A UML/MARTE Extension for Designing Energy Harvesting in Wireless Sensor Networks

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Abstract Power supply is the major concern in the wireless sensor networks (WSNs) applications. Currently, the node lifetime is limited by a battery supply which is a short lifetime, unmanageable and uneconomical. Energy Harvesting was proposed as a promising alternative to power sensor nodes in many application fields. Several energy harvesting concepts are considered in WSNs systems such as solar, vibration, thermal, kinetic, acoustic noise, radio frequency (RF), biochemical and hybrid energy sources. The existing modeling design for the power supply section of sensor nodes is limited to the design of solar energy harvesting method which is mostly employed in outdoor applications with sufficient sun light. However, other energy harvesting concepts are potential ambient sources of energy which offer an enough amount of power for sensor nodes. In this paper, we propose a high level methodology based on UML/MARTE standard to model specifications of outlined energy harvesting devices in the WSNs. We define new packages extending the "HW_Harvesting" package which is extending the "HW_PowerSupply" package. A case study of a WSNs system regarding leak detection in water pipeline monitoring is used to evaluate the practical use of our proposal.

Keywords WSN · Energy harvesting · MDE · MARTE

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1 Introduction

During the last decade, there has been a considerable research area in the development of WSNs. These WSNs systems are used in a variety of applications such as health care systems [1], environmental management [2] and many others. The common focus in WSNs applications is the energy efficiency. Typically, sensor nodes have a limited power resource for operating the network requirements. Currently, they are supplied by a local battery which is a short lifetime and its replacement becomes time consuming, uneconomical and unfeasible in some cases. Several techniques are investigated in the literature to maximize the lifetime of sensor nodes. Among these approaches, energy harvesting is an interesting technique. Energy harvesting is a promising alternative of meeting the network energy requirements, in which ambient energy is extracted from the environment and is converted into electricity to power the sensor nodes. A review of the possible sources of energy which could be extracted from the environment is given in [3]. There are numerous sources of energy to power the sensor network such as solar power, kinetic energy, mechanical vibrations, temperature differences, magnetic fields, etc. The identification of the energy harvesting strategy is according to the operating environment and the system's energy requirements. Since energy harvesting approach offers an adequate power supply for sensor nodes, designers need to integrate this powerful technique in the development cycle of WSNs systems. The Model Driven Engineering (MDE) [4] paradigm is commonly being adopted to design complex systems. The use of the Unified Modeling Language (UML) profiles, to deal with real time constraints and performance issues of embedded systems, reduces the design complexity. In this context, the Modeling and Analysis of Real Time and Embedded systems (MARTE) [5] standard offers a rich support for modeling and analyzing real time embedded systems. The MARTE profile provides the concepts needed to describe real time features and the semantics of embedded systems at different abstraction levels for enabling performance analysis. MARTE standard proposes in its Non Functional Properties (NFPs) package the HW_Power package for annotating power issues and heat dissipation of hardware (HW) components. MARTE also provides HW _PowerSupply and HW_Battery packages to supply energy. However, MARTE standard does not provide a support to specify the diversity of possible harvesting energy sources in WSNs applications. An earlier work proposed in [6], in which authors modeled the power supply section of sensor nodes and proposed a MARTE extension of the HW_PowerSupply package by adding the HW_Harvesting stereotype to define energy harvesting devices and specially focus on solar energy (the HW_PV stereotype). Solar energy is probably the most exploited to power WSNs, but it is not always available due to its strong dependency on weather, day and night. While solar energy is limited to outdoor applications with sufficient sun light, other potential ambient sources of energy has been considered for energy harvesting. Therefore, exploiting and introducing these energy harvesting kinds by extending MARTE profile is necessary. In this work, we aim to extend MARTE profile to support possible

WSNs energy harvesting techniques including vibration, thermal, kinetic, acoustic noise, RF, biochemical and hybrid energy sources to provide new unlimited energy sources enhancing sensor network capabilities to power itself and achieve a longer lifetime. We will add therefore other MARTE extensions to satisfy outlined energy harvesting types. An interesting domain application of WSNs is the water pipeline monitoring to detect leaks and control the water quality. A case study of a WSNs system regarding water pipeline monitoring using a vibration energy harvesting device is used to evaluate the practical use of our extension. In the present paper, we present a high level methodology based on UML/MARTE standard to model specifications of various energy harvesting devices in the wireless sensor network. In Sect. 2, we outline MARTE capabilities for power section modeling. Section 3 describes our proposed extensions. Section 4 describes the behavioral analysis of the proposed extensions. In Sect. 5, we give an overview about energy harvesting methods used in water pipeline monitoring and we give a case study illustrating our proposed extensions. We end our work with conclusions and perspectives in Sect. 6.

2 MARTE Capabilities for Designing Power Section

MARTE profile is a standard UML profile promoted by the Object Management Group (OMG). UML/MARTE is decomposed into several sub-profiles such as Global Resource Modeling (GRM), Hardware Resource Modeling (HRM) and Software Resource Modeling (SRM), etc., which each one has its own specifications. MARTE profile offers a support for annotating NFPs of embedded systems. This UML profile defines in its HRM and NFPs packages, the generic package HW_Power for modeling power consumption and heat dissipation of HW components according to its specifications [5]. In particular, the HW_PowerSupply package specifies the energy supplies. While our major constraint in WSNs design is the energy efficiency, this entity should be extended and refined to contain more properties necessary to perform energy sources. MARTE standard represents a model for energy harvesting which focuses only on solar energy scavenging device, described in [6], in which "HW_Harvesting" stereotype describes the harvester device. This stereotype is extended with "HW_PV" to describe the harvesting done by a solar panel. However, this proposed model lacks an explicit and rich support to exploit the other energy harvesting kinds in order to maintain the sensor network lifetime. Therefore, MARTE needs to be refined and extended to offer a powerful high level model to design the power section of a WSNs node. In the rest of paper, we propose to develop a generic model that focuses on different energy harvesting techniques including vibration, thermal, wind, acoustic noise, RF, biochemical and hybrid sources.

3 The Proposed Extensions

We propose to extend the “HW_Harvesting” package to add the other energy harvesting devices: vibration, thermal, kinetic energy, acoustic noise, RF, biochemical and hybrid energy harvesting types.

The structure of the extended profile is shown in red in Fig. 1. To include all necessary properties to design outlined energy scavenging types, seven new classes are introduced in MARTE profile. The content of each of these new stereotypes is described in the following subsections.

3.1 Vibration Energy Harvesting: HW_Vibration

One class of energy harvesting systems is the vibration energy source. Vibrations are mostly present in built environments such as bridges, roads and rail tracks. Vibration harvester captures the energy from the mechanical motion and convert it into electricity. Three basic mechanisms [7] are used for transforming vibration into electrical energy: piezoelectric [8], electrostatic [9] and electromagnetic [10]. This extracted energy from the vibration source depends on the amplitude of vibration and the frequency of the source vibration object. Figure 2 shows the “HW_Harvesting” extension with the “HW_Vibration” stereotype to describe a vibration device.

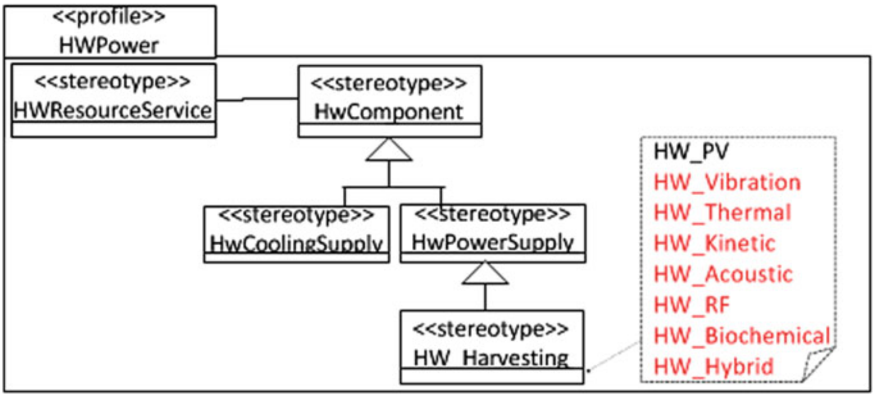
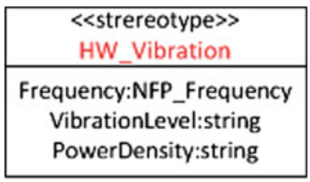


Fig. 1 Structure of the extended HW_Harvesting package

Fig. 2 Proposed MARTE extension for vibration energy harvesting modeling



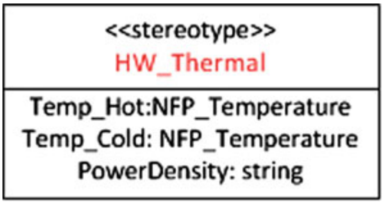


Fig. 3 Proposed MARTE extension for thermal energy harvesting modeling

3.2 Thermal Energy Harvesting: HW_Thermal

Another method is the thermal energy harvesting [11]. This technique produces electricity using the Seebeck effect when there are differences in temperature or gradients. Thermal energy sources can be machines, animals, human body and others. The thermoelectric conversion depends on the temperature's difference between the two sides of the transducer and the power density achieved by the harvester. Figure 3 shows the "HW_Harvesting" extension with the "HW_Thermal" stereotype to describe a thermal device.

3.3 Kinetic Energy Harvesting: HW_Kinetic

Among existing kinds of renewable energy resources, the kinetic energy is an important source for powering sensor network. Kinetic energy can be harvested in the environment from the wind flow and moving water in rivers or in pipes. The technological concepts associated with energy harvesting from flowing water or from the wind are similar. Kinetic energy is mostly harvested using turbines. The importance of harvesting energy from water and wind to power sensor network is highlighted in [12]. The extracted energy depends on the density of the source, its velocity and the cross area. Figure 4 shows the "HW_Harvesting" extension with the "HW_Kinetic" stereotype to describe a kinetic device.

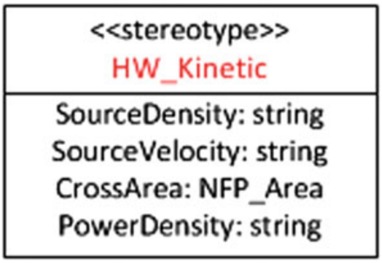


Fig. 4 Proposed MARTE extension for kinetic energy harvesting modeling

Fig. 5 Proposed MARTE extension for acoustic energy harvesting modeling

3.4 Acoustic Energy Harvesting: HW_Acoustic

Acoustic energy [13] is another viable form of ambient energy. It is the process of converting continuous and high acoustic waves from the environment into electrical energy by using an acoustic transducer or resonator. The extracted energy depends on the frequency of piezoelectric material and the frequency of resonator. Figure 5 shows the "HW_Harvesting" extension with the "HW_Acoustic" stereotype to describe an acoustic device.

3.5 Radio Frequency Energy Harvesting: HW_RF

Other technique of energy harvesting is the RF [14] energy harvesting. The RF energy is captured by a receiving antenna which is attached to each sensor node. The antenna is characterized by its frequency, the impedance,the size and the directivity. Then, this captured energy is converted through a power conversion circuit into DC energy which is stored in an energy storage device to power the sensor node. Figure 6 shows the "HW_Harvesting" extension with the "HW_RF" stereotype to describe a RF device.

3.6 Biochemical Energy Harvesting: HW_Biochemical

Another harvesting strategy employed to power sensor nodes is the biochemical energy harvesting technique [15]. It indicates the process of generating the electricity

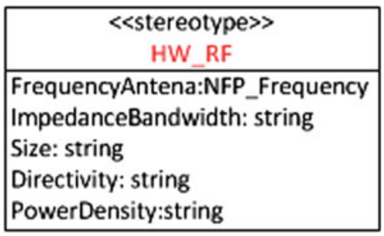


Fig. 6 Proposed MARTE extension for RF energy harvesting modeling

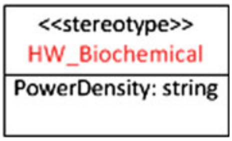


Fig. 7 Proposed MARTE extension for biochemical energy harvesting modeling

by converting the chemical energy of a fuel (e.g. hydrogen) through a chemical reaction with an oxidizing agent. The harvested energy is mainly used for small-scale powering applications. Figure 7 shows the "HW_Harvesting" extension with the "HW_Biochemical" stereotype to describe a biochemical device.

3.7 Hybrid Energy Harvesting: HW_Hybrid

Several existing approaches for energy harvesting are focusing on one type of energy while other types of energy are wasted. Developing hybrid models with the combination of several energy harvesting strategies in the same device can increase the capability to power the sensor node from more than one source which leads to store more energy and have persistent batteries. We present four hybrid approaches: Hybrid solar and thermal cell, hybrid solar and mechanical cell, hybrid solar and biochemical cell and hybrid biochemical and biomechanical cell. We have extended the "HW_Harvesting" stereotype with the "HW_Hybrid" stereotype to describe an hybrid device which is characterized by the output voltage which represents the sum of multi energy harvesters. Then, we have extended the "HW_Hybrid" stereotype by outlined hybrid techniques which is illustrated in Fig. 8.

3.7.1 Solar_Thermal

In this hybrid Solar Thermal cell [16], we integrated a dye sensitized solar cell (DSSC) and thermal-electric cell (TG) in the same device. Solar energy is converted

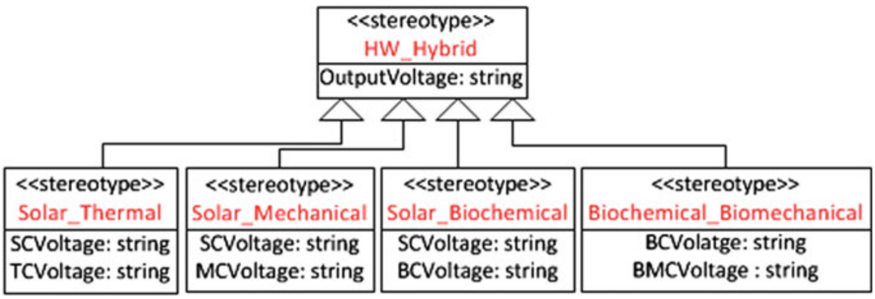


Fig. 8 Proposed MARTE extension for hybrid energy harvesting modeling

into electrical energy and heat. Then, the heat is transmitted to the TC used for thermoelectric conversion. Every cell is characterized by its voltage.

3.7.2 Solar_Mechanical

In this hybrid Solar Mechanical cell [17], we integrated a DSSC and piezoelectric nanogenerator (NG) in the same device. This type is used specially for small electronics devices. Every cell is characterized by its voltage.

3.7.3 Solar_Biochemical

In this hybrid Solar Biochemical cell [18], we integrated a DSSC and Biofuel cell in the same device. Every cell is characterized by its voltage.

3.7.4 Biochemical_Biomechanical

In this hybrid cell [18], we integrated a Biofuel cell and NG in the same device. This type of cell is used for devices implemented in the body (for biomedical applications). Every cell is characterized by its voltage.

4 Behavioral View of the Proposed Extensions

To describe the behavioral view of the new proposed stereotypes, we propose to use of the "ResourceUsage" stereotype which is a class from the GRM profile. The ResourceUsage package is used for representing the consumption of a resource. The HW_Vibration, HW_Thermal, HW_Kinetic, HW_Acoustic, HW_RF, HW_Biochemical and HW_Hybrid stereotypes are regarded as resources such as they produce energy and power to supply the wireless network. The ResourceUsage package provides the UsageTypedAmount package which represents different types of amounts of resources in terms of energy memory and size of data sent in the network. Two general forms of ResourceUsage are defined the DynamicUsage and the StaticUsage.

5 Case Study

In this section, we give an overview about energy harvesting methods used in water pipeline monitoring and we present a case study to illustrate our extension for modeling energy harvesting devices.

5.1 Energy Harvesting Methods in Water Pipeline Monitoring

An interesting application domain of WSNs is monitoring the water distribution systems where WSNs are a potential alternative to maintain a continuous monitoring of water infrastructure by detecting different failure mechanisms such as leaks in the pipeline, change of water quality and other anomalies. Harvesting energy from ambient environment would be an attractive option in water pipeline as sensor nodes are currently supplied by unmanageable batteries in inaccessible environment such as buried underground water pipelines. Several possibilities exist to harvest energy from the water pipe and its environment [19]. A direct way to generate power from water is harvesting energy from the water flow using turbines. In [20], authors proposed this technique as a solution to power sensor nodes. This technique called kinetic energy from water flow. It allows an enough amount of power, but it suffers from the big size of turbines, their hard installation and water quality disturbance. Another technique is the vibration energy harvesting. This alternative is feasible to power water pipeline network [21]. Flow-induced vibration is one of the potential energies can be harvested from water for powering sensor nodes. Piezoelectric energy harvester [22], electromagnetic energy harvester and electrostatic energy harvester are used in this field. Another renewable energy source is the thermal energy produced by the heat flow caused by the temperature gradient between the water and the ambient air. In [23], authors described thermal energy harvesting between the Air/Water Interface for powering sensor nodes.

5.2 A Case Study on Water Pipeline Monitoring

In order to illustrate our extension for the modeling of the energy harvesting devices in WSNs systems, we consider, in case study form, a wireless sensor node used in water distribution monitoring to detect and localize leakages in the pipe. A node consists basically of four units: sensing unit, processing unit, transceiver unit and a power unit. The proposed system consists of a pressure sensor to measure the water pressure in order to localize leaks in the pipe. This pressure sensor is powered by a AA Lithium battery which provides 3.9 V with an operating frequency equal to 2.4 GHz and its life time vary from 2 months to 1 year. To solve the energy supply problem in water monitoring pipeline and extend the network lifetime, we integrate energy harvesting module to the sensor node to harvest energy from the water flow in the pipe and then recharged the battery with the harvested energy. The potential solution is using a vibration harvester based on the vibration induced by the water flow. The best mechanism to harvest energy from flow induced vibration is the piezoelectric technique which offers the higher voltage level compared to electromagnetic and electrostatic mechanisms [24]. We consider a piezoelectric energy harvester used for harvesting energy from water flow

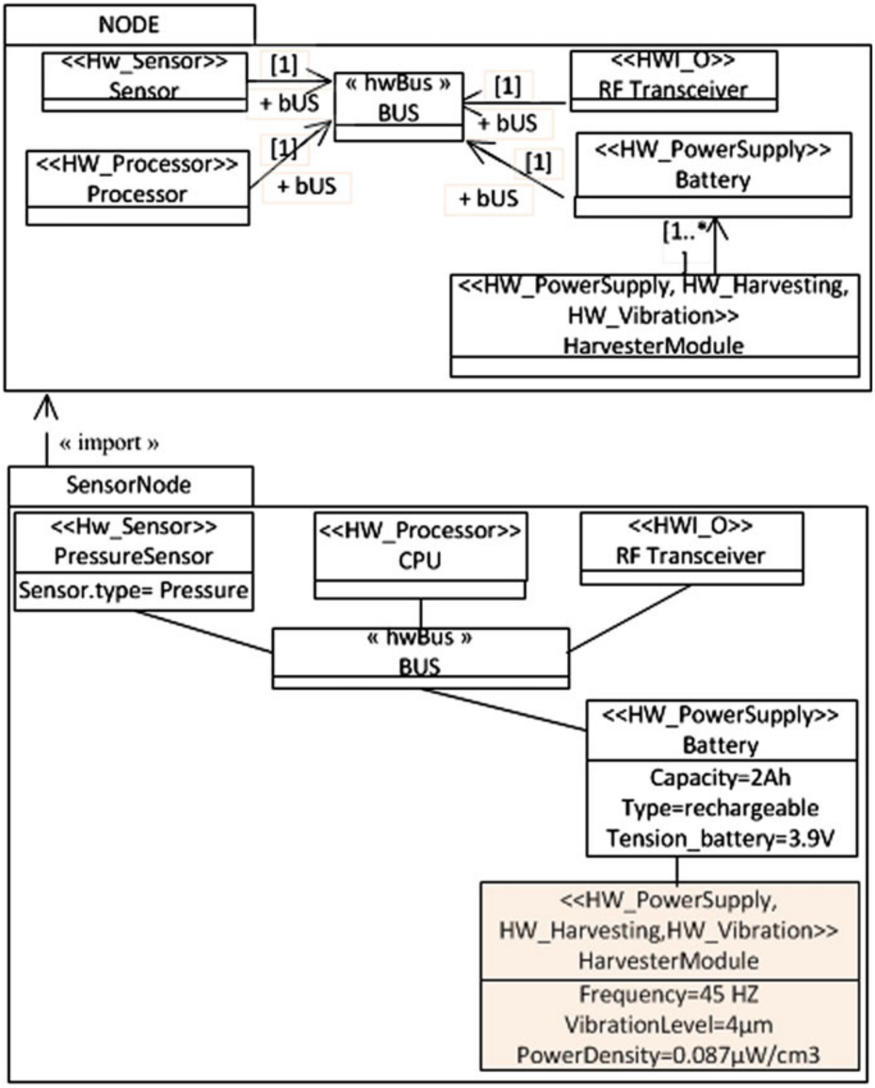


Fig. 9 Class diagram annotated by MARTE/HRM stereotypes describing the proposed sensor node structure

described in [25]. The sensor node is considered as a Hardware (HW) component in MARTE standard. To model the wireless sensor node, MARTE uses the HRM) sub-profile. Each sensor node is specified by the "HW_Device" stereotype. Figure 9 specifies a class diagram annotated by MARTE/HRM stereotypes describing the sensor node structure. The processor is specified by the stereotype "Hw_Processor". The sensor is modeled as a "Hw_Sensor" component. The RF transceiver is specified by the stereotype "HwI_O". Finally, the battery is modeled by the stereotype "HW_PowerSupply" and the energy harvesting module is modeled by the proposed stereotype "HW_Vibration" for modeling the vibration energy harvesting device.

6 Conclusion

This paper presented a high level methodology for designing different energy harvesting types for a WSNs node. We provided an overview of the UML/MARTE standard capabilities for modeling the power section of such system. We then presented our contribution to the modeling of energy harvesting devices by extending MARTE profile with new semantics to design harvesting devices. We are interested on seven energy sources: vibration, thermal, kinetic, acoustic, RF, biochemical and hybrid. This contribution makes UML/MARTE standard able to support energy harvesting devices which present a potential alternative to extend the network lifetime in WSN applications. As an example, we have illustrated our proposed extension with a water pipeline monitoring application which aims to detect and localize leaks and failures in the pipe. We plan in future works to deal with reconfigurable wireless sensor node and we aim to define a high level modeling of this system by extending MARTE standard in order to minimize the energy consumed by the process of reconfiguring sensor nodes.

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