ENS: An Energy Harvesting Wireless Sensor Network Platform

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***Abstract*—We present the design and implementation of an energy harvesting wireless sensor network platform, the Energy Neutral Speck (ENS). The design and implementation of the photo-voltaic and battery powered platform is described including the hardware, firmware and operating system and the architecture and implementation of software for interfacing with the network and visualisation and storage of sensor data,**

I. Introduction

Energy harvesting technologies are now widely used in Wireless Sensor Network (WSN) deployments to extend battery life or support perpetual operation. A large body or work has been undertaken in the field to take advantage of energy harvesting power supplies in areas including platform design[1], long-term deployments[2], power management[3] and solar aware routing[4].

In this paper we present the design and implementation an energy harvesting wireless sensor network platform, the Energy Neutral Speck (ENS). The ENS platform has been designed to investigating the potential of perpetual solar powered networks, particularly those deployed in indoor environments. As indoor light levels are significantly lower than that of sunlight, the goal of perpetual indoor networks is taken into account in the selection of components and design of the platform.

The motivation for design perpetual indoor sensor networks is to provide a platform for deployment of services and applications in 'Smart Buildings'. Such applications including tracking of people and assets[5], building management[6], way finding[7] and emergency evacuation[8]. The large scale of networks required for high fidelity sensing in large buildings makes network wide battery replacement a time consuming and costly enterprise, whilst provision of a large capacity battery will increase the volume of the device. A low volume, unobtrusive platform with an energy harvesting power supply is therefore desirable.

The remainder of this paper is organised as follows. Section II discusses related work in the design and analysis of energy harvesting platforms. The design and implementation of the ENS platform is described in Section III. We conclude and present future directions of work for the platform in Section IV.

II. Related Work

Although a number of potential sources of harvested energy have been identified, the most commonly used are solar or photo-voltaic supplies[9][10][11] and mechanical energy harvesting from strain[12] or vibrations[13][14]. Although vibration generators have been shown to be capable of powering a sensor node in a deployment environment[14], the power supply is greatly dependent on the external source of the vibration. Solar powered networks have been more widely considered as the photo-voltaic supply is more consistently and widely available in the majority of deployment environments.

A number of solar powered sensor platforms are compared and analysed in [1]. Several distinguishing factors between designs are identified including the use of hardware or software battery protection, different storage technologies and a number of suggestions made for the design of solar powered platforms. The design recommendations include: dynamic duty cycle adjustment to match sensor operation to available power, the use of two stage energy storage to reduce the number of charge-discharge cycles, solar cell output point matching and dynamic adjustment of the solar cell inclination angle to increase incident solar radiation. Two platforms, Trio and Heliomote, are identified as leading examples of different approaches in design.

The Trio platform[10] was developed and deployed as a large scale WSN testbed. The Trio platform is based on a Telos Mote[15] and a Prometheus energy harvesting module[16]. The Prometheus module uses a two-level storage system of super capacitor and rechargeable battery, battery charging and protection is software controlled by the sensor device. The deployed Trio network was able to operate at a duty cycle of 20-40% to support testing of applications, tools and protocols.

The Heliomote module[11] is a solar harvesting supply for wireless sensor platforms. The design of the Heliomote module uses only one level of storage, the solar cell is directly fed to NiMH batteries. Charge control and battery protection are implemented in the module hardware, simplifying the dependence between the power supply and sensor device. The hardware charge control allows the Helio module to be used with many comparable platform but as the parameters are fixed limit its efficiency at matching the load with the maximum power point of the solar cell[1].

Another approach in design of energy harvesting platforms has been to design battery-less platforms[9][14] where a single tier of storage is implemented using super capacitors. The use of capacitors as the only energy storage can reduce the size and cost of a device and does not require the same level of charge control circuitry as a battery based design. The long term performance of such a device may be limited in situations with variable environmental energy supply as battery based designs typically include much greater storage capacity.

III. Design and Implementation

The ENS platform was designed with the goal of allowing deployment in a variety of environments, particularly to support indoor network deployments powered by energy harvested using photo-voltaics. Previous work had and a review of existing platforms was taken into account in the selection of components and in setting several goals for the design of the platform. Specific requirements in the design of the platform were:

- Power Consumption Control: to remain perpetually powered, sensor networks are typically heavily duty cycled. In indoor lighting a small photo-voltaic supply provides very little energy compared to those in outdoor sunlight. An indoor network will therefore be heavily duty-cycled and may remain in a low power sleep mode for extended durations, controlling the power consumption in these modes by powering off any unnecessary hardware is therefore required.
- Perpetual Power Supply: to enable a perpetual network each device must include sufficient energy storage capacity to operate through periods of darkness when no energy can be harvested from the photo-voltaic supply. In indoor environments this may be variable with occupation as cyclical lighting activity as with outdoor deployments.
- Low Volume/Profile Design: to deploy large scale indoor networks, we identified that large volume devices may be obtrusive or difficult to deploy, a thin, low profile format was decided upon to allow for unobtrusive positioning on walls. The volume of the device is is largely set by the area of the solar panel, a trade off exists as output of a solar panel is dependent on the cell area but large areas of panel intrude and affect the aesthetic. A aim was to fix the area of the deployed device to $50mm^2$ as this was deemed a reasonable size for both the panel and the platform circuit boards.
- Compatibility with other devices: previous work had developed a platform[17] and testbed[18] using IEEE 802.15.4 communications, a requirement to remain compatible with these and other platforms was to retain the Chipcon CC2420 radio transceiver.

As part of the the ENS project a new hardware platform, device firmware and programming interface and PC based software framework for network control and visualisation have been developed. An overview of the structure of the ENS is shown in Figure 1, the implementation has been divided into

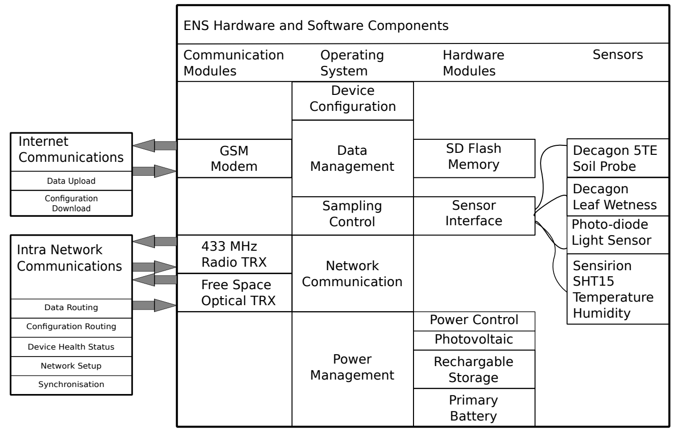

Fig. 1. ENS Platform Modules

a number of hardware and software modules. The operating system has been developed as a part of the project and includes configuration, scheduling, synchronisation, routing and medium access control (MAC) protocols. The operating system also allows expansion of the platform hardware for additional communication or data storage devices. Although the platform does not include any sensors on-board, interfaces have been developed for a variety of sensors for environmental and agricultural monitoring. Additional hardware modules have been designed and implemented including a multi-directional free space optical communication board and an SD-Card memory extension for data storage.

A. Platform Hardware

The ENS platform is based on previous experience with the Prospeckz[17] platform and a review of existing wireless sensor platforms. The Prospeckz platform is based around a Cypress Programmable System on Chip (PSoC) including an 8-bit MCU and a Chipcon CC2420 radio transceiver. Experience with the PSoC had identified that although the reconfigurable nature allowed for flexibility in design of protocols and sensor interfaces, the MCU core on the chip is not ideal for a WSN platform due to relatively high power consumption compared to the AVR and MSP processors used on a number of motes and other devices.

Figure 2 shows an unpackaged ENS device and a device packaged for indoor deployment the core hardware of the platform can be seen, this includes a $45x45mm$ PCB, solar panel and thin film lithium polymer battery. The core components of the ENS platform are a Texas Instruments MSP43F2410 16-bit Micro-controller (MCU)[19] with 56KB of flash memory and 4KB of RAM and a Texas Instruments CC2420 2.4GHz radio transceiver[20]. Power management and control circuitry includes a PCF8563 Real Time Calendar/Clock, shutdown circuitry and battery charge protection. The power management and operating modes are discussed in Section III-B. A PCB antenna is used to reduce component cost and complexity, a folded dipole layout is used as this offers good performance when positioned flush against a wall surface.

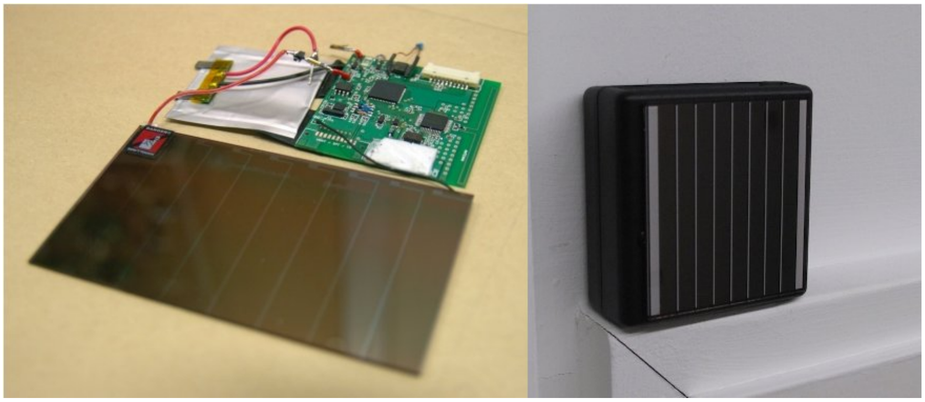

Fig. 2. ENS Devices

The size of solar cell and capacity of the battery are limited to reduce the volume of a completed device. The devices shown in Figure 2 show Sanyo Amorton AM1816 and AM5814, the smaller AM5814 is included in packaged devices as it better fits the design goal of a low volume device and offers improved performance in well lit conditions[21].

The battery is a Varta PLF084441 rechargeable lithium polymer $50\,\mathrm{mAh}$ battery, the battery was chosen to reduce the volume of the device. Although the current off-the-shelf shown in Figure 2 casing has a depth of 20mm, the platform itself has a thickness of only 5mm. The $50\,\mathrm{mAh}$ capacity is sufficient to allow the device to operate through extended periods of darkness. The platform includes protection circuitry for the battery to disconnect the solar supply when the battery has reached capacity.

If lighting conditions are such that the solar supply cannot be relied upon to supply all required energy a secondary battery pack such as a number of primary cells can be added to be used when the rechargeable battery is insufficiently charged. The software power management module monitors the state of the rechargeable battery to prevent damaging deep discharge of the cells.

B. Power Management

The device is designed such that all components can be individually shutdown through disconnection of their power supply. This is implemented in hardware and software and allows a number of low power sleep modes to be used and minimises power consumption whilst retaining functionality that an application or communications protocol requires. A combination of firmware and control circuitry allows for even the MCU to be fully powered off when waiting for external stimulus. The operating modes and power consumption of the device are shown in Table I. A sensor application requiring periodic sensing and transmissions need only maintain supply to the Real Time Clock (RTC) between sensing activities, the device will then be in the Clocked Shutdown mode. Where a more complex MAC protocol stack is used, the RAM and radio transceiver state are preserved and an inactive device will be in a Sleep mode.

The lowest power mode is achieved by removing the power supply to all but the power control circuitry when waiting for an external interrupt source, the power consumption of the platform core in this mode is $10\,\mathrm{nA}$. The raising of a voltage on the external interrupt pin will cause the device to power up in less than $1\,\mathrm{ms}$. This mode is used when an external Free Space Optical (FSO) wake-up transceiver is added to the platform. The wake-up transceiver includes a very low power receiver that can be continuously powered in indoor lighting. When a transmission is received the FSO transceiver wakes the ENS device from sleep. As the receiver is not duty cycled, the FSO based protocol is able to achieve significantly better performance than a duty cycled radio MAC protocol when awaiting asynchronous transmissions[22].

The power management module of the operating system controls the sleep state of the device based on the activity of the application and protocols, minimising current consumption during periods of inactivity.

C. Network Communication

Network wide synchronisation has been implemented following the FTSP protocol[23]. Nodes synchronise a timer clocked from the $32\,\mathrm{kHz}$ oscillator used for the RTC, this allows for synchronisation to with $60\,\mu\mathrm{s}$. The timers are synchronised by periodically appending current values to transmissions in the MAC layer as in FTSP protocol. The synchronisation is structured in trees routed at powered base-station node, each node synchronises to its parent within the tree.

A dynamic Time Division Multiple Access (TDMA) protocol is used for medium access control. The TDMA protocol allows for very tight control on the duty cycle of the radio and for a static analysis of communications to be performed to determine the optimal duty cycle given the communication requirement and the energy available from the photo-voltaic supply. The MAC protocol can be configured after deployment to assign transmission and receptions slots for each node.

Routing is performed using a tree based shortest path protocol when routing data to the nearest base-station or collection point. The AODV[24] protocol can be used when

TABLE I
DEVICE OPERATING MODES

Mode	MCU State	Radio State	Active Clocks	Power Consumption
Shutdown	Shutdown	Shutdown	None	10 nA
Clocked Shutdown	Shutdown	Shutdown	RTC	700 nA
Unclocked Sleep	Sleep	Shutdown	None	29.5 μA
Clocked Sleep	Sleep	Shutdown	RTC	49.5 μA
Active	Active	Sleep	RTC, HF Osc.	2.9 mA
Radio RX	Active	Receive	RTC, HF Osc.	21.7 mA
Radio TX	Active	Transmit	RTC, HF Osc.	19.5 mA

more complex Ad-Hoc routing is required within the network.

D. Sensors

External sensors and devices can be connected to the platform via the expansion header. The platform can sample up to eight individual analogue inputs and can be interfaced to other digital devices through standard buses such as UART, I2C and SPI.

E. Network Interface Software

The ENS Network Software framework provides a environment for collection, storage, and display of data from the ENS sensor network. The architecture of the framework is shown in Figure 3. The software framework has three component applications that use Java RMI to communicate remotely: Serial Proxy, Server, and Viewer. This architecture allows each component to be positioned at differing geographical locations whilst still providing reliability and scalability to the platform.

Multiple instances of each of the components can exist in the platform, depending on the sensor network. For example, one scenario might involve multiple serial proxies forwarding data to a cluster of servers with many viewer applications manipulating the data. Additionally, at any stage, third party applications can be included such as the Sensor.Network data exchange or the Google Maps API.

1) ENS Serial Proxy: The Serial Proxy (SP) program provides the link between the wireless sensor network and the software platform. Nodes in the sensor network route data to a base-station, an ENS or other 802.15.4 capable device connected via USB or serial interface to a PC. The SP program forwards received packets to an appropriate server application to handle. The SP also provides a control interface to the network as transmissions can also be sent into the network to perform on-the-fly node, network, and application configuration and maintenance. Due to the flexibility of the system, multiple serial proxies can be configured allowing redundant routing and partitioning in the network.

The SP is fully extensible allowing incoming packets from the sensor network to be sent to a number of assigned applications. In Figure 3, incoming packets are forwarded to the ENS Server for processing and storage. Additional third party data stores can be utilised easily, such as the Sensor.Network global exchange of sensor network information.

2) ENS Network Server: The ENS Server is central to the software platform by performing three categories of function: packet processing, database management, and data retrieval. The server uses a database abstraction layer to reduce coupling with any specific database implementation, allowing drop-in replacements for the database back-end. Two databases are utilised to improve data management - one for current live data; one for historical log data.

Incoming packets from the Interface Proxy are received by the server, processed and passed to the database abstraction layer for storage. Any connected applications are notified of new data via push technology - allowing up-to-date information to be viewed in the client software immediately.

The server additionally provides data retrieval services and authentication for connections via the ENS Network Viewer application.

3) ENS Network Viewer: The client-facing side of the software platform is provided via the ENS Network Viewer software, shown in Figure 4. The software connects remotely to the ENS Network Server application to manage and retrieve information regarding the state of the network.

The Viewer allows custom visualisers and overlays to be installed to allow the state of the network to be represented in multiple ways. For example, a monitoring application could display blueprint plans of a built environment or maps using the Google Maps API for a natural environment, overlaid with real-time network status. Additionally, live data from the network can be viewed in a tabular format to provide real-time sensor and node information.

The graphing component of the viewer application allows historical network data retrieved from the sensor network from multiple sensors to be visualised using custom time and date ranges. Additionally this data can be post-processed to provide statistical information, rather than the entire dataset.

Using the live data retrieved from the network, alarms can be set that will trigger on a programmed condition to alert the user to an undesired state in the network.

IV. CONCLUSION

We have presented the implementation of an energy harvesting platform for wireless sensor networks. The platform is powered by a photo-voltaic and battery supply and has been designed primarily for use in indoor environment where energy available is significantly lower than in sunlight. The design of hardware, operating system and communication protocols has been targeted for operation within this restricted power budget.

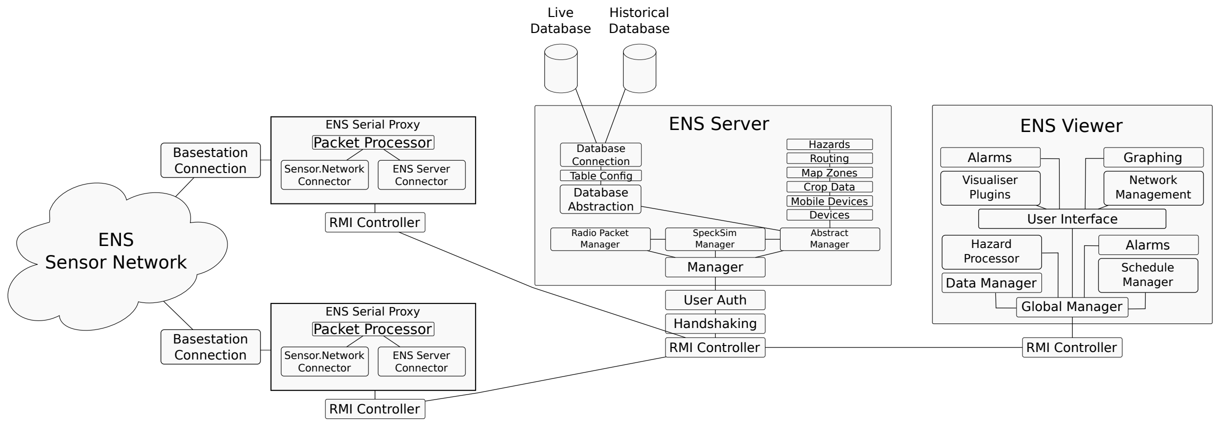

Fig. 3. Network Interface Software

Fig. 4. ENS Network Viewer Application

V. Acknowledgements

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