consumption in deep sleep mode are included in Table 2.

TABLE 2: CURRENT CONSUMPTION MEASUREMENTS RESULTS.

Measuring Steps	Deep sleep mode current consumption [μ A]
DR1048 sensor board	1598.41
Prototype board (18K Ω)	258.32
Prototype board (10M Ω)	9.58

To determine the current consumption for the disconnected mode, the same setting illustrated in Fig. 5 was used, but instead of connecting the sensor board to the A and B points, the energy-aware interface was introduced and the sensor board which contains the wireless communication module JN5148 was connected to the EAI (Fig. 6) at points C and D.

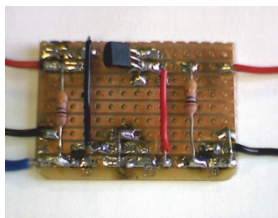


Fig. 6. Energy-aware interface board for testing.

The measurements for current consumption in disconnected mode are presented in Table 3.

TABLE 3: CURRENT CONSUMPTION MEASUREMENT USING THE ENERGY-AWARE INTERFACE FOR ALL MEASURING CONFIGURATIONS.

Boards for testing	Disconnected mode current consumption [μ A]
JN5148 (wireless microcontroller)+DR1048(Sensor Board)	1.19
JN5148 (wireless microcontroller)+Prototype Board (18K Ω)	1.19
JN5148 (wireless microcontroller)+Prototype Board (10M Ω)	1.19

Considering the results measured for the circuit's low energy state, and knowing that for the deep sleep mode another external circuit needs to be added to "wake-up" the module, thus adding another consumer besides the wireless module, the implementation of the energy-aware interface not only resolves the issue of energy consumption during long inactivity periods, but can also be applied to other wireless modules on the market.

V. CONCLUSION

The present paper describes at all three levels – hardware, software, and data transmission – the design and implementation of a wireless communication system suitable for all types of ultra-low vibration energy harvesters, by taking into consideration the present standards, protocols and electronic technology offers.

In terms of practical challenges encountered during system implementation, the choice of a license free frequency is worthwhile mentioning. The frequency of 2.4 GHz was found to be the most suitable for the system because it is a license-free radio frequency, and its advantage over the other two license-free frequencies used for transmitting in the IEEE 802.15.4/ZigBee standards, i.e. the European 868 and the North-American 915 MHz, is that it is a worldwide recognised license-free frequency that uses 16 channels with a 5MHz-wide bandwidth for data transmission instead of the single-channel European 868 MHz frequency, or the ten-channel North-American 915 MHz frequency. The downside of using the 2.4 GHz frequency is that the distance range and obstacle penetration is shorter than in the case of the 868/915 MHz frequency bands, and that the water concentration from its propagation environment is severely absorbing or reflecting the radiation. Another deficiency is that most of the active microwave devices (i.e. microwave ovens, Bluetooth devices, car alarms, WiFi networks, cordless phones, etc.) use the same frequency, and the interference danger is high.

To overcome some of these challenges, a multichannel transmission is implemented by employing the three channels which do not overlap with the standard approved wireless devices and appliances. The channels 15, 20, 25, and 26 do not overlap with 802.11b in North America, and the channels 15, 16, 21, and 22 do not overlap with 802.11b in Europe [5].

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