Design of a flexible and robust gateway to collect sensor data in intermittent power environments

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Abstract: The development of a Wireless Sensor Network (WSN) gateway is challenging for sites where limited infrastructures lead to frequent power shortages and network unreliability. In this paper, we present a low-power, low-cost 802.15.4 and 802.11 compatible solution which uses open source software to meet local conditions. Using the SunSPOT motes on a system which is mostly platform independent, our system is based on the Fox embedded Linux board and equipped with a USB flash drive and a USB WiFi adapter. The system can be solar powered, and the results of a solar system design are presented. All the hardware components are available off-the-shelf and are easy to assemble. We conclude that our system is preferred for applications in remote areas, where a stable power supply and a reliable network infrastructure are lacking. Furthermore, it can be used to extend the range of WSNs by layering a network of long-range motes above islands of low-range motes.

Keywords: WSN; wireless sensor network; embedded device; wireless.

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1 Introduction

Wireless sensor networks (WSNs) are emerging as one of the fastest growing segments of the current generation communication industry. They are being deployed in a wide variety of civil and military applications such as security management, surveillance, automation, environmental monitoring, health monitoring and water quality monitoring. A sensor network is composed of a large number of sensor nodes, which are densely deployed inside the phenomenon or very closed to it to perform different forms of sensing activities. These include seismic, acoustic, chemical or physiological. As pointed out by many researchers, sensor nodes are limited in computational, memory and power capabilities, thus their deployment appeal to careful design and/or management of the energy consumption. Wireless sensors may be deployed in the same field with different processing powers but are generally ranked into two categories: sensor nodes, also referred to as ‘motes’, and sink nodes, usually called ‘base stations’. While motes are used to report any activities happening in its surroundings and relay the information received from neighbour nodes to other nodes in transit to the base station, the base station plays a role similar to a cellular base station which collects all the information received from the motes and sends this information via satellite or a fixed or wireless network to a place where the information is processed and appropriate decisions are taken.

1.1 Traditional gateway design

As depicted in Figure 1, most emerging WSN gateways are USB-powered systems which take advantage of the power supplied by the USB interface of a computer system to relay management information into the WSN network or collect the information sensed from the WSN motes for analysis and further processing.

Figure 1 A typical WSN gateway (see online version for colours)

However, such systems are economically inefficient in many places where (a) power shortages occur frequently and the voltage provided is unstable and (b) network connectivity is unreliable. The design of a gateway system that caters for these constraints is an important parameter upon which WSN gateways for regions such as developing countries should be designed.

1.2 Contributions and outline

This paper describes the design of a low-power gateway to access sensor data in intermittent power environments. This system will be used as a prototype in Malawi and applied to other developing countries, which are limited by similar constraints. The main contributions of our solution consist of addressing in one gateway design the most important challenges that, to the best of our knowledge, have not been addressed by other WSNs deployed in developing countries. These challenges include low-power, low-cost data-logging capabilities, accessible both via Ethernet and wireless connections and long-range deployment. Our solution differs from previously deployed solutions by many features.

- *Power consumption*: In India, for example, WSNs have been used to monitor water quality (Ramanathan et al., 2006) and to measure soil moisture for irrigation (Panchard et al., 2007). In Sri Lanka, wireless sensors have been used to monitor the road surface conditions (De Zoysa et al., 2007). However, in most of these projects, data are collected and visualised using a laptop or a PDA. A laptop runs for about 4–6 hours before its batteries are depleted (Mahesri and Vardhan, 2004). It is also relatively big and bulky. A PDA is smaller and less power hungry (Pasricha et al., 2003) than a laptop, but does not have an Ethernet connection and is not usually capable of running a web server. An iPaq PDA consumes between 1.72 W and 2.8 W depending on the backlight brightness level.
- *Communication*: The SeeMote (Selavo et al., 2006) is a low-power, small and low-cost solution, but it does not offer Ethernet or 802.11 connectivity. Its memory device (a SD card) needs, therefore, to be physically removed to read the data. It consumes 180–330 mW depending on backlight intensity of the display.
- *Economic efficiency*: Other specialised gateways such as the Stargate and the NetBridge from Crossbow and Meshlium from Libelium are not low-cost. The NetBridge does not offer wireless connectivity and the Stargate has been discontinued.
- *Long-range deployment*: While different other projects have been deployed in the context of short-range deployment, our solution is suitable for long-range deployment by using a multi-layer WSN architecture where a network of long-range WSN devices (gateways) is layered above islands of short-range WSN devices using our gateway to achieve inter-layer communication.

The remainder of this paper is as follows. Sections 2, 3 and 4 present the gateway systems design while solar powering process is proposed in Section 5. Section 6 discusses the relevance of using our solution while Section 7 introduces an implementation scenario in Malawi. Our conclusions and some directions for future work are presented in Section 8.

1.3 System design

The proposed gateway system was designed based on the principle that data coming from the WSN need to be stored in a server with a battery backup to maintain a continuous supply of electric power when utility power is not available. The lower the power used by the server, the longer it can work without utility power and the smaller the solar panel can be. From the connectivity point of view, in many regions of the world network infrastructures do not exist or are unreliable (Zennaro et al., 2006). The availability of computers is also limited, and a generic PC can better be used as an office computer than a specialised server. From the beginning it was clear that this scenario required a device would be designed around the following constraints:

- *Low-power consumption*: The device should be low powered, have long operation time using batteries and should be reachable both locally via Ethernet and externally via a wireless connection.
- *High storage capabilities*: It needs to store large amount of data – transmitting them over the network may be impossible for long periods of time due to power shortages (no power for the PC) or due to lack of network infrastructures (no wireless link to the internet).
- *Low-cost device*: It must also be low cost. The final goal of our project is to demonstrate that WSNs are a suitable technology for developing countries, and thus affordability is very important (Brewer et al., 2006).
- *Web-based design*: Using a web-based gateway to host the data offers many advantages: there is no need to install special software on the client's computer (just a web browser), the interface can be designed to be user friendly and in local languages and the software can be installed on a more powerful server if needed.
- *Long-range deployment*: It is widely recognised that current generation WSNs are technologically range limited. This may be in disagreement with some application requirements when economic and engineering may require links that span longer distances.

As developed, our solution addresses all the concerns mentioned above by providing data-logging capabilities for the SunSPOT motes manufactured by SUN and accessibility both via Ethernet and wireless connections. It is low power, low cost, battery powered and can therefore be used in such an environment. It also enables long-range deployment by allowing a multi-layer topology where

1 based on a star topology, devices with a longer communication range (gateways) are connected to an access point via WiFi or GPRS

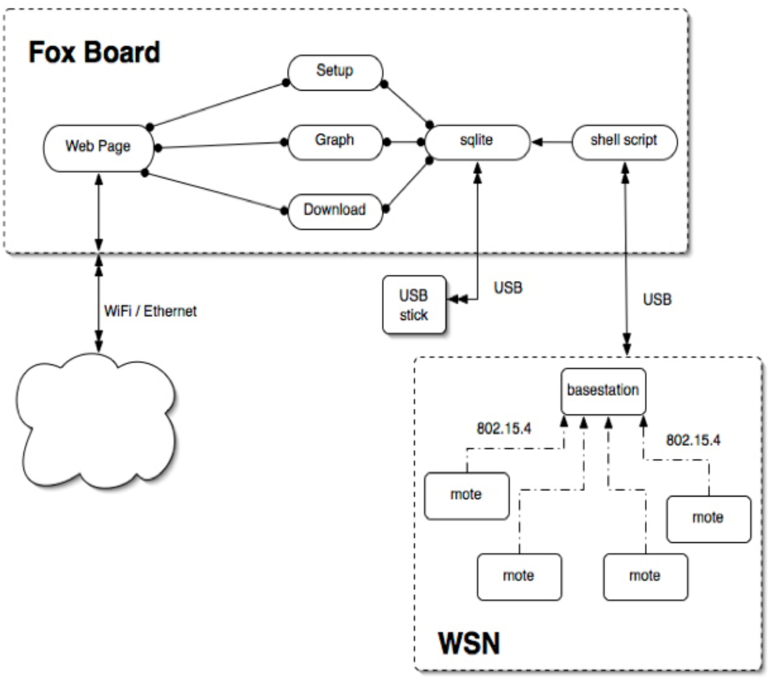
2 SunSPOT nodes are connected into a star or mesh topology to a local gateway node.

1.4 Hardware design

Our solution can be used to extend the reach of a WSN through inter-layer communication between short- and long-range communication devices such as the SunSPOTs and the gateways. While the SunSPOT devices are range limited to 100 m, the gateway devices may achieve up to 1.5 km coverage in some conditions (with the use of an external antenna, for example). This provides the potential of extending the range of a classific WSN from a hundred of metres to some kilometres.

Besides extending the range of a WSN, our system was designed as a solution to store sensor readings and host them to clients via network connections. The components that form the gateway are an embedded board, a USB flash drive and a USB WiFi card. Figure 2 shows a scheme of the overall system. The board is interfaced to the sensor network via the SunSPOT base station, connected with a USB cable. The base station is in communication with the SunSPOTs, taking the measurements via a wireless 802.15.4 connection. A USB hub is needed to connect all the USB devices to the embedded board. We discuss the single components in the following subsections. Figure 3 shows a picture of the assembled system.

Figure 2 The overall system scheme



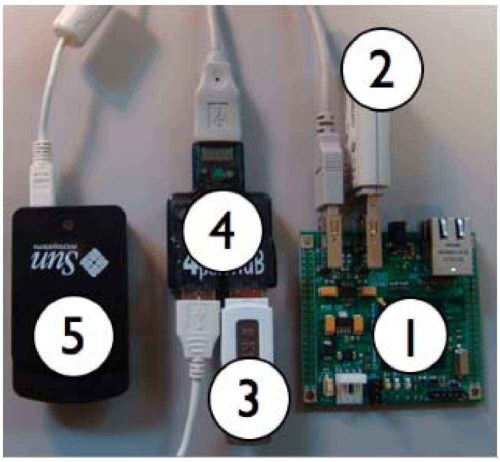
1.4.1 SunSPOT

A SunSPOT (Sun Microsystems, 2009) (Sun Small Programmable Object Technology) is a WSN mote. What distinguishes the SunSPOT from comparable devices is that it runs a Java Micro Edition Virtual Machine directly on the processor without an operating system. The SunSPOT system uses JavaTM technology to up-level programming. Developers can write a program in Java, load it on a wireless sensor device, run it, debug it, as well as access low-level mechanisms, with standard Java IDEs. Each device comes with a 180 MHz 32-bit ARM920T core, 512K RAM, 4 M non-volatile Flash memory, 802.15.4 radio, 8 multi-colour LEDs and a USB interface. The default hardware configuration includes several sensors, such as an accelerometer, temperature and light sensors. Six analog-to-digital converter inputs and five general purpose I/O pins can be used to add custom sensors and devices. Furthermore, four high-current output pins (100 mA) are available to control actuators such as servo motors. The devices are battery powered and thanks to their very efficient power management they can run up to one year without recharging.

1.4.2 Fox Board

The system requires an embedded board powerful enough to store the data and serve it to clients in the form of graphs/files. Power consumption needs to be as small as possible. We decided to use the FOX Board (Model FOXLX832) made by AcmeSystems (http://www.acmesystems.it/?id=4) for its processing power, low-power consumption, low cost and small size (66 × 72 mm). It is equipped with an ETRAX 100LX microprocessor (a 100MIPS RISC CPU made by Axis), one Ethernet and two USB 1.1 ports. Memory is 8 MB Flash and 32 MB RAM. It runs a special Linux (not a uC Linux) distribution, based on the 2.4.31 kernel. Through the 10/100 Ethernet interface it is possible to have access to the internal web server, FTP server, SSH, Telnet and the complete TCP/IP stack.

Figure 3 The assembled system, with the embedded board (1), the USB WiFi adapter (2), the USB flash drive (3), a USB hub (4) and the SunSPOT base station (5) (see online version for colours)



1.4.3 WiFi adapter

The FOX Board has direct driver support for the DLINK USB WiFi adapter model DWL-G122 (DLink, 2009). This is a compact, pocket-sized, lightweight wireless adapter, and is 802.11 b/g compliant. It can be used in peer-to-peer mode (ad-hoc) to directly connect to other 802.11 b/g wirelessly enabled devices for direct file sharing, or in client mode (infrastructure) to connect with wireless access points or routers. The output power of the DWL-G122 is 14 dBm, and the maximum range it can reach is around 400 m outdoor without an external antenna.

1.4.4 USB flash drive

A USB flash drive is used to store data coming from the sensors. USB flash drives are compact, fast and reliable due to their lack of moving parts and durable design. Memories of 1 GB are now widely available at limited cost. The FOX Board supports USB flash drives directly, and they can be mounted automatically at boot time.

1.4.5 Cost and availability

The total cost of the system is 200 Euros. The Fox Board sells for 140 Euros, the USB flash drive for 10 Euros, the USB WiFi adapter for 40 Euros and the USB hub for 10 Euros. All components are available off-the-shelf, and the system is very easy to assemble. The data storage can be easily upgraded, and does not require any software modification.

1.5 Software design

The software has two primary functions: to log the sensor's data on the USB flash drive and to present them via a web page. These functions can be accomplished using the LAMP software bundle consisting of Linux, Apache, MySQL and PHP. This software suite does not come installed by default on the FOX Board, but Kdev (http://www.kdev.it/) developed a free third-party firmware suite called foXServe that includes a full-featured Apache 1.3.37 server, PHP 5.0.5 and SQLite. SQLite is a small C library that implements a self-contained, embeddable, zero-configuration SQL database engine (http://www.sqlite.org). This engine offers good performance and supports databases up to 2 terabytes in size.

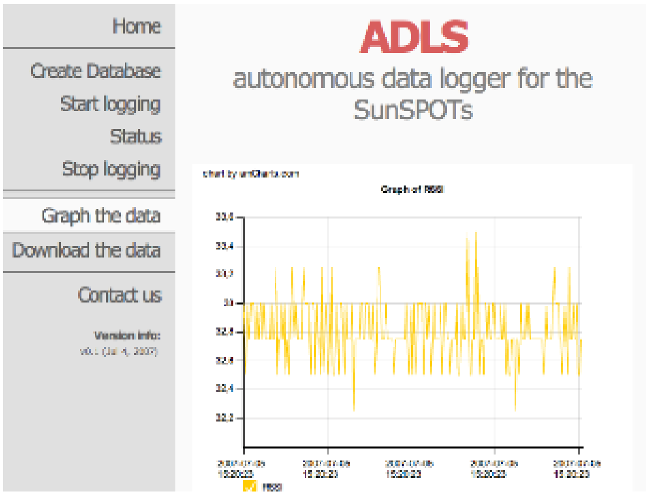
1.5.1 Data logging

In order to log data coming from the sensors, the SunSPOT base station must be connected to the FOX Board via USB. The data stream coming from the base station is read in Linux using the USB ACM protocol. The USB CDC (Communications Device Class) ACM (Abstract Control Model) is a vendor-independent publicly documented protocol that can be used for emulating serial ports over USB.

1.5.2 User interface

The main focus in designing the user interface has been to make data easy to interpret for the researchers. The data collected are made available through a dynamic, user-friendly web-based application. This application contains two modules in which the user can download or plot data retrieved from the database. The user can choose what data to download/graph by selecting the SunSPOT number, the date, the time and the type of data. This information is retrieved from the database and dynamically presented in a drop-down menu. If the data are to be downloaded, a link to a text file with the data obtained from the database is offered. If the data are to be graphed, a chart is produced using amCharts, a free and widely used flash-based charts library (http://www.amcharts.com/). The user will be able to zoom into the span of time of his/her interest and turn on/off value balloons, as shown in Figure 4. amCharts works with Adobe Flash Player 8 and higher.

Figure 4 The graph of some measured data (see online version for colours)



1.5.3 Software testing

The system has been tested for 6 months, in the author's laboratory and during a student's project using SunSPOTs. Some bugs have been corrected and the user interface has been modified following the student's suggestions. Overall the system has been working fine, logging the data and enabling a simple interpretation of the results.

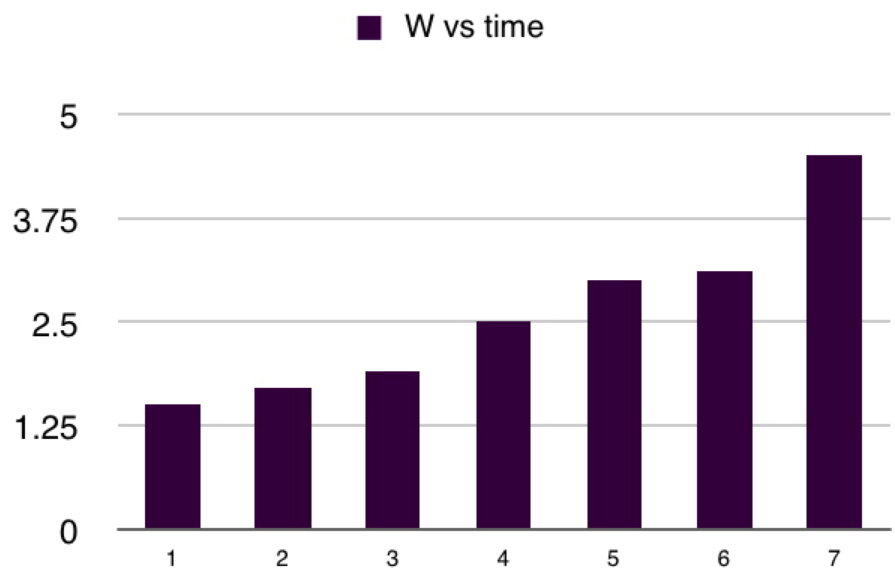
1.6 Solar powering

1.6.1 Energy consumption measurement

In order to correctly dimension the solar system, we had to measure the power consumption of the gateway. We used a Watt's Up DC Ammeter by Powerwerx (http://www.powerwerx.com/product.asp?ProdID=3809&CtgID=3575) that measures eight parameters, e.g. Amp hours (Ah), Watt hours (Wh), voltage, Watts and captures peak current (Amps), peak power (Watts) and voltage sag (minimum Volts). Figure 5 shows the power consumption in the following conditions: Fox Board with no device connected (time slot 1), Fox Board with USB hub connected (time slot 2), Fox Board with USB hub and USB memory connected (time slot 3), Fox Board with USB hub, USB memory and WiFi card connected (time slot 4), Fox Board with USB hub, USB memory, WiFi card and SunSPOT base station connected (time slot 5), Fox Board with USB hub, USB memory, WiFi card and SunSPOT base station receiving data (time slot 6) and Fox Board with USB hub, USB memory, WiFi card sending data and SunSPOT base station receiving data (time slot 7).

Most of the time the gateway is going to be in the condition where it consumes around 3 W (time slot 6). In this situation, the gateway drains 280 mA when a voltage of 12 V is provided. When a user downloads the latest data or produces a graph, the gateway will use the maximum power of 4.5 W.

Figure 5 The graph of measured power consumption (see online version for colours)



1.6.2 Dimensioning of the solar system

Solar energy is the solution for powering the gateway outdoors and ensuring its proper operation time along. The solar energy kit we used is composed of a 20 W solar panel by Kyocera (Kyocera, 2009), a 12 V charge controller to protect the batteries from overcharge and excessive discharge (GSE, 2009) and a 25 Ah deep-cycle Lead Acid AGM (Absorbed Glass Mat) type battery. The function of the controller is to automatically assure the battery is fully charged. It takes the uncertain voltage from the solar panel and conditions it to safely charge the battery. The following chart explains the number of working days that can be obtained depending on the number of daily sun hours, using the 25 Ah battery. When the energy added by the solar panel is greater than the energy consumed, the gateway can work indefinitely. The daily average of peak sun hours for most of Africa based on full-year statistics is of 4–5 hours (Global, 2009). We are therefore confident that our system is going to work with no interruption based on solar energy. A battery can be used to create an autonomous powered gateway with or without a solar panel. Given our current drain of 280 mA and using a 25 Ah battery, we will be able to run the gateway for approximately 4 days (25 Ah/0.28 A = 89 h). The cost of the solar system is: 200 Euros for the solar panel, 85 Euros for the 25 Ah AGM battery, 45 Euros for the charge controller and 50 Euros for the waterproof housing and wiring, for a total of 380 Euros.

Table 1 Solar system performance

Sun hours	*Voltage (V)*	*Current (mA)*	*Power (W)*
4	12	280	3.3
5	12	280	3.3
6	12	280	3.3
Sun hours	*Cons. (Wh)*	*Energy (Wh)*	*Working days*
4	79.2	80	always
5	79.2	100	always
6	79.2	120	always

1.7 Relevance of the proposed solution

Some of the other advantages of using the Fox Board in a multi-layer fashion include:

1 Reliability by storing data in the Fox Board memory before transmission to the processing location. As shown in Figure 6, if Link 1 is not available due to a power shortage the data are safely stored in the Fox board memory and will be transmitted once the link becomes available again. In some of the regions of our interest, power shortages can be as long as one week.

2 Flexibility by providing communication through a GPRS module. In addition to WiFi, it is possible to use FOXGM (FOXGM, 2009), a carrier board for the Fox Board designed to use GSM/GPRS networks. This enables communication in remote locations where no internet access is available. This feature is shown as Link 2 in Figure 6.

3 Remote deployment in places where the internet is neither available nor reliable. In remote locations, such as a jungle or a volcano, no internet access is available in a short range from the sensor network. By providing WiFi connectivity, it is possible to use an access point located kilometres away from the sensed area.

4 Compatibility with ZigBee. It is possible to use FOXZB (FOXZB, 2009), an add-on board equipped with a placement for a MaxStream XBee module, allowing it to log data coming from ZigBee networks. It is therefore possible to use USB-equipped based stations such as the SunSPOT or the Sentilla Perk, as well as ZigBee motes such as the SquidBee.

1.8 Long-range deployment

Point coverage is one of the most realistic WSN layout schemes that accounts for geospatial constraints by placing the sensors only where they are needed. It consists of covering only some points of interests in the environment which is under investigation. While flat architectures are range limited to achieve point coverage, our gateway solution provides the potential to achieve efficient sensing operations in point coverage constrained environments by extending the range of a WSN. This is achieved by layering a gateway network above islands of sensor motes to achieve different network topologies. While in an environment where ten motes, for example, could achieve only 1 km coverage when deployed in a flat fashion, such hybrid deployment can lead to cover 3 km at an additional cost of just two Fox Boards. Four different routing architectures can be derived from the use of our gateway solution. These include: (a) Multi-star, (b) Multi-mesh, (c) Hybrid-SM and (d) Hybrid-MS topologies.

As illustrated in Figure 7, the *Multi-star* topology uses a topology where a star gateway network is layered above islands of star mote networks. This topology seems to be one of the most flexible since it does not require any multi-hop routing capability neither at the level of the islands of motes nor on the level of the gateway network. However, it requires gateways which are endowed with GPRS or other wireless interfaces that convey the information wirelessly to the processing places without local relay.

The *Multi-mesh* architecture illustrated in Figure 8 uses a topology where a mesh gateway network is layered above islands of mesh mote networks. In such a network, multi-hop routing is implemented both at the level of the gateway network using protocols such as OSLR, BATMAN, AODV, etc., and also at the level of motes using the AODV protocol supported by SunSPOT.

In a *Hybrid-SM* architecture, a mesh gateway network is layered above islands of star mote networks as depicted in Figure 9. In such a network, multi-hop routing is only implemented at the level of the gateway network using protocols such as OSLR, BATMAN, AODV, etc. In this deployment, not all the gateway devices need to convey the information to the processing place.

The *Hybrid-MS* architecture uses a topology where a star gateway network is layered above islands of mesh mote networks. Such architecture is illustrated in Figure 10 where only the sensor network will be using AODV multi-hop routing while the gateway is based on a single-hop point-to-point transport.

Figure 6 Flexibility in point coverage

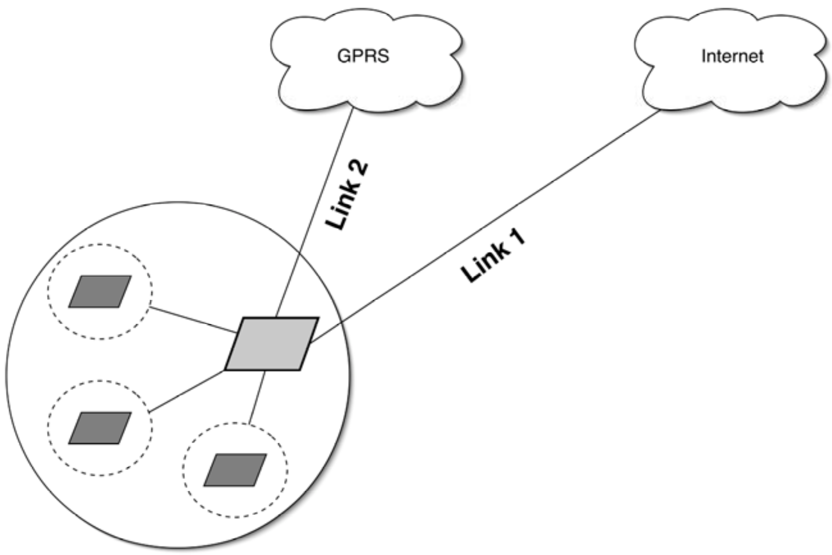


Figure 7 Multi-star deployment (see online version for colours)

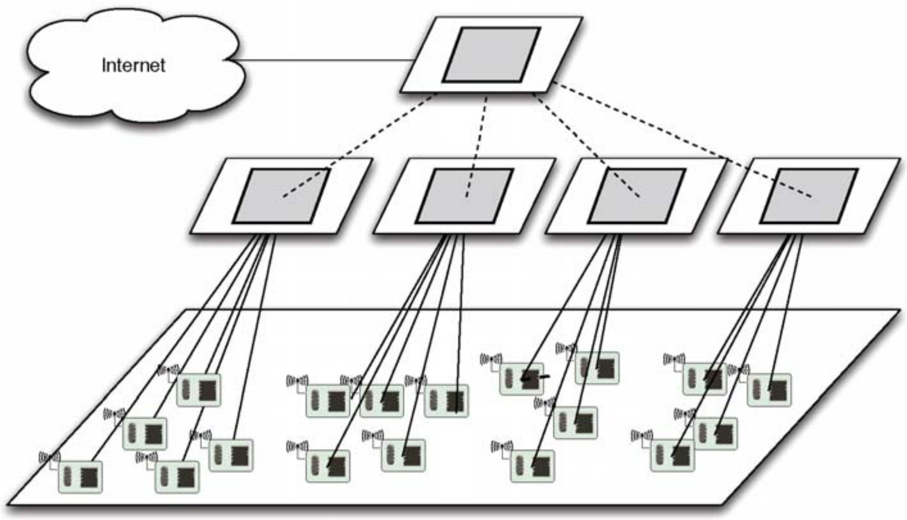


Figure 8 Multi-mesh deployment (see online version for colours)

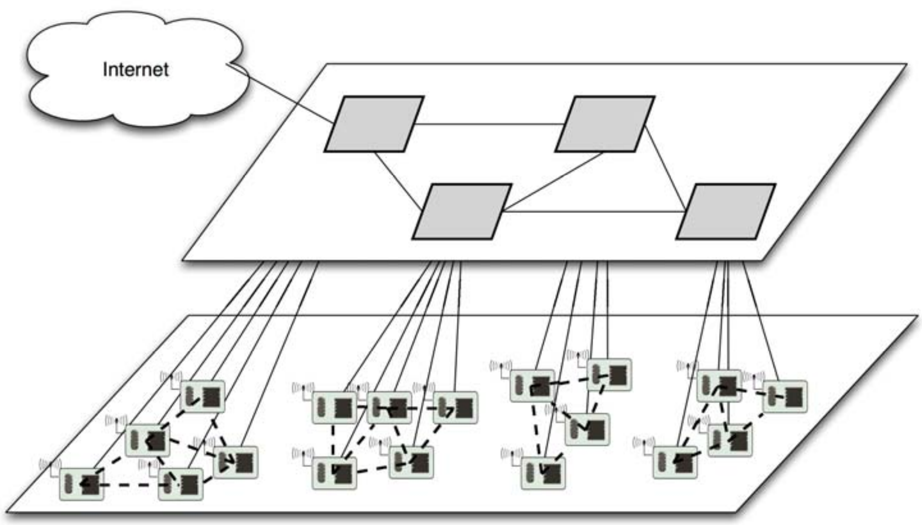


Figure 9 Hybrid-SM deployment (see online version for colours)

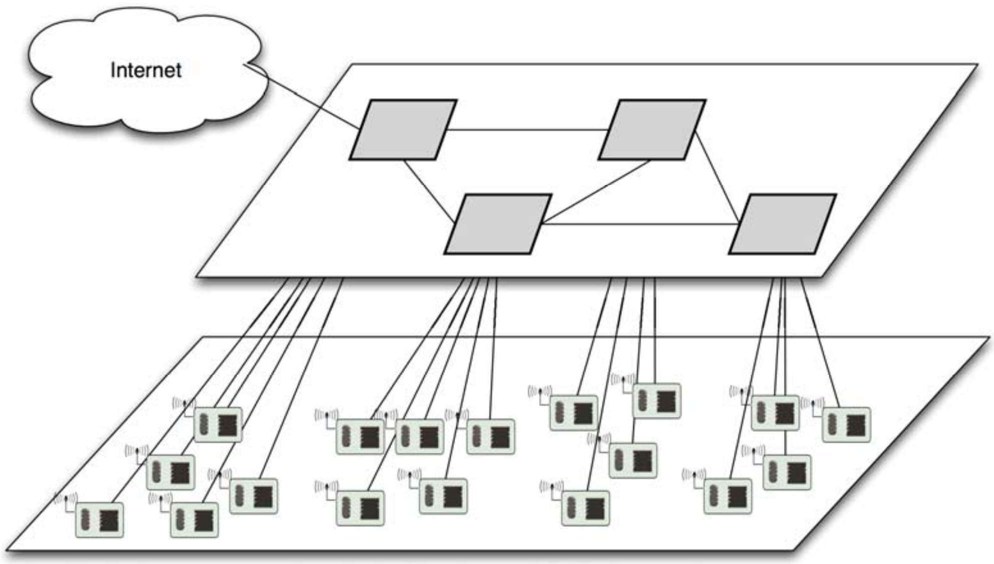
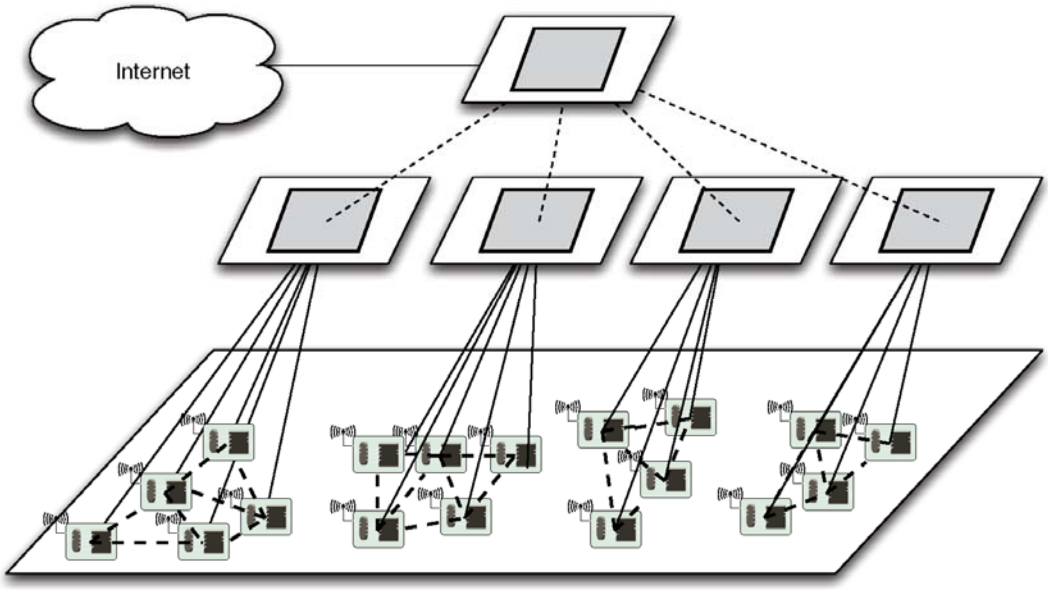


Figure 10 Hybrid-MS deployment (see online version for colours)



1.9 A MySql-oriented middleware for WSNs

As depicted in Figure 11 and implemented in our Middleware, the use of smart boards as gateways allows the deployment of hybrid star/mesh networks referred to as Hybrid-SM where a mesh network of smart boards (gateways) is layered above islands of star WSNs. This section describes the Hybrid-SM middleware component as implemented by the Wireless Sensor Network Management system using SunSPOT technology in our testbed. A middleware is an important component of a WSN. As currently designed, wireless sensor Middlewares are tightly coupled to the particular wireless sensor application that uses the wireless sensor technology. Such situation raises issues as the use and number of WSNs spreads. The design of a generalised interface layer which fulfils the required management roles in WSNs will be a major milestone in the adoption of the technology. In WSN middleware approaches, how the network is abstracted is of outmost importance, as it determines how the user wanting access to the network's data will interact with the WSN. The middleware proposed in this section is based on the database abstraction model known as one of the most commonly proposed middleware approaches for WSNs. As described the database abstraction can be loosely defined as an abstraction whereby the WSN is viewed as a logical ordered set of data, stored within a rational database.

Figure 11 The implemented model (see online version for colours)

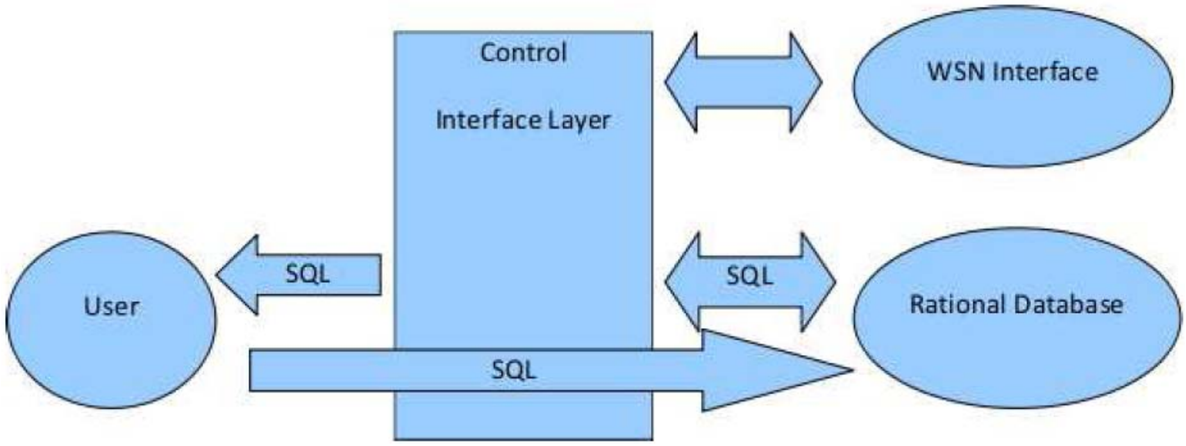


Figure 11 depicts the main components of the implemented middleware model for a testbed network using the SquidBee technology. These components include:

- *User*: An abstraction of the service that requires data from the WSN. It queries the WSN using the widely used Standard Query Language (SQL) and receives responses in the standard SQL format.
- *Control/interface layer*: This interface monitors the response from the rational database to the user. Trigger conditions can thus be set, that will get activated upon certain conditions and perform tasks, such as the timestamp of the data requested is too far in the past from the current time. The layer would in this case update the data in the database using the data from the WSN interface. Hence, this layer can also interact with the WSN interface, and use it to update the rational database.
- *WSN interface*: This is the interface to the actual WSN that transforms sensor readings in terms of voltage values into human friendly values. Depending on the WSN and the user requests and WSN responses, different formats are used for the sensor readings. In our case, it is linked to the format provided by foXServe.
- *Rational database*: The virtual version of the WSN is stored in this database. The structure of the database is dependent on the projected most common requests for data.

Some of the strengths of the proposed model are detailed hereafter:

- Well-established external interface (SQL).
- Control of actual data requests sent to the WSN, this allows for high-level policy setting to control traffic volumes and hence minimises power cost on the WSN itself.
- Provided a WSN interface is available, potentially any WSN can be interfaced with.
- Can facilitate a high volume of external requests fairly easily.

1.10 Implementation scenario

According to recent studies, 20% of the world population does not have access to safe drinking water (WorldWater, 2009). One of the Millennium Development Goals (MDGs) specifically addresses halving the proportion of the global population that lacks sustainable access to safe drinking water supply and basic sanitation by 2015, compared with the 1990 levels (UNESCO, 2009). The experience is also salient in view of the new Decade Water for Life established by the UN agencies for the period 2005–2015. In cooperation with the concerned authorities in Malawi, we proposed to develop, deploy and demonstrate an online water quality monitoring system using WSNs. The quality of the monitoring process would benefit significantly if at least some basic parameters would be monitored automatically (Dewan, 2009). This will enable the research groups to provide an early warning system that can trigger appropriate treatment. The trend towards online monitoring has been growing stronger in the developed world during the last decade. The first implementation will be at the Blantyre Water Board in Malawi, responsible for delivery of water supply and services in the city of Blantyre. After a site survey at the Chichiri premises, we decided to place three wireless sensors to monitor water quality: one in the water basin and two following the treatment process, shown in Figure 8. The distances between the nodes are of about 100 m. The results of the analysis are used both at the Water Board and at the Malawi Polytechnic, so a web server publishing the results is a must. From the connectivity point of view, the Water Board has an ADSL connection and we are going to use that to connect to the internet. We have not deployed our system in the field yet, but we have designed it thinking about the conditions in Malawi, where we have been working. Our system provides data-logging facilities for SunSPOTs in an Ethernet and 802.11 compatible, low-power, low-cost device. The device is based on open source software and offers a user-friendly interface. It has a USB flash drive that allows for removable storage.

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