The Design and Implementation of a Wireless Mesh Sensor Network for a Housing Community

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Abstract— Wireless mesh sensor networks typically consist of a cluster of intelligent radio nodes which transfer data between each other directly in a hop, or indirectly through two or more hops via adjacent nodes. These nodes contain one or more sensors. Wireless mesh sensor networks provide a solution in monitoring and controlling the physical world around us and offer far reaching potential applications. This paper presents a novel design, implementation and prototype realization of one such potential application, namely the use of a wireless mesh sensor network to monitor the events and activities in a housing community environment. In this network, transmit-only sensor nodes are employed in order to obtain a low cost, easy to deploy and low power solution. A small-scaled version of the proposed network is deployed in a controlled environment, allowing for practical testing and verification of the final design. The results obtained are presented and discussed within.

Keywords – Wireless mesh sensor networks, transmit-only sensor nodes, housing community sensor network.

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I INTRODUCTION

Wireless mesh sensor networks (WMSNs) are a collection of intelligent wireless nodes equipped with one or more sensors. These nodes work together in order to facilitate collaborative measurements. They form interconnecting mesh networks which provide data paths which can route data from source nodes to destination nodes. WMSNs provide a solution in monitoring and controlling the physical world around us.

In recent years the area of low power localised wireless sensor networks (WSNs) has attracted a vast amount of research interest, mainly due to the fact that these wireless sensor networks encompass many different areas of technology, including wireless technology, networking, computation, sensors and circuitry [1].

The home and living environment is currently attracting much interest as an area for wireless applications. Research is looking at wireless technology to effectively create the smart home of the not too distant future. Wireless home automation will provide more flexible management of lighting, heating and cooling, security, and home entertainment systems from anywhere in the home. The idea of automating the living space through wireless control and sensors is on the threshold of becoming commonplace in many homes. RF wireless systems such as ZigBee [2], Bluetooth [3], Z-Wave [4], RFID [5] and Wi-Fi (IEEE 802.11) [6] offer the means to achieve this.

Here, we look at extending the wireless technology beyond the house and into the housing community, an area which is yet to be fully exploited. Wireless applications such as remote meter reading and RFID tags for refuse bins have already found their way into the community. These systems have been developed by the service providers with their interest in mind, namely cost savings and ease of service. Arguably, communities can benefit from these initiatives also, as service providers may choose to pass these benefits onto the consumer in terms of cost savings and quality of service.

Networks already exist between many houses in a housing estate. At present this is mainly through the internet protocol TCP/IP, which in most cases is an indirect link provided by Internet Service Providers (ISPs). Wireless links are also becoming more prevalent, with Wireless Local Area Networks (WLANs) based on the IEEE 802.11 (Wi-Fi) standards [6]. Many of these WLANs have a gateway to the internet provided by wireless broadband service suppliers.

This paper proposes and presents the design and development of a novel housing estate network based on licence exempt, low power wireless technology, not in competition with IEEE 802.11. This system is both affordable and beneficial to a housing community. Furthermore, the benefits may also extend to the service providers of the housing community. The final design is prototyped and

deployed in a small-scale controlled environment for the purposes of testing and verification. In this case, the environment chosen is that of the Electronic Engineering building at NUI Maynooth. The results obtained confirm the validity and operation of the proposed WMSN.

The rest of the paper is structured as follows. The next section outlines the key requirements of the proposed housing community WMSN system and presents an overview of the final design. The detailed design and implementation of the WMSN mesh and sensor nodes are presented in sections III and IV respectively. Details of the system deployment and verification are given in section V while the paper ends with some conclusions in section VI.

II OVERVIEW OF WMSN
a) System requirements

The final system design is based around a wireless sensor network. Such networks should be low power, contain a sensor or sensor interface and transmit small amounts of data. They should also be low cost, easy to deploy and reliable. Additional requirements for the proposed system include:

- *Radiolocation:* The system should be able to identify the location of any wireless sensor node, within a single property or a single location in a housing estate.
- *Single Destination point for data*: All sensors send their data to one central point, the base station.
- *Ease of maintenance:* Maintaining the system should be achieved centrally, i.e. the base station must be capable of determining if maintenance is required.
- *Scalability*: The system should cater for a range of housing estate sizes, without having a detrimental effect on the system's performance.
- *Extend the RF range beyond that of a single radio device:* In order to transfer data over varying distances and objects, wireless nodes should be able to relay data to a destination.
- *Easy access to sensor data:* The base station will store all sensor data. Access to this data will be via SMS or Web Access.

b) System overview

The proposed housing community network comprises both wireless infrastructural mesh nodes and wireless sensor nodes. Figure 1 depicts the topology of these devices together with a base station. Mesh nodes are strategically placed to give full zoned coverage of the target area (i.e. the housing estate). They act as wireless routers in the system relaying sensor node data to the base station, where the data is then processed. The mesh node contains two radio interfaces. One is used for inter-mesh communications using the 868Mhz band while the other is a dedicated receiver for the sensor node operating at 433Mhz.
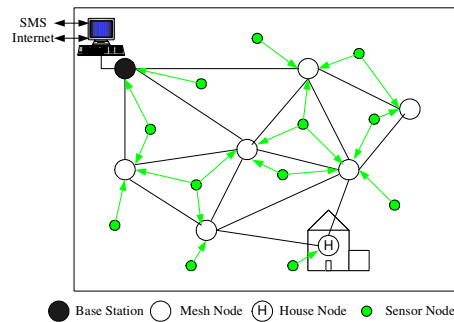

Figure 1 - Housing Community WMSN Topology.

The sensor node is a battery powered single channel wireless device. The main function of this device is to read sensor inputs and transmit the data to any/all mesh nodes within radio range. This device contains a 433Mhz transmit-only radio. The number of sensor nodes in each mesh node zone will tend to be evenly distributed due to the uniform physical layout of housing estates in general. However, some of the sensor nodes within the network will be mobile. These nodes will be free to move between mesh zones and are intended to be used for radiolocation purposes. Additional mesh nodes may be added or removed on an ad-hoc basis. These additional nodes can be used to assist in more accurate radiolocation and for blind-spot coverage.

The proposed system has many possible benefits in a housing estate environment including oil tank monitoring, house alarm notification, locating of assets and people, refuse services and personal aid notification.

The key components in the proposed WMSN are the mesh nodes and sensor nodes. The design and implementation of each of these components are now considered in turn, along with the protocols for dealing with the flow of data through the nodes.

III MESH, HOUSE AND BASE NODES
a) Hardware

The mesh and house nodes form the wireless mesh network. A set of wireless mesh nodes form a fixed infrastructure, giving full coverage of the housing estate. Additional house nodes may be added and removed on an ad-hoc basis. The wireless mesh node consists of a main board with a micro controller unit (MCU), a mesh node radio module using the Texas Instruments (TI) CC1101 radio chip, a PC (USB) interface module, a sensor node receiver module and a power source. Figure 2 shows all these main components in block diagram format.

The infrastructural mesh node, the house node and the base node are all variants of the wireless mesh node. All three utilise a common hardware platform (main board) based around the Microchip PIC18F4550 MCU (mesh node MCU). The mesh node *MCU* and *Radio Module* are common to all three variants. The *Sensor Node Receiver Module* and the *Battery/External Power* are used in both the

infrastructural and house nodes but not required for the base node. The base node is the only node which requires the *USB Module*. This USB module also provides power for the base node.
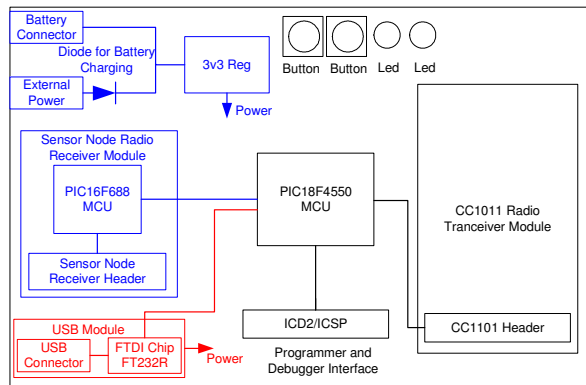

Figure 2: Wireless mesh node block diagram.

b) Mesh radio

The mesh interface radio communications is based on the Texas Instruments sub 1 GHz transceiver chip, CC1101, operating at 868 MHz. This is a low power low cost device. This device requires a number of external components such as a crystal and antenna matching circuit. This radio chip together with these additional required components, and an external antenna, are designed as a plug-in module. The mesh node MCU communicates with the mesh radio via SPI (Serial Peripheral Interface), enabling the mesh node MCU to send and receive data to and from other mesh nodes via this radio.

The mesh radio is configured to send a preamble automatically. On the receiver side this preamble is decoded without any user intervention. Another convenient feature is that the device can operate in broadcast mode or single destination mode. Broadcast mode is where transmissions are received and stored in the receive FIFO by all other devices in range. Single destination mode is when an id is used to specifically target another device. In this case if a mesh radio receives a data packet targeted for another device then it will ignore this data packet. This is very useful when routing data packets to particular mesh nodes.

c) Mesh routing algorithm

The mesh nodes route the sensor data back to the base station. These nodes have little or no mobility as they will be deployed in a fix infrastructure. Therefore the system is suitable for implementing a simple proactive routing strategy. The nodes will maintain routing tables. These tables will be ordered in terms of the best route to the base station, determined by the number of hops required. As the nodes have no mobility, once the route is determined it will always be the same for individual nodes, while all mesh nodes operate correctly. If a route is blocked, the next route from the table will be taken. The routing tables are established once all

mesh nodes are in place. The nodes are set to a 'discovery mode'. Once in this mode, a broadcast is sent by the base station to all nodes in range. The nodes which receive this broadcast set their hop count to 1. These nodes then rebroadcast the signal. This is done at slightly different times in order to avoid data collision. The nodes that receive this broadcast, and don't have a hop count, set their hop count to 2. This continues until all nodes have a hop count. Once done, all nodes report back to the base station with their hop count number in order to verify the creation of the mesh network.

This facilitates a very simple routing method. With the information about adjacent nodes stored in tables, data is simply sent to an adjacent node with the lowest hop count. If this route is blocked the next route in the table is used.

d) MAC protocol

The MAC (medium access control) protocol for the mesh nodes is based on CSMA (carrier sense multiple access). Figure 3 shows a basic flowchart for this protocol. When a mesh node wants to send data it uses the receiver signal strength indicator (RSSI) from its radio to determine if any other mesh node within radio range is currently transmitting. If the radio channel is clear the mesh node starts transmitting immediately. This then reserves the radio channel for the complete transmission of its data. Once the data has been transmitted the mesh node waits a finite time for an acknowledgement from the receiving node. The transmission sequence ends when this is received. If no acknowledgement is received after three attempts, the failed flag is set and this will alert the node to try an alternative route next time.
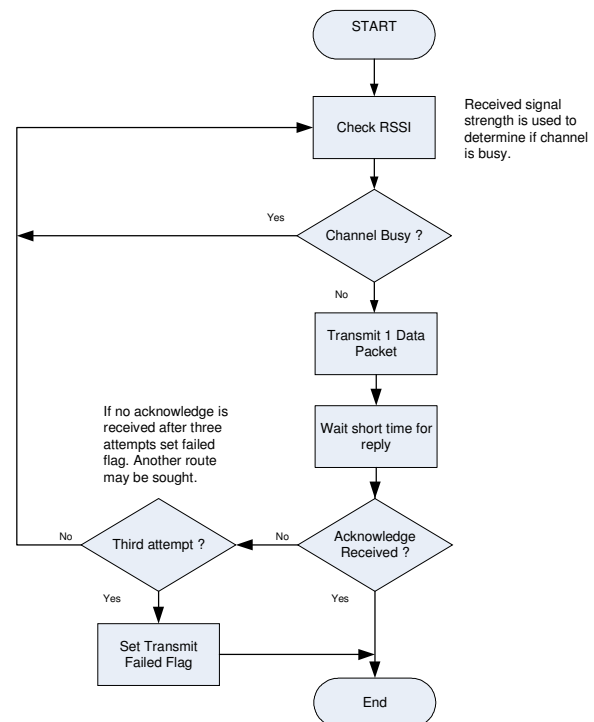

Figure 3: Mesh node MAC protocol.

e) Sensor node interface

The sensor node interface is a wireless interface provided by an ASK radio receiver module. This receiver is a 433MHz device compatible with the transmitter in the sensor node. A dedicated sensor interface MCU (PIC16F688) is used to decode the data received by this radio. This MCU also stores and forwards this data to the mesh node MCU. A second MCU in the mesh node aids in distributing the processing tasks and simplifies the overall software development.

f) Power

The wireless mesh nodes need to be powered continuously. Mains power will not be available for outdoor infrastructural mesh nodes. Therefore these nodes must be powered by a combination of rechargeable battery and energy scavenging. The positioning of the mesh nodes on roof tops and on lamp posts make them ideal for scavenging power from natural resources such as sun and wind. The design of these nodes, allow for the use of solar and wind as a supplement power source. The design of this power source for the mesh nodes requires careful consideration, as it has to cater for the worst case scenario, i.e. the continuous powering of the device during short winter days with little or no wind.

The house nodes are intended to be powered by domestic supply, but also contain a rechargeable battery to ensure the device remains operational in the event of a loss of power.
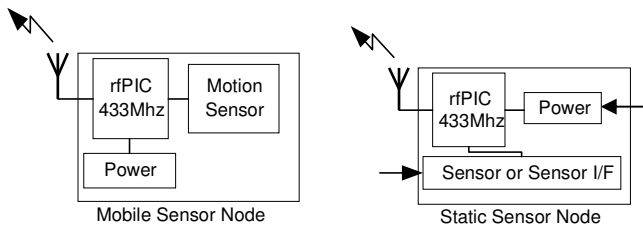

Figure 4: Wireless sensor node block diagram.

IV SENSOR NODES

a) Hardware

The wireless sensor node (WSN) is a battery powered single channel wireless device. The main function of this device is to read sensor inputs and transmit the results to a mesh node. The sensor node contains an rfPIC12F675 unit, which is both a microcontroller and an RF transmitter integrated into one package. This device provides the intelligence and radio transmitter capabilities of the sensor node in a very small footprint.

The WSN may incorporate on-board sensors. It also includes a sensor interface to enable external sensors to be attached. This node can also be deployed as an active RFID tag. In this case the node will transmit a unique identification code only. Transmitting this information alone is sufficient for the purpose of radiolocation. For this reason there are two variants of this node (see Figure 4), namely a

mobile device used mainly for radiolocation and a static device used to monitor sensors at fixed locations. Both variants of the WSN are based on the same hardware platform, with their differences given in table 1 below:

Feature	Mobile WSN	Static WSN
Activation	Movement Only	Event driven, Timed
Low Power Mode	Turned Off	Sleep Mode
Power Source	Battery Only	Battery, Mains, Energy Scavenging
Sensors	Motion Sensor Only	Various Sensors

Table 1: Wireless sensor node (WSN) variants.

b) Sensor radio

The design of the wireless sensor node uses an rfPIC operating at 433MHz and utilising ASK modulation. The transmission range of the rfPIC depends on its output power and antenna, but can be up to 50m indoors and 300m outdoors. The RF output power is selectable by use of a single external resistor. The selected radio is compatible with the receivers used in the mesh nodes.

c) Power

Power for the mobile sensor node is provided by a button cell battery (CR2032 or similar). The sensor node is designed to operate normally from a single battery for more than 5 years. This is mainly achieved with the device being either off, or in very low power sleep mode, when not transmitting.

The static sensor node has a number of options depending on its physical deployment location. It may be powered by battery, if necessary, or by mains if located in or around a house. It may also be powered by scavenging energy from natural resources such as solar or wind, depending on its application.

d) Sensors

The wireless sensor node incorporates an on-board passive movement/vibration sensor. This sensor and has the ability to detect movement in all directions and is able to activate the sensor node from a low power mode such as sleep.

If the wireless sensor node is required to sense anything other than movement or vibration then it will need to incorporate an external sensor. The wireless sensor node provides a digital and analogue interface for external sensors. A possible addition to the on-board sensors would be a low battery level sensor.

e) MAC Protocol

The wireless sensor nodes are effectively transmit-only devices with respect to data, i.e. 'transmit and hope'. They have no possibility of knowing if their data has been received correctly. It is therefore the responsibility of the system to ensure

the highest possible success rate for sensor data to arrive at its destination, the base station. Before data can be transferred to the base station it must first be received by the mesh nodes. This requires the implementation of the wireless MAC protocol between sensor nodes and mesh nodes to reliably transfer the sensor node data.

Two different approaches on how to transfer data reliably from the transmit-only sensor nodes to the mesh nodes are presented in [7] and [8] respectively. The former utilises a wireless protocol based on TDMA and uses the MSF atomic time broadcast as a synchronisation signal for the TDMA sequence. The latter is based on a 'transmit and hope' scheme and is implemented here. In brief, it is impossible to achieve total collision avoidance with transmit-only devices. As such, the 'transmit and hope' protocol uses a number of techniques to reduce the possibility of data collision. A scheme of three random transmissions in three consecutive ten second periods is used. The reader is referred to [8] for a detailed explanation. It is shown that the probability of data collision between sensor and mesh nodes is very low. In practical terms this figure is less than 0.1% and deemed more than acceptable for the current application.

f) Radiolocation

A key requirement of the WMSN system is to implement a simple, effective and reliable radiolocation method. One of the practical issues with the mobile sensor node is that its RF range will be affected by movement and RF obstacles. If the transmit range is increased to combat these effects then this will introduce other issues such as power consumption and increased data, at times, in the network. The increased data would be due to an increased number of mesh nodes simultaneously receiving the stronger signal from the sensor node. All mesh nodes receiving this would then try to route this data back to the base station, resulting in an increase in network data traffic. One positive outcome of the increased transmission power (range) is that the base station can infer radiolocation by triangulation if three or more mesh nodes report back data from the same sensor node at approximately the same time.

A simpler method, and the one implemented here, is to reduce the transmit range of the mobile sensor nodes to 20m for example. If a mesh node receives data from a mobile sensor node then this node must be within 20m of the mesh node. Once the base station receives a data packet containing mobile sensor node data, it need only look at the source (mesh node) of this single packet to know the approximate location of the mobile sensor node. The trade-off here is that mobile sensors may not be in coverage at all times and, hence, location could mainly depend on last know location.

V   SYSTEM DEPLOYMENT & VERIFICATION
a) System setup

The system consists of 8 mesh nodes, 11 sensor nodes and a base station. The mesh nodes are deployed as a mesh network over three floors of the Electronic Engineering building, at the National University of Ireland Maynooth (NUIM). One of the mesh nodes is located outdoors and is powered by a combination of rechargeable batteries and solar panels as in Figure 5(a). This allows us to explore the use of energy scavenging to power such nodes.

Eight of the sensor nodes are deployed as static nodes. Three operate as temperature sensors, reporting their temperature once every minute. The other five are used as door activation monitors. These sensors are deployed over the most active doors in the building and activated by the vibration of the door opening/closing. Figure 5(b) shows one of the static nodes positioned over a door. The remaining three sensor nodes are mobile and used for tracking people and objects. Figure 5(c) shows one of these used for tracking a key.
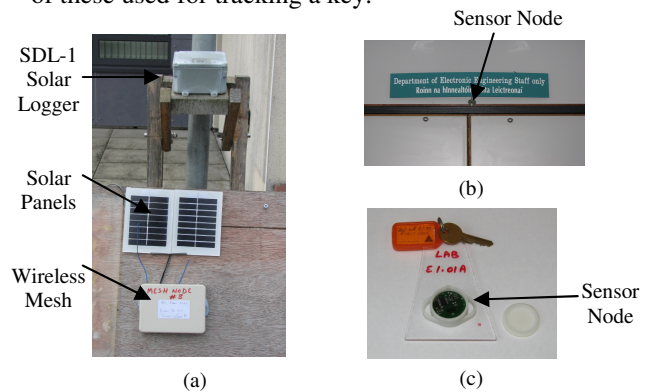

Figure 5: (a) Mesh node with solar energy scavenging; (b) Static sensor node (door); (c) Mobile sensor node (key).

The base station is a PC connected to a mesh network transceiver. This transceiver simply passes data between the mesh network and the PC, it does not process or analyse any data. The system is monitored and controlled by customised PC software. A GUI has been written specifically for the test network set up in the Engineering Building at NUIM and records and logs all the data received from the sensors, including the path taken through the mesh network. The software also includes commands for initiating 'discovery mode' and the sending of a test SMS, if necessary.

b) Verification of operation & reliability

Data has been, and continues to be, successfully collected and logged from all mesh and sensor nodes. By way of illustration, Figure 6 shows a sample of the data logged for the outdoor mesh node in Figure 5(a) (in this case, for the period of one week in January 2011). Here, the voltages obtained from the solar panel and contained in the node's battery are communicated back to the base station. In addition, Table 2 outlines the number of

packets expected and received for the 3 temperature sensors over a weekend period (in this case 16th -19th March 2012). These sensors were chosen as they communicated data once every minute, allowing for the number of expected packets to be accurately determined, as presented. The results show that, overall, 1 packet was lost from an expected total of 18, 216 packets. This corresponds to a 0.0055% loss. Furthermore, it should be noted that these numbers refer to single packet transmission. The actual MAC protocol transmits a packet 3 times within any given transmission window. Hence, while a packet is lost, the actual data is still being obtained at the base station. In other words, data can only be considered lost when at least 3 consecutive packets are lost.

Temperature Sensor	# Packets Expected	# Packets Received
Sensor 1	6072	6071
Sensor 2	6072	6072
Sensor 3	6072	6072

Table 2: Packets Received for temperature sensors.

These results clearly validate the operation of the WSMN, proving that the sensor data was transferred correctly from the sensor to the base station, as required. Furthermore, the system is highly reliable, with a very small percentage loss of packets and, to date, no loss in data. However, it is worth mentioning that these results pertain to a small-scale deployment of the WSNM, where data collision is significantly less in comparison to a large-scale implementation of the same.

c) Radiolocation

The radiolocation method adopted for the system is that of last known location/zone. The radius of the detection zones is governed by the transmission range of the sensor nodes. With the deployment area being relatively small (compared to a typical housing estate) the sensor node transmission range was reduced to approximately 5m. Any sensor node transmitting within 5m of a mesh node would be detected. Detection was only guaranteed as long as the sensor node transmitted while in a detection zone. Tests show that the WSMN successfully logged data from the mobile sensors, allowing for monitoring and tracking of the attached objects, such as the key in Figure 5(c).

d) Power scavenging

Figure 6 shows the solar panel and battery voltages for the period 11th-18th January 2011. During this period there was approximately 8 hours of daylight each day. These were among the shortest days of the year and provided a good scenario for the solar energy scavenging test. The horizontal line in Figure 6 indicates the shut down voltage (3.3V) for the mesh node. The results clearly show that there is sufficient power available through solar for powering the WMSN system. Hence, solar is indeed a viable source of power for mesh nodes would be deployed outside in a housing estate environment.
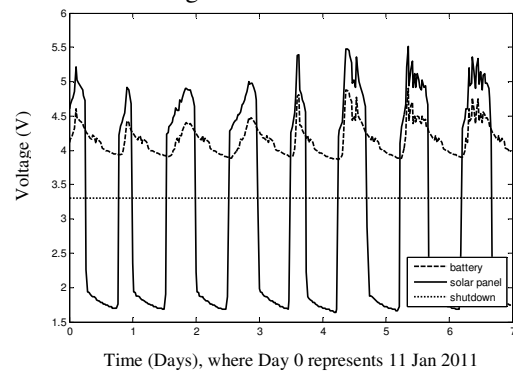

Figure 6: Solar charging of outdoor mesh node.

Due to a lack of space, this paper only contains a selection of results for the WSMN. A more detailed set of analysis and results can be found in [9].

VI   CONCLUDING DISCUSSION

This paper has outlined the design and implementation of a novel low cost, low power, easy-to-maintain, wireless mesh sensor network for a housing community. This network was deployed in a controlled environment using a small number of mesh and sensor nodes. The test setup verified the operation of the network indicating that it was highly reliable in transferring data from the sensors, through the network, to the base station. In addition, it was shown that the mesh nodes (and indeed static sensor nodes) can easily be powered through solar energy scavenging, thus allowing long periods of operation without the need to replace batteries.

Currently, the system is a monitor-only system. Future work will investigate incorporating control aspects into the system, such as remotely switching on/off lights, controlling temperature and even watering garden plants.

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