Using MARTE for Designing Power Supply Section of WSNs

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***Abstract*— Probably the biggest issue while tackling Wireless Sensor Networks design has always been providing them with adequate power supplies. Energy Harvesting was proposed as an essential feature for Wireless Sensor Networks (WSN)s in many application fields when the amount of energy contained in a commercial battery does not allow fulfilling the required mission. Solar energy is the most widespread mechanism used to harvest energy of the environment because of its good power density. However it introduces a level of uncertainty on the amount of energy available in the system. In this paper we propose a high level methodology for designing the power supply section of sensor nodes. In particular we suggest how to use MARTE UML design language in order to collect requirements for the application and transform them into specifications of the power supply system. The framework we propose aims at validating the design by simulating appropriate scenarios.**

I. Introduction

Recent improvements in microelectronics technologies allowed the creation of small inexpensive nodes with the capabilities of transmitting and receiving information from a wireless channel and processing it. Such nodes may be equipped with sensors and networked creating a Wireless Sensor Networks (WSN)s. WSN can be composed of many nodes that should organize themselves and comunicate in order to accomplish the intended mission. There are a plethora of applications for such systems from environmental management to space exploration and many others. The majority of application scenarios require the node to be supplied by a local power source (i.e. a battery), thus, power consumption requirements is the utmost constraint, also because power sources are usually not replaceable [13]. On the other side, central nodes may have less stringent low-power requirements because they have better power supplies.

Recently, in [12] it was observed that monitoring WSN, which operates with nodes supplied only by small batteries, is not an acceptable assumption, unless in prototypal laboratory settings. *Energy Harvesting* becomes an essential feature in many context when it is not possible to have adequate power supply. Different techniques were explored to harvest energy from external environment (e.g. by means of temperature gradients, through vibrations, solar energy etc. [7]). Solar energy is the most exploited energy harvested resource because of its availability and because, through a mature technology, the amount of harvested energy suits the needs of wireless applications.

The scientific community in the last years has shown an increasing interest in the evaluation and optimimization of systems supplied by harvested energy. The approach used in most of such works is similar to that used for schedulability analysis. Operation of the network is partitioned into tasks, which in the case of WSN may involve communication, computation or sensor sampling (obviously even more activities). The energy necessary for a particular task is evaluated and scheduling of the task depends on the available energy. Various task scheduling policies suitable for energy harvesting WSNs nodes were carefully studied in [4], [5]; instead, in [6] algorithms for maximizing a function of merit of the devices are proposed. Appropriate voltage/frequency levels selection depending on the available energy is studied in [9] and [10]. In this paper we propose a high level methodology for designing power section for a WSN node. Given the fact that operation of systems that have energy harvesting can be analyzed in a way similar to real-time systems, MARTE profile can be suitably proposed for this scope. However there is need of some additions to the profile in order to enable full modelling of such systems. In addition, a summarised study on the description of the behavior of this power section in MARTE and how power analysis is performed, is provided.

II. System Description

We consider a WSN node as our reference system. In our design we can define four main aspects that constitute the core of our problem.

- Energy Scavenging Device : Is the apparatus we use in order to collect energy. It can use different mechanisms (e.g. solar, vibrations etc.) and has various characteristics to be defined (e.g. dimensions, maximum energy etc.).
- Energy Accumulating Device: In general it is either a battery or an UltraCapacitor. Various parameters must be specified in the design phase(e.g. dimension, leakage etc.).
- Consumption of the Node : While the system operates energy is consumed, and obviously the amount of energy that is consumed depends on how the system activities are orchestrated. Therefore some knowledge on system operation (so to be able to simulate it) is necessary for properly designing power section.
- Recharging Energy : In general it depends on probabilistic phenomena. When we dimension the system we should take assumptions on such phenomena and this impacts on reliability of the system.

The problem then reduces to defining which are the appropriate characteristics of the Energy Scavenging and Accumulating Devices so to sustain operation of the system under some recharging conditions.
The energy consumed by the system can be evaluated - through high level analysis - with the methodology that we proposed in [14] [15]. The information on the recharge of energy should be mapped to create appropriate simulation scenario, either by inserting the scavenger in the previously mentioned simulation environments or by estabilishing simulation scenarios for such systems.

III. MARTE Profile for Describing Power Section

In MARTE specification [1] there is a section dedicated to power modelling. In particular the HwPower package contains some entities that are useful for analysis of energy supplies. Inside the package the HW_Battery extending HW_PowerSupply can be used to map the energy accumulating device. While for a coarse-grained simulation this structure may be enough it should be refined in order to contain more properties that may be necessary when simulating the system. The leakage of the battery, and possibly some field referring to temporal evolution [16] of the battery device should be present and are added in our proposal.
More importantly in MARTE specification there is no trace of energy scavenging devices. We propose extending HW_PowerSupply whith such a stereotype. In the HW_Harvesting section there must be members that describe conveniently the activity of the device. The particular kind of harvesting used (solar, vibrations etc.) may be reflected by various extensions of this entity.
For the time being we propose developing a general model that is focused on the harvesters based on solar energy (for the reasons we explained in the introduction). A part of the characteristics of the scavenging device should impact on the architecture of the system that is modelled (e.g. available energy, recharge of the battery, possibility of executing some operations before a given time etc.). The kind of harvesting has also an impact on the testing of the system as requirements for the testcases may be refined using properties of the harvester. As an example a probabilistic estimate on the maximum length of time in which the harvesting does not produce energy constitutes the basis for defining the testcase for guaranteeing operability of the device.

IV. Changes and Extensions to the MARTE Profile

In order to include all available information to design the power section of a WSN node, powered by an energy harvesting device, three new classes have been introduced in MARTE and one has been changed to ensure a thorough description. As seen in fig.1 we have extended HW_PowerSupply, part of the Detailed Resource Modelling (DRM) subprofile with HW_Harvesting. Then HW_Harvesting has also been extended with HW_PV to describe the harvesting done by a solar panel, a photovoltaic (PV) device. Of course HW_Harvesting can be also extended to describe all kind of harvesting devices. Moreover, a stereotype class, called

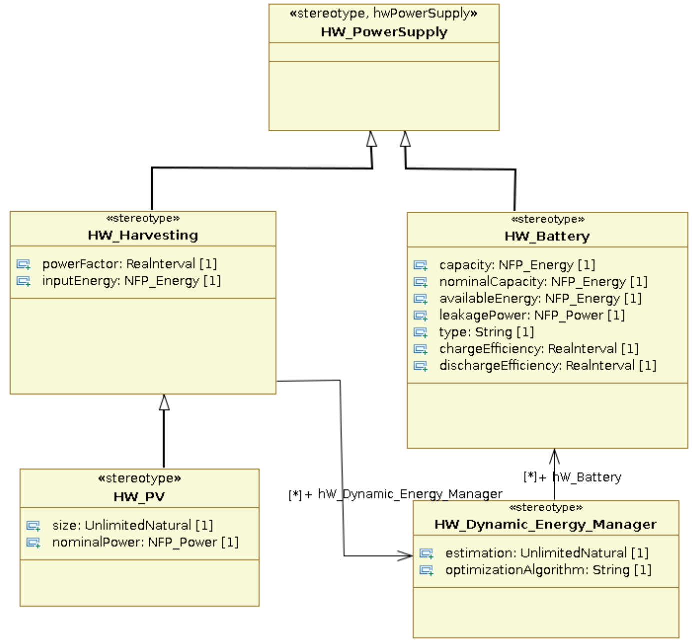

Fig. 1. Proposed UML/MARTE extesion of the HW_PowerSupply

HW_Dynamic_Energy_Manager, has been added, to predict the future amount of energy that will be extracted from the environment and apply an algorithm to optimize the behavior of the system, according to its predictions. Finally, we have modified the HW_Battery and have added new attributes. All these features can be described as follows.

A. HW_PowerSupply

As described in [2], HW_PowerSupply is a power supplier from the HW_Power package. No changes have been performed in this class.

B. HW_Harvesting

This class describes a device, which can be called a harvester or a scavenger, that gathers energy from the environment and powers up the system, either by storing the energy in a battery or by supplying energy straight to the WSN node. It is composed of two parts. The module that collects energy, such as a photovoltaic (PV) and a circuit. Since PV modules behave non linearly in various conditions, it is very important to find the voltage at which it should operate to obtain the maximum output power. This operating point is called Maximum Power Point (MPP) and the circuit that tracks this point is called a Maximum Power Point Tracker (MPPT). Such devices have been proposed in [3], [8].

- Attributes
  - inputEnergy:NFP_Energy, the amount of energy coming to the device from the environment, e.g. from the sun.
  - powerFactor:Real, the factor which the input energy is multiplied to obtain the amount of energy that flows out of the device. It takes values between 0 and 1.

- Associations
  - hW_Dynamic_Energy_Manager specifies that HW_Harvesting provides data to the HW_Dynamic_Energy_Manager.
- Generalizations
  - HW_PowerSupply

C. HW_PV

Until now, almost only devices that harvest solar energy are used to power up such small systems as a WSN node. For this reason, and since this is a very first attempt to use MARTE to describe in high level scavenging devices we have only extended HW_Harvesting with HW_PV, which naturally describes a PV device. It is very easy to create extensions for other kind of devices, e.g. vibrations.

- Attributes
  - nominalPower:NFP_Power, the nominal power of the photovoltaic device.
  - size:UnlimitedNatural, the size of the solar panel used, in square centimeters.
- Associations
  - None
- Generalizations
  - HW_Harvesting

D. HW_Battery

As mentioned before, HW_Battery is the only used class in MARTE that describes an energy accumulating device, while its single attribute is the capacity. It is quite obvious that this is not enough in order to describe a system in detail, especially if you need information for simulation. With the attributes that have been inserted, the battery of a system is seen as a device that provides both static (capacity, type, leakage power) and dynamic information (available energy, charging and discharging efficiency).

- Attributes
  - nominalCapacity:NFP_Energy, the nominal capacity of the HW_Battery, i.e. the maximum energy a battery can hold.
  - capacity:NFP_Energy, the capacity of the HW_Battery in a given time. This attribute takes into consideration that the capacity of accumulating devices declines over time.
  - type:String, the type of the HW_Battery, either a rechargable battery or a ultra capacitor
  - availableEnergy:NFP_Energy, the energy status of the HW_Battery at a given time. An attribute very important for simulation purposes.
  - chargeEfficiency:Real. For batteries and ultra capacitors there is always an overhead in charging them. This overhead for HW_Battery is modeled with the chargeEfficiency attribute.
  - dischargeEfficiency:Real. The same applies when discharging an energy accumulating device.
  - leakagePower:NFP_Power, the leakage power of the HW_Battery, i.e. the power loss when it is idle.
- Associations
  - None
- Generalizations
  - HW_PowerSupply

E. HW_Dynamic_Energy_Manager

The HW_Dynamic_Energy_Manager is a new class that has been introduced to control the energy behavior of the whole system. In particular it controls when the charging and discharging of the battery occurs and the scheduling of the processes on the WSN node. Such managers and predictors, which have been proposed in [5], [6], gather information of the past behavior concerning the amount of energy offered, e.g. the past luminosity, and apply prediction algorithm that determines the scheduling of the device.

- Attributes
  - estimation:UnlimitedNatural, the future estimations of the offered energy made by the predictor.
  - optimizationAlgorithm:String, the implemented algorithm that determines the behavior of both the computing and the accumulating device, according to the collected data.
- Associations
  - hW_Battery, specifies the fact the charging and discharging of the HW_Battery follow the ”orders” of the HW_Dynamic_Energy_Manager.
- Generalizations
  - None

V. Behavioral Analysis of HW_Harvesting with MARTE

To describe the behavior of HW_Harvesting, we decided to extend the Hardware Resource Modeling (HRM) package of the DRM subprofile, because it specializes generic concepts offered by the General Resource Modeling(GRM) package. Thus, we have the capability to define our proposed power section in detail, while we can use MARTE to describe its behavior efficiently. In particular, HW_Harvesting, and the whole HW_PowerSupply class, can be considered as any other resource, with the exception that it is a resource providing energy and power instead of consuming. So, the ResourceUsage stereotype class, which is a part of GRM, can be efficiently used to describe its behavior.

According to [2] the ResourceUsage is used in general to describe the consumption of a given resource in terms of memory, power and number of bytes sent through a network, all these under the concept of UsageTypedAmount. There are two extensions of ResourceUsage defined, StaticUsage and DynamicUsage. In order to portray the offer of power from HW_Harvesting, negative values should be used in the attributes of UsageTypedAmount, specifically powerPeak:NFP_Power and energy:NFP_Energy. Also, since the behavior of this kind of power supply is dependant on time, DynamicUsage should be preferred.

VI. MARTE Power Analysis Mechanisms

A last point that needs attention is the lack of a specialized subprofile for power analysis. Currently, the Generic Quantative Analysis Modelling (GQAM) subprofile can be used for this particular purpose. It is composed of four packages, GQAM, GQAM_Workload, GQAM_Observers and GQAM_Resources, the purpose of which can be easily understood by their respective names. All these are very important for power analysis. However, a thorough study to specialize and standardize them into a collection of modules that describe the aspects in this domain seems to be of growing necessity, as not only the significance of power in embedded devices grows larger, but the power supply section gets more and more complicated. These extensions of MARTE, in the same spirit as they have been already implemented for schedulability and performance analysis are also mentioned in the MARTE specification [2].

VII. A Case Study

As a case study we exhibit the use of our MARTE extensions to describe the power section of a WSN node. This node is part of a network used to measure and keep track of the temperature in the microclimatic conditions of a vineyard. It operates in two manners. In the beginning, the temperature is measured ten times per day and the collection of the daily measurements is sent once. We consider a threshold temperature $T = 10°$ Celsius. For each temperature sample Ti, and only if it is higher than T, we calculate their difference $Vi = Ti - T$. When $\sum Vi > 200$, the node moves to the second manner of operation, which means sending data ten times per day, once for each measurement. This obviously means that a boost in energy consumption is observed.

By using our MARTE extensions we can efficiently describe the power section of such a system, which is composed of a harvester, i.e. a solar panel, and a simple rechargeable battery. Of course, a manager to apply different power schemes is also needed. With HW_PV and HW_Harvesting we model the harvester, providing high level information, such as the size of the panel and the nominal power. We also describe the energy from the environment at any given time, and the factor which scales it. With HW_Battery we model of course the battery, providing information, which goes further from the capacity, to the energy left in the accumulator and the charge and discharge efficiency to know the loss in energy. Finally, HW_Dynamic_Energy_Manager maps the manager that, based on the operation of the node and the offered energy from the environment, applies the best behavior.

VIII. Conclusions

The problem of designing an appropriate power section is of primary importance when designing a WSN node. Such design depends on how the nodes operate, therefore it should be tackled when designing the rest of the node. We think that the trend will be that of developing the application together with the power section and not just collecting requirements for the amount of energy necessary at the end of the design cycle and building the power section based on it. The use of MARTE in such context may open the way for an innovative design approach that allows early evaluation of power requirements and their coupling to the power section of the device. The obvious advantage would be that of being able to design the application with the complete system specified. Moreover, given the similarities in the techniques developed for analysis of energy harvesting devices with those used for real-time systems, MARTE profile is suitable for this scope.

In order to accomplish this ambitious goal, MARTE profile should be extended to contain some more elements and some existing element should be enriched with more members. In particular in the current version there is no modelling support of any energy harvesting devices.

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