Energy Aware Architectural Design for Sensor based Environmental Information Systems

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Abstract

Energy efficiency is a crucial issue of sensor based environmental information systems. As most of the sensor based environmental information systems require simple, low-cost, and long-life sensors to fulfil their intended objectives, many designers are desired to have a low-powered based sensor networks to save systems operational costs, this raising demand for energy resource as new system requirements. However, energy aspects are not often considered in the design phase, hence a systematic way of analysing and optimising energy consumption of sensor based environmental information systems throughout the design phase is lacking. This work proposes a description of the energy-aware architectural designs to facilitate the design of energy efficient sensor based environmental information systems and the extension of our approach for enabling the simulation of design decisions of the proposed architecture description. A case study of Forest Fire Detection System that measures the physical parameters of the forests mainly temperature, humidity and smoke to predict the occurrence of fire illustrate the proposed approach and as our analysis shows achieves considerable energy savings.

1. Introduction

Sensor based environmental information systems are environmental information systems which employ the sensing techniques to manage the data about the soil, air water and other things such as vehicles in the world around us. The utilisation of sensor based environmental information systems is increasing worldwide. Application areas of interest include detection of forest fires, wildlife reserves, air and water quality monitoring among many others [1] -[2]. Sensor based environmental information systems consist of distributed autonomous nodes for monitoring environmental phenomena e.g. temperature, pressure, gases, relative humidity etc. Each node is typically made up of sensor units, energy sources, CPU, and transceiver. Hundreds or even thousands of such nodes are distributed randomly and normally deployed together forming wireless sensor networks (WSNs). Sensor based environmental information systems consist of three subsystems namely sensor and actuator, information control centre and communication subsystems [3].

The energy consumption is a fundamental concern of sensor based environmental information systems designs. The energy constraints of sensor networks are unlikely to be solved soon due to the slow evolution of battery capacity and energy scavenging since battery capacity only doubles in 35 years [4]. The involvement of battery-powered sensors in sensor based environmental information systems without human control and absence of energy efficient techniques led into the sensors battery drainage in a short time. The increasing demand of longer lifetimes of these sensors/actuators motivates the researchers to explore energy efficiency solutions from various perspectives. In addition, the energy consumption of information control centre and communication subsystems is crucial to meet the required objectives of the system.

Conventional techniques for energy efficient sensor based environmental information systems focus at a late stage of software development life cycle are insufficient as they focus within a single subsystem (sensor/sensor networks subsystem) while ignoring others hence led to the unnecessary consumption of energy. The effective optimization of energy consumption in sensor based environmental information systems should involve the reduction of energy consumption in all subsystems (sensor and actuator, information control centre and communication subsystems). The accommodation of all subsystems could be well achieved by designing energy-aware software architecture. Software architecture is a more effective and desired approach as it could take into consideration the optimization of energy consumption from an early stage of software development life cycle (designing phase). To the best of our knowledge, most researchers have not investigated energy-efficiency taking into account the software architecture. The impact of architecture designs on energy efficiency of sensor based environmental information systems is yet unclear and unexplored. The actual viewpoints or designs that facilitate energy efficiency are missing.

The main contributions of this paper are energy-aware architectural designs that facilitate the development of energy efficient sensor based environmental information systems and simulation of design decisions of the proposed architecture description.

1.1. Forest Fire Detection System

Before proceeding with the related work section, we introduce a case of sensor based environmental information systems in the form of forest fire detection system. The main objective of forest fire detection system is to prevent the occurrence of forest fire by monitoring temperature, humidity, and smoke. This system is divided into three subsystems; sensor subsystem is located in forest where the sensor nodes are deployed, information control centre is responsible with processing and storage of information collected by the sensors and communication subsystem which facilitates the interaction between aforementioned subsystems.

The Wireless Sensor Network (WSN) for forest fire detection system consists of quite a large number of sensors deployed in the forest. The temperature, humidity, and smoke sensors are required to measure the temperature, humidity and smoke parameters of the forest. The data generated by these sensors is transmitted to the base station in a multi-hop way to the information control centre for further processing. The mission of this system typically takes several numbers of days or months. However, the nature of monitored environment i.e. forest does not support the energy replenishment or replacement of sensors during the operation. Hence the sensors near the base station tend to deplete their energy faster than those at far because they are responsible for relaying other sensors' data to the base station. This unbalanced energy consumption minimizes the network lifetime, thus affect the performance of such systems. Therefore, there is a need of energy-aware forest fire detection system to accomplish the intended mission.

The remainder of this paper is organized as follows. The existing energy efficiency techniques are given in Section 2. Section 3 presents energy efficiency perspective on Software Architecture. The evaluation is presented in Section 4. The paper ends with the conclusion in Section 5.

2. Existing Energy Efficient Techniques

The existing energy efficient techniques of sensor based environmental information systems are classified into three levels based on their architectural ; sensor and actuator, information control centre and communication subsystems.

2.1. Sensor and Actuator based Techniques

These techniques emphasize the performance of individual nodes (sensors/actuators) by utilising their operational states i.e. duty cycling. Duty cycling is defined as a fraction of time nodes are active during their lifetime [5]. Typically the radio energy consumption, sensing, actuating and communication subsystems of nodes consume higher energy. The main power-saving opportunity that comes nodes' idle periods allows power managers to utilise the ultra-low-power inactive modes. These techniques employ the topology control and power management protocols.

Topology control protocols facilitate the dynamic adoption of network topology based on the application requirements. These protocols prolonging the nodes network lifetimes by minimizing the number of active nodes. There are two types of topology control protocols mainly location driven and connectivity driven protocols. In location driven protocols, the location of a node determines the operational state of that node. In Connectivity driven protocols, the network connectivity or sensing coverage determines the number of nodes be inactive or sleep mode [6].

Power management protocols are integrated with the MAC protocol or implemented as independent sleep/wake-up protocols on top of MAC protocol. There are three main schemes of sleep/wake-up protocols; on-demand, scheduled rendezvous and asynchronous schemes [7]. On-demand sleep/wakeup schemes, the nodes are in a wake-up state when they are required to receive packets from neighbouring nodes. In scheduled rendezvous schemes, all neighbouring nodes wake up at the same time. These nodes are in wake up state periodically to check the potential communications and thereafter return to sleeping state [8]. In asynchronous schemes, each node is allowed to wake up independently overlapped active periods with other neighbours [9].

2.2. Information Control Centre based Techniques

These techniques focus on the reduction of data being produced, processing and transmitted. The main strategy of data reduction is via data prediction and aggregation methods. There are several data prediction methods that have been exploited such as a use of models, time series forecasting, and algorithms.

In *model-based prediction methods*, a model describing the sensed phenomenon is constructed. Normally, two instances of a model in the network exist at a sink and node. The model at the sink responds to the queries without requiring sensor hence reduces energy consumption. Sensor nodes collect the data and compare with the predicted data. If the collected data is within an application-dependent tolerance then the model is valid, else the collected data is transmitted to update the model [10].

In *time series forecasting based prediction methods*, a set of chronological values that have been obtained periodically predict future values. Moving Average (MA), Auto-Regressive (AR) or Auto-Regressive Moving Average (ARMA) models are typical methods that characterise time series. Initially, a set of sampled values provided by the sensor nodes compute the first instance of the model and send it to the sink [11].

In *algorithmic based prediction methods*, the sensed phenomenon is described by heuristic or state-transition model. Each sensor node is associated with upper and lower values bound. These specified bounds are also sent to the sink. Then the sensors collect data and compare against the bound, if they fall outside the bounds, the data sent to the sink to update the bounds [12].

In *data aggregation methods*, data originated from various nodes are combined to eliminate redundancy and minimize the number of transmissions hence saving energy. The clustering based aggregation protocol minimizes communication and maximizes network lifetime [13].

2.3. Communication-oriented Techniques

Communication-oriented techniques optimize energy consumption of sensor based environmental information systems by the following mechanisms; minimization of transmissions' energy consumption and exploitation of multi-hop aspects of network communications. As the energy spent in transmission rises exponentially with distance [14]. All these mechanisms are achieved through the use of various protocols in network topology formation and operations.

The energy consumption of transmissions is minimized based on a type of the network. For instance, in the cluster-based sensor network, a cluster head is selected to combine data generated by various sensors and send it to the base station [15]. The individual sensor does not need to send the data directly to the base station, this shortens a transmission distance hence conserve energy.

The exploitation of multi-hop aspect of network communications is attained through a routing strategy. A routing strategy should guarantee the smallest amount of energy consumption in order to increase the lifetime of sensor network [9]. A routing strategy focuses on the selection of paths for routing data. For instance, a localized model called directed diffusion is presented in [16]. Some routing strategies utilize battery information and energy cost to and optimal (best energy-efficient) routes [17]. Other routing strategies rely on the node's location, transmit energy and residual battery capacity to determine the optimal routes of data transmissions [18].

One of the key research questions that arise is how to utilize these existing methods to provide the holistic view of optimising energy consumption of the sensor based environmental information systems. This could be addressed by extending the sensor based environmental information systems architecture views with an energy consumption perspective.

3. Energy Consumption Perspective on Software Architecture

A desirable approach to provide a holistic view of the optimization of energy consumption of sensor based environmental information systems is via an architectural perspective. All the energy efficient techniques described in section 3 require some implementations which are reflected by the energy-efficient architecture.

This section provides a description of energy aware that adopts the standard IEEE 42010-2007 Recommenced Practice for Architectural Description of Software-Intensive Systems [19]. This standard provides key steps toward the design of software architecture which includes the identification of stakeholders, concerns, viewpoints and views. There are several stakeholders, concerns and viewpoints that have been proposed in this research. However in this work, the stakeholders, and their concerns pertaining a single viewpoint are described. The class and deployment diagrams from Unified Modelling Language (UML), a de facto standard in the software industry are utilized to design the architectural viewpoints and views.

3.1. Stakeholders and Concerns

The identified stakeholders are sensor experts, network operators, developers and architects and their main concerns is to know how the environmental phenomena data can be effectively acquired while minimizing system’s energy consumption.

3.2. Proposed Architectural Design

The intention of this architectural design is to optimise the energy consumption of sensor based environmental information systems taking fire detection system as a case of study while addressing the aforementioned concerns.

- **Architectural Tactics:** To address the energy consumption concerns for sensor based environmental information systems, some tactics are applied. A *tactic* is a decision that assists an architect to realize a desired property or requirement of a system, hence this require some architecture descriptions that represent the optimisation of system’s energy consumption. Data reduction is the main tactic that has been employed in the following viewpoint.

- **Proposed Viewpoint:** Viewpoints describe the conventions that enable the creation, illustrations and analysis of views. The viewpoints provide a means to describe energy efficiency strategies that should be realised in software. The proposed viewpoint is an acquisition viewpoint which focuses on how the data is being acquired. This viewpoint addresses the aforementioned concern of the stakeholders. The acquisition viewpoint is depicted in Figure 1. In which the *Sensor*, *Server*, *UserInterface* and *Database* are the main components involved in collecting data. The *Sensor* sense and transmit the environmental phenomena to the server. The *Server* collects and aggregates the information from various sensors and stores it in the *Database*. The *UserInterface* enable the user to access the system. From an energy perspective, it is essential to have the energy-aware sensing mechanism in both sensor and actuator and information control centre subsystems to reduce the data to be transmitted.

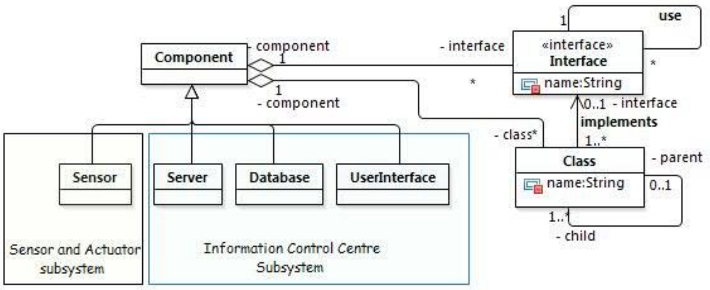

Figure 1 Acquisition Viewpoint

3.3. Acquisition View

Views illustrate the actual representation of one or more structural aspects of a particular system. Views are instances of viewpoints. Hence to develop energy-efficient fire detection system, the acquisition view of fire detection system could be deployed. As described in section 1.1, the fire detection system utilizes the temperature and humidity sensors via *Tempsens and Humidtysens* as shown in Figure 2. The *SensCollServic* interface implemented by *SensCollImp* defines the essential operations of getting the data from sensors associated with a range of values to be transmitted. Also, the *SensorConnector* interface implemented by *SensImp* defines the sensing operations based on the specified range of values (model). When the server receives a data request from the *UserInterface*, the *SensCollServic* searches the available proxy through a *SensorProxy* interface which is implemented by *SensorProxy* instead of querying the sensors directly. The *SensorProxy* acts as a proxy to sensed data to represent the real data collected by the sensors. The use of proxy minimizes the data transmission operations hence save the energy.

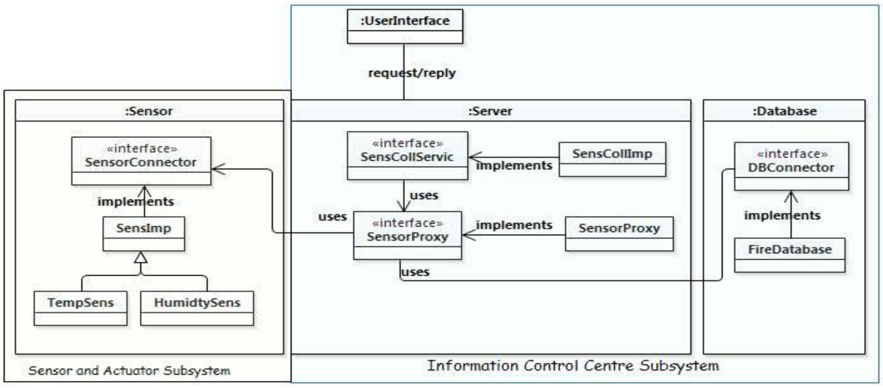

Figure 2: Acquisition View of Fire Detection System

4. Simulation and Results

The performance of the proposed architectural designs is evaluated by simulation using NS3 version 3.24.1, in which the wireless sensor nodes are deployed in ad hoc manner. The sensor nodes monitor temperature and humidity levels that are likely to trigger a fire in forest based on the Fire Weather Index shown in Table 1.

Table 1 Temperature and humidity thresholds as adopted from [20].

FWI class	**Value range**	**Type of Fire**	**Potential Danger**
Low	0-5	Creeping surface fire	Fire will be self-extinguishing
Moderate	5-10	Low vigor surface fire	Easily suppressed with hand tools
High	10-20	Creeping surface fire	Power pumps and hoses are needed
Very High	20-30	Very intense surface fire	Fire will be self-extinguishing
Extreme	30+	Developing active fire	Immediate and strong action is critical

The parameters and its associated value (placed in parenthesis) used in the simulation are as follows: type of traffic (UDP), simulation time (100 seconds), number of nodes (2), packet size (100 bytes), protocol (DSDV), network work area (500mX500m), data generation rate (50kbp/s to 500kbp/s), low battery threshold (10%), radio transmission current (0.380 ampere), radio receiver current (0.313 ampere), and DSSS rate (1Mbps). The transmission range of each node is 50 m. The sensor nodes sense and transmit temperature and humidity values from to the server when the detected values beyond the threshold values in Table 1. Actions are taken by stakeholders depending on the level of the potential danger and the type of fire associated with it. In addition to these parameters, the simulation run on a DEL Inspiron 11, 3000 series laptops with 4GB of internal memory (RAM) and Intel (R) Core (TM) i3-4010U CPU at 1.70GHz processing speed, and Ubuntu Linux with CentOS. The simulation was performed based on the acquisition view of fire detection system.

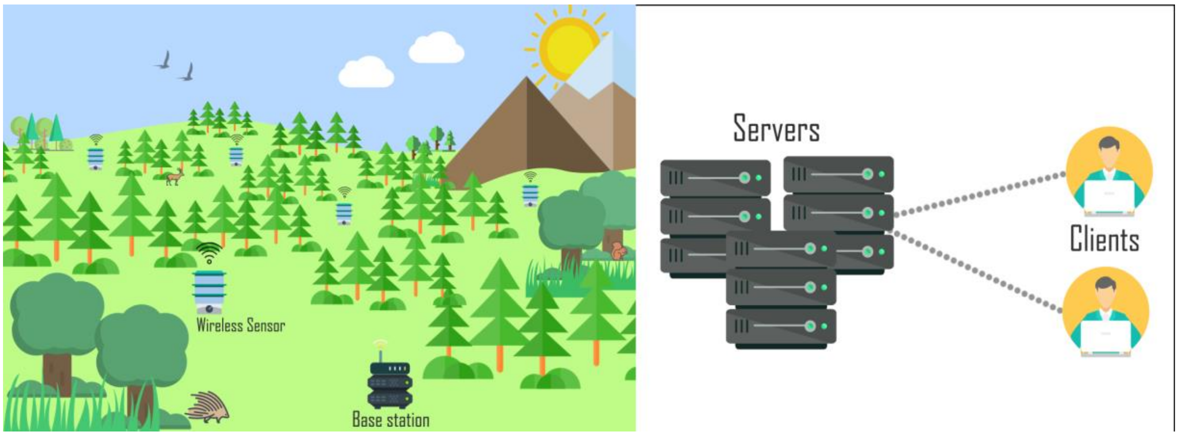

Figure 3: A typical Fire Forest Detection System

The simulation employed the Ad-hoc On-demand Distance Vector (AODV) routing protocol was used in forward packets from the source node to the receiver node. The simulation was performed to report the temperature and humidity levels beyond the threshold values.

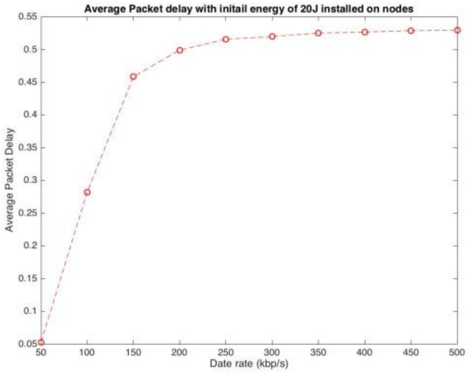

Figure 4: Data Rate vs. Average Packet Delay

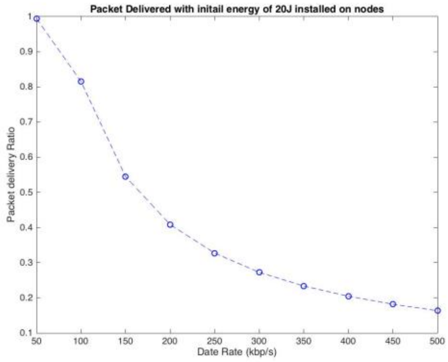

Figure 5: Date Rate vs. Packet Delivery Ratio

From Figure 4 and 5, 20 Joules of energy were installed on the nodes and the number of packets delivered at the receiver was calculated. The packet delivery ratio (PDR) vs. data rate graph shows PDR dropped from 1.0 to 0.2 at increasing data generation rate. In this scenario, the nodes consumed almost all the 20 Joules of energy leaving no remaining energy. Moreover, the nodes experience less delay in the transmission and reception of packets at lower data generation levels but yield a 100% PDR. shows that at the data acquisition level, the energy consumed largely depends on the request/reply between the sensor nodes and the user actions at the server side.

5. Conclusion

Energy is one of the most critical resources of sensor based environmental information systems. Most of the researchers emphasize energy conservation as a crucial mechanism of optimising energy consumption of the systems. However, most of these researchers focused on optimising energy consumption of only sensor/sensor network subsystem at a late stage of software development while ignoring other subsystems (information control centre and communication subsystems). This led to the unnecessary loss of energy as well as a lack of holistic view of optimising the energy consumption of the sensor based environmental information system.

Since the awareness of architectural design is a promising paradigm that can provide a holistic view of optimising energy consumption of a system at an early stage of software development while meeting the system demands. This work extends the sensor based environmental information systems architecture views with an energy consumption perspective taking fire detection system as a case of study. This paper proposes an architecture description with one viewpoint among the required viewpoints for an energy efficient architecture of sensor based environmental information systems. The applicability of the proposed viewpoint is demonstrated through the instantiation to the design of fire detection system view and the simulation of design decisions of the proposed architecture description in fire detection system. In the future, all the remaining viewpoints of the energy-efficient architecture for sensor based environmental information systems will be identified, designed and instantiated to demonstrate their applicability in real scenarios.

6. References

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