Wireless Sensor Networks Final Report

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Executive Summary

There is presently great interest in wireless sensor networks (WSNs). To clarify the issues, in this study we have needed to separate technology push from market pull. Performing this separation has shown the push to often be greater than the pull. In particular we have found no killer application for WSNs, although we expect a steady growth in the future market based on a diversity of industrial and automation applications, for example smart buildings. We expect that the two main barriers of firstly node powering and secondly perceived spectrum crowding can be removed or reduced over time.

We began by looking at WSNs in order to identify any technology barriers. Firstly we established that there is certainly no shortage of sensor types – basic transducers are available to sense many mechanical, thermal and optical phenomena. Moreover, the advent of iMEMS – integrated micro electromechanical machines, where the sensor and the support electronics are integrated onto the same silicon die – is driving down prices. However having a large number of sensors on the one hand and turning this into a sensor network on the other hand, are quite different challenges. In the past, implementers of WSNs have needed broad expertise in sensing technologies, in order to interface and calibrate them, as well as broad experience of networking. Much bespoke programming has been needed each time a new application was encountered. Fortunately this has changed with the advent of the IEEE1451 standard for smart sensors. A smart sensor contains its own datasheet parameters in memory and has a standard interface for wired or wireless connections, such as ZigBee or Wi-Fi.

Having thus found a solution for practical sensor networking, the next essential enabler to seek was a suitable power source for wireless sensor nodes. Here the road ahead was not so easy. Although sensors can be battery powered for 3-5 years, this is not always enough for some commercial deployments, since the maintenance cost of replacing batteries is so prohibitively high. If a revolutionary increase in battery performance were on the horizon, then the issue would be solved. But we have not found this to be the case. Much battery technology is relatively mature and on only an incremental improvement curve. New power technologies such as fuel cells are still a long way off for sensors, and safety concerns may mean they are not deployable in all applications. We believe that the way ahead for sensor powering is most likely to include energy harvesting. Useful potential sources include solar, wind, thermal and, perhaps most interesting, vibration in pipelines and motors and even the 50/100 Hz vibration from adjacent equipment.

Applications of WSNs include environmental monitoring of transport and general infrastructure, including elements of the London Underground, for example. Smart buildings also receive much interest, where WSNs may optimally control HVAC (heating, ventilation, air conditioning) and lighting. The installation of a WSN in each example is quick, requires no wired infrastructure and is easily reconfigurable. But installations have not been without their problems, as we saw when looking at the University of St Andrews wireless test bed. During commissioning, the WSN node supplier ceased production, meaning that a homogeneous network build will not be possible. The desirability for WSNs to cope with a diversity of node implementations was thus highlighted, which points again to standards based approaches being most appropriate.

In terms of network architecture we found, as we did with mesh networking during earlier Ofcom work, that the presence or absence of network infrastructure is a key determinant of network capability and application suitability. We also found that much academic research centred around structure-less WSNs and we presume that the military interest is once again responsible for this. But for civil applications there is no driving need for unstructured operation and, in contrast, structured networks are often more suitable. It is undoubtedly the case that the standards community agrees with the need for structure as we can see from the example of 802.15.4/ZigBee,
where most popular implementations are stars and trees, as these are both relatively low complexity and well suited to real world civil applications. In fact ZigBee also contains a third option for a flat mesh, so either structure option could be accommodated.

When considering the likely time to market for WSNs we needed to identify the barriers for uptake. These include the powering issues already mentioned, plus a perception of reliability issues and naturally the cost factor. Costs are likely to fall due to general industry pressure, but the reliability issue is more complex. It is connected with the fact that when a user experiences unreliability in a network, he or she may simply conclude that ‘wireless is unreliable’. However it may be the case that the environment is unsuitable, or the frequency in use may be subject to avoidable interference. Both these options are familiar to engineers, but it cannot be expected that sensor users will necessarily be aware of them. The danger is that WSNs could stall in the market due to unfair perceptions of their unreliability.

Overall we conclude that the WSN market is still at an early stage. Many of the providers are small or start-up companies rather than integrated larger players. This indicates that the market still has to develop confidence in the use and acceptability of WSNs. Nonetheless, there are specific niches of activity, notably where an evolution of a wired approach into a wireless approach is attractive since the benefits can be clearly seen to outweigh the costs. We do not see such clarity of benefit in the general case, nor do we see many revolutionary applications and hence no evidence of a killer application. However, where there is interest then a standards based approach based on 802.15.4 is widely predicated to be most popular, such as in the smart buildings industry.

In terms of spectrum usage we see much interest at 2.4 GHz, since this is a globally available band and it supports the widest range of data rates and the most channels. Unfortunately the popularity of 2.4 GHz extends well beyond WSNs, so interference from other users is likely to be a problem. Avoiding interference is not as easy as might be expected since if all three non-overlapping Wi-Fi channels are in use, then only 4 (from a possible 16) 802.15.4 channels remain available. But even if these channels are used, then interference is still possible if the physical separation is not large enough. Moreover, problems can still occur for quite large frequency separations, for example even with a frequency difference of 22MHz (1/4 of the band). IEEE simulations show that a minimum separation of 7m is still required if ZigBee is not to be a victim of Wi-Fi. Conversely if we consider Wi-Fi is a victim of ZigBee, then a separation down to 3m can be tolerated. The clear conclusion is that ZigBee is less able to tolerate Wi-Fi than vice versa. The concern which arises from this is that such effects can only heighten perceptions of ZigBee unreliability from a typical user’s point of view. We see the general situation as ZigBee being especially sensitive to any future spectrum crowding problems, rather than it being the cause of them.

In the light of all the above, we feel that, as a perception of unreliability could stall the WSN market, some level of education and information directed towards the typical user would benefit the proper operation of the market. This action might be catalysed or facilitated by Ofcom, leading on to the industry taking steps to help itself. In addition, whilst we conclude that the total WSN spectrum likely to be needed is not excessive even for dense deployments, Ofcom may wish to modestly increase the amount of spectrum available for licence exempt devices in response to market demand. Apart from avoiding a spectrum crowding issue, the major signpost to watch for which predicts upcoming growth in the WSN market is the availability of suitable powering schemes for WSNs, such that they can become more truly fit and forget.
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1 Wireless Sensor Networks Introduction

This section first briefly provides the background to why this study is being performed, then gives an introduction to wireless sensing in a network environment, including showing, by example, what constitutes a typical WSN node.

1.1 Background to the study

In setting and reviewing its policies, Ofcom needs to understand how technologies are likely to develop, and how that development will affect and be affected by the associated economics and technology use by society. This study seeks to reach an understanding of how widely wireless sensor networks may (or may not) be deployed in future – and their likely spectrum requirements.

1.2 Wireless Sensor Networks

The role of a wireless sensor network is essentially that of a monitor. What is being monitored can usually be placed within one of three groups:

1. Area monitoring – i.e. monitoring somewhere; examples include the Environment or area alarms (intrusion etc.)
2. Entity monitoring – i.e. monitoring something; examples include a civil structure (bridge, building etc.) or a human body
3. Area-Entity interaction monitoring – i.e. monitoring something, somewhere, in context; examples include natural disaster sites, asset tracking or a manufacturing process

As to why a sensor network is important, it is most simply understood by realising that, often, individual sensors themselves are normally limited in their ability to monitor a situation. Specifically a single sensor may not embody sufficient scope to sense a whole situation, nor is its reliability likely to be very good, since it presents a single point of failure. Communication to a wider network may also bring a challenge. The power of a sensor network comes from the fact that even though the nodes are quite limited, the whole array becomes very powerful when networked. Thus sensor networks are likely be large in scale, in the sense that they have many nodes and they are likely to be self configuring, to promote reliability. Also the nodes themselves are likely to be cheap, such that many nodes may be economically deployed.

1.2.1.1 WSN node (mote) component parts

A practical wireless sensor node must consist of the following:

- A sensor (e.g. a MEMS accelerometer, or a light sensor)
- A signal converter (usually an analogue to digital converter)
- A processor and memory (minimum capability for minimum power drain)
- A network interface (wireless; either radio or optical)
- A suitable packaging solution (a reliability and cost driver)
- A power supply (or a method of harvesting power in situ, e.g. from vibration or light etc)
A diagram of what a sensor can look like is shown in Figure 1-1. These sensors, when used as a network, form a mini weather station. They use commercially available hardware and software.

![Figure 1-1 A wireless sensor node (mote)](image)

Note the component labelled a ‘mote’ in Figure 1-1. The dictionary definition is ‘speck of dust’ or similar and this describes the role of an individual sensor node very well; each is relatively small, like a speck of dust, but there are a lots of specks of dust in the network. The mote in Figure 1-1 is a commercially available mote (see xbow.com), to which the user is expected to add all the relevant ancillary components. Note, however, that the term ‘mote’ is used broadly and often the whole wireless sensor node is referred to as a mote.

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1 Culler et al., “Overview of WSNs”, IEEE Computer, August 2004

2 Interestingly, perhaps, this appears to stem from a biblical reference, which stated that any hasty, would-be critics should, first and foremost, consider first the beam [big splinter] in their own eyes before criticising the mote [tiny speck] in other peoples’ eyes.
2 Wireless Sensor Technologies and Example Applications

We have surveyed the various sensor types and begin this section with an overview of sensors themselves. We have found that the variety of sensors is very large and appears sufficient to encompass a wide diversity of potential applications. In this section we will also look at what else remains to be provided at the physical level in order that we might proceed to use sensors easily in applications, i.e. what are the outstanding technical enablers. Firstly, a key aspect of sensor networks is the powering of the sensor nodes hence we survey battery technology and power scavenging techniques and how they might be improved in the future. Secondly, we introduce Transducer Electronic Data Sheets (TEDS) and interface standards, which are an aid to the practical usage of any sensor. Finally, we cite real examples of WSNs and we also look at how a current WSN test bed is progressing from its planning stage to its current deployment status.

2.1 Sensing Technologies

A sensor is a transducer which produces a measurable response to an external stimulus of, say, a change in a physical condition such as temperature, moisture or electromagnetic field, or to a change in chemical concentration. The following sections highlight key sensor technologies that can find application in WSNs. As this is an actively evolving engineering field, these sensor technologies are intended as illustrative examples rather than an exhaustive list. Broadly speaking, sensors can be classified under different categories based on their fundamental scientific principles. These are

- Mechanical Sensors
- Thermal sensors
- Optical sensors
- Chemical sensors

The sensor technology has a key role as a cost driver for the whole wireless node. Whilst we will address cost later in section 5.2, we note here that there have been some fairly recent breakthroughs in integrating sensors onto silicon, which is the watershed enabler for integrated devices and hence lower cost. Examples are MEMs accelerometers and gyroscopes, as we show in section 2.1.1.2.

2.1.1 Mechanical Sensors

By making a physical contact with the measurand\(^3\), mechanical sensors provide a direct inference of any detectable changes in the system. The main types are piezo, capacitive and combinations of these two. Many acoustic sensors use resonance effects, which are often detected by piezo methods.

2.1.1.1 Piezo-resistive

The piezo-resistive effect converts an applied strain to a change in electrical resistance that can be sensed using electronic circuits such as a Wheatstone Bridge. In contrast to the piezoelectric effect, the piezo-resistive effect causes only a change in resistance and does not produce electrical charges. Discovered by Lord Kelvin in 1856, the sensitivity of a piezoelectric material in characterized by its gauge factor,

\(^3\) The measurand means that which is to be measured
\[ K = \frac{(\Delta R/R)}{\varepsilon}, \]

where \( \Delta R \) the changes in resistance, \( R \) the material resistance and \( \varepsilon \) the resultant strain.

Both metal and semiconductor materials exhibit piezo-resistivity. The latter has been used for sensor devices employing germanium, polycrystalline silicon, amorphous silicon, and single crystal silicon [3].

### 2.1.1.2 Integrated MEMS

Since silicon is today the primary material for integrated digital and analog circuits, the use of piezo-resistive silicon devices invites the integration of transducers with silicon circuits. In fact, many commercial devices such as pressure sensors, Hall Effect sensors and accelerometers already employ the piezo-resistive effect in silicon, with increasing numbers at the MEMS (Micro Electro-Mechanical Systems) scale.

Having a MEMS device close to its associated electronics brings operational benefits and reduces the cost, particularly if it is on silicon process, which is now very well understood. Such devices are called integrated MEMS, or iMEMS. Figure 2-1 gives an example of an iMEMS piezo-resistive accelerometer from Analog Devices.4 This device also includes capacitance sensing, described later.

![Figure 2-1 dual-axis piezo-resistive accelerometer: (1) SEM of the MEMS structure; (2) micrograph of the integrated chip](image)

Another device which includes piezo and capacitance principles and which has integrated electronics is the nano-gyro, or iMEMS gyro. Figure 2-2 shows this device, also from Analog Devices.

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The importance of this device is not that it is a new device, since gyros have been around for very many years. Its importance lies in the fact that this device is now affordable to enable many more applications. For example, rather than use GPS alone to track vehicles, perhaps for theft recovery or road user charging, an iMEMS gyro can augment GPS with inertial navigation. This has the potential to work where GPS will not. It also could not be jammed in the same way as GPS.

### 2.1.1.3 Piezoelectric

The piezoelectric effect converts an applied stress (force) to a charge separation or potential difference (voltage). Barium titanate (PZT) and single-crystal quartz are examples of traditional piezoelectric materials. The piezoelectric effect is reversible, so that a change in voltage also generates a force and a corresponding change in thickness. The same device therefore can be both a sensor and an actuator\(^5\). MOSFET solid-state circuitry and highly insulating materials such as Teflon and Kapton significantly improved the performance and increased the use of piezoelectric sensors into many modern technology and industry applications\(^6\). Figure 2-3 lists different vibration modes that have been employed for the sensor and actuators\(^7\), which include pressure, vibration, displacement, acceleration, force, infrared and ultrasound sensors.

Piezoelectric sensors offer advantages such ruggedness, excellent linearity over a wide frequency amplitude range as well as insensitivity to electromagnetic and radiation – making them an attractive choice in harsh conditions. Acellent, for example, has marketed SMART Layer\(^8\), a network of distributed piezoelectric actuators/sensors on thin dielectric films for structural integrity monitoring in the aircraft, spacecraft, automotive and civil industries\(^8\).

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2.1.1.4 Capacitive

The capacitive principle measures the effect of changes of an electric field in the space between two conducting plates. An applied relative displacement between two plates, $\Delta d$, generates a change in capacitance

$$\Delta C = \varepsilon A / \Delta d$$

where $A$ is the cross-sectional surface area and $\varepsilon$ the dielectric constant of the medium in the electric field.

Capacitance sensors have been extensively used, such as for object detection, high precision displacement of conductive and non-conductive surfaces, tactile interface, sonar and biometric e.g. fingerprint authentication. A silicon-based capacitive MEMS micro sensor has been developed for implantable medical devices$^9$. One of the most widely used applications to date is in the human-machine interface (HMI) touch sensor in equipment and consumer electronic devices. Figure 2-4 shows how a capacitance tactile sensor operates$^{11}$.

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9 D. Tsoukalas et al, “Capacitive Microsensors for Biomedical Applications,” Encyclopedia of Medical Devices and Instrumentation, 2006, John Wiley and Sons

10 [http://www.tronics.eu/](http://www.tronics.eu/)

In the iMEMS gyro described earlier, capacitance changes of the order of $10^{-21}$ Farads (zeptofarads) are detected, using a differential circuit to reject noise and interference.

### 2.1.2 Thermal Sensors

Thermal sensors include devices that detect changes of temperature directly or through measurement of heat flux. The physical principles exploited include:

- Thermo-mechanical
- Thermo-resistive
- Thermo-electric

#### 2.1.2.1 Thermo-mechanical transduction

This phenomenon is used for temperature sensing and regulation in a wide range of control and sensing applications. On changes in temperature $T$, all materials exhibit (linear) thermal expansion of the form $\Delta L/L = \alpha \Delta T$, with $L$ the length and $\alpha$ the coefficient of linear expansion. A joint structure of two metallic strips can be fabricated with different thermal expansions. This is known as a bimorph and gives a radius of curvature that depends on the temperature change, see Figure 2-5.

One of the innovative thermo-mechanical sensors in the current market is Siemens’ patented Senstec™ bimorph sensor that can be installed on steel, concrete and synthetic composite materials to measure the structure-borne signals caused by mechanical and thermal deformation, from fire for example. It is targeted for remote seismic detection and security monitoring of safes, cash dispensers and vaults\textsuperscript{13}, see Figure 2-6.

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{sensor}
\caption{(a) Senstec™ bimorph sensor, (b) Seismic detector, both by Siemens}
\end{figure}

Reversing the transduction effect allows thermo-mechanical actuators to be developed, especially for applications requiring high-precision displacement control in demanding operations. PICMA® multilayer piezo bender actuators, Figure 2-7 by Physik Instrumente (PI) are examples of such products in the market, which provides a deflection of up to 2mm, forces up to 2N (200 grams) and response times in the millisecond range\textsuperscript{14}.

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{actuators}
\caption{PICMA® Multilayer piezo bender actuators from Physik Instrumente}
\end{figure}

\textsuperscript{13} http://www.siemens.cz/siemjet/en/home/search/search_press/Main/30959.jet

\textsuperscript{14} http://www.physikinstrumente.com
MEMS-level actuators have also been developed, for example by researchers at Birmingham University who have successfully produced micro thermal bimorphs, Figure 8, using Focused Ion Beam (FIB) technology.\[^{15}\]

![Figure 2-8 Fabricated micro structure of thermal bimorphs](image)

2.1.2.2 Thermo-resistive

Thermoresistive effects are based on the fact that, for many metals, the change in resistance $\Delta R$ and temperature $\Delta T$, are related by

$$\Delta T = (\Delta R/R).TCR$$

where TCR is the temperature coefficient of resistance of a given material. This may be positive, as it is for metals, or negative, for certain semiconductors. Also, it may be zero for some metal alloys.

The relationship for semiconductors such as silicon and metallic oxides is well developed within the application class of thermally sensitive resistors with a negative TCR. These are known as thermistors and are well used in the electronics industry, where their negative thermal coefficient, or NTC, is useful. Thermistors are a mature technology, and are available off-the-shelf in many different types of package sizes, as shown in Figure 2-9 and Figure 2-10.

![Figure 2-9 Various types of thermistor packages from Quality Thermistor Inc.: (a) glass-bead radial leaded, (b) interchangeable radial leaded, (c) military grade, (d) axial Leaded, (e) surface mount](image)

\[^{15}\] [http://www.micro-nano.bham.ac.uk/teng.htm](http://www.micro-nano.bham.ac.uk/teng.htm)
Resistance temperature detectors (RTD) are another widely known class of thermoresistive sensors. Platinum is often used because of its reliably high and reproducible TCR, while copper and nickel may be substituted for low-cost applications. All metals have a positive TCR (PTC). Figure 2-11 provides some examples of RTD packages in the market\textsuperscript{16}.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2-10.png}
\caption{Simistor\textsuperscript{™} silicon thermistor IC from Andigilog}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2-11.png}
\caption{Different types of RTD from Omega Engineering Ltd (a) encapsulated sensor, (b) cement-on elements for surface temperature measurement, (c) thin film, (d) laboratory probes, (e) industrial Probes with metal protection head}
\end{figure}

\subsection{2.1.2.3 Thermo-electric}

Thermoelectric sensors are based on the Seebeck effect, whereby a pair of dissimilar metals are joined at one end, and if there is a temperature difference between the junctions, a current flows in the circuit to generate a Seebeck voltage given approximately by

\[ V = \alpha(T_1 - T_2) + \gamma(T_1^2 - T_2^2) \]

where \( T_1, T_2 \) are the temperatures at the two junctions, and the coefficients \( \alpha \) and \( \gamma \) depend on the properties of the two materials.

The most common thermoelectric sensors are thermocouples (TC). Semiconductor TCs generally have higher sensitivities than metal thermocouples. Thermocouples are inexpensive and reliable, and have typical outputs on the order of 50\( \mu \)V/°C operating temperature ranges of -270°C to 2700°C. Standard TCs are denominated with different letter codes, such as T, J, K, S, R to indicate different junction metal configurations. For example, type J (the most popular) is made of iron and constantan. Figure 2-12 (a) shows a standard ceramic bead thermocouple and (b) a schematic of its construction.

Thermopiles are another variant of thermocouples, with one junction coated in a gold or bismuth black absorber, being generally used to measure heat output from thermal conduction or radiation.

\textsuperscript{16} http://www.omega.co.uk
2.1.3 Optical Sensors

Optical sensors are one of the non-contact detection technology platforms most widely used in the industry. Many sensors are based either on measuring an intensity change in one or more light beams or by detecting the phase changes in the light beams by causing them to interact or interfere with one another. With the exception of detecting natural luminescence or generated radiation, a light source and detector will be required in an optical sensor system. The source may be a light emitting diode (LED), infrared emitter or laser. Optical detection is based on the photoelectric and/or photoconductive phenomena.

In addition, optical fibres themselves can be fabricated as sensor devices, notably where a grating is etched along a very short section of fibre, to act as wavelength filter, whose properties may be sensitive to its environment.

2.1.3.1 Photoelectric

The photoelectric effect is a quantum electronic phenomenon occurring after the absorption of energy from electromagnetic radiation such as visible light, ultraviolet light, infrared light or gamma radiation\(^{17}\). The result is a current flow known as a photocurrent and the overall mechanism is sometimes referred to as photo-generation, meaning photo-generation of charge carriers in the material. Photoelectric devices may operate without any bias voltage, i.e. they may be zero-biased. Photoelectric devices include photodiodes, phototransistors and photovoltaic cells.

**Photodiodes**

A photodiode is essentially a light-controlled variable resistor with a relatively high resistance in total darkness. When the PN junction is exposed to an external light source, its internal resistance decreases due to the increase in its photocurrent. Figure 2-13 shows a wide range of different package types for photodiodes presently on the market. In applications, the resultant light is aimed at the photodiode through a transparent "window" placed over the semiconductor chip. Because photodiodes can respond quickly to changes in light intensity, they are extremely useful in digital applications such as communications and measurement.

\(^{17}\) e.g. [http://scienceworld.wolfram.com/physics/PhotoelectricEffect.html](http://scienceworld.wolfram.com/physics/PhotoelectricEffect.html)
The operating wavelengths of photodiodes are dependent on the material used to make them, since only photons with sufficient energy to overcome the material band-gap will produce photocurrents. Materials commonly used include those shown in Table 2-1.

<table>
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<tr>
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<td>Germanium</td>
<td>400–1700</td>
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<tr>
<td>Indium gallium arsenide</td>
<td>800–2600</td>
</tr>
<tr>
<td>Lead sulphide</td>
<td>&lt;1000-3500</td>
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Table 2-1 Common photodiode materials

Phototransistors

A phototransistor produces more output current for a given light intensity than a photodiode, due to internal amplification. They are essentially conventional transistors with the base terminal exposed. In the phototransistor, instead of applying a current to the base, the photons from the incident light control the base current and hence the output current. Figure 2-14 shows some off-the-shelf, packaged phototransistors.

Photovoltaic

Photovoltaic (PV) cells can be classed as large photodiodes which generate useful levels of

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19 [e.g. http://www.rswww.com](http://www.rswww.com)
electrical power from incident light. First generation PV solar cells comprised a large-area silicon wafer. This contained p-n junctions with a potential barrier chosen to be capable of generating usable electrical energy within the wavelength range of natural sunlight. Figure 2-15 gives an illustration of the PV solar cell function\textsuperscript{20}. Newer generations of PV cells are manufactured with advanced technologies such as thin-film deposition of semiconductors, photo-electrochemical (PEC), polymers and mixture of nano-crystals for higher conversion efficiency at lower costs.

![Figure 2-15 Functional schematic of a silicon PV solar cell](image)

\textbf{2.1.3.2 Photoconductive}

Photoconductive sensors are based on the change in the conductivity of the device material upon absorption of energy from electromagnetic radiation. Most of these detectors are heavily doped semiconductors or metal oxides that have a finite electrical conductivity that changes with incident light level. Their response can be such that they are useful for infrared detection, which is a major application. In contrast to a photoelectric device, photoconductive detectors are biased at a fixed voltage, and the wanted signal is the current flowing through the detector. Some examples are shown in Figure 2-16.

\textsuperscript{20} http://www.ucsusa.org/clean_energy/renewable_energy_basics/how-solar-energy-works.html
2.1.3.3 Fibre Optics

Optical fibre sensors (OFS) have been developed on various principles, which include intensity modulation, interferometry, polarization effects, refractive index changes and reflectometry. Common primary measurands are polarization, phase, frequency, intensity or a combination. OFS can be further classified as:

1. Intrinsic sensors, by which the fibre functions as both the transmission and sensing element. Thus the parameters to be measured change the light guiding properties of the fibre, which effect can subsequently be detected.

2. Extrinsic fibre sensors, the fibre merely acts as the transmission medium, bringing light to and/or from the sensing medium.

One of the mature OFS principles in the industry is the Fibre Bragg Grating (FBG). Bragg gratings are manufactured by illuminating the core of a suitable optical fibre with a spatially-varying pattern from a high-power UV laser to distort the structure of the fibre and marginally vary its refractive index in sympathy with the pattern. This modified fibre serves as a wavelength selective mirror, as follows. Light travelling down the fibre is partially reflected at each of the tiny index variations. These reflections interfere destructively at some wavelengths but, usually over a particular narrow range of wavelengths, constructive interference also occurs\(^\text{21}\). In this way a band-reject filter function is embodied. By monitoring the phase and/or frequency changes between the input and reflection spectra when the fibre is thermally, mechanically or chemically loaded, FBGs can be used for measurement of strain and temperature. Common examples are structural health monitoring in the construction, geotechnical and offshore industries. Figure 2-17 shows the principle of a FBG sensor, with an example industrial device shown in Figure 2-18.

\(^{21}\) http://www.smartfibres.com/Attachments/Smart%20Fibres%20Technology%20Introduction.pdf
2.1.4 Chemical Sensors

Chemical sensors include oxygen sensors, and carbon monoxide detectors, for example. In the oil and gas industry, mercury vapour sensors are important safety devices which determine whether an environment is safe for operating staff to enter.

Taking the mercury sensor as an example, the property to be detected may be resistance change. This resistance change is that produced in a gold film when in the presence of mercury, when the mercury is adsorbed. This particular sensor cannot be used continuously, since when the mercury-gold interaction is advanced, sensitivity will fall and the sensor must be purged before reuse: The mercury must be driven off, often by heating.

An alternative mercury sensing method is to build the gold electrodes as a surface acoustic wave filter (SAW filter). Change in resonance is then the parameter to be detected.

Chemical sensors also cover biological sensors. These devices often use an assay which will react to a target sample, leading to a change in a conveniently measurable property of the assay. This might be resistance or light transmission. Typically these assays are use-once devices.
In fact there is much research into new biological sensors, where types under investigation operate on principles including:

- Chemi-resistor Sensors
- Chemi-capacitor Sensors
- Chemi-mechanical Sensors
- Calorimetric Sensors
- Amperometric Sensors
- Acoustic Wave Sensors
- Gas Chromatograph
- MEMS Chemical Gas Sensor

As suggested by their names, some use techniques already covered earlier in this section.

By way of example, a MEMS sensor is shown in Figure 2-19. The principle is that, as chemical changes occur on the assay printed at the end of each cantilever structure, its weight changes. This is detectable via piezo vibration techniques, via a change in resonance of the silicon microbeam.

![Figure 2-19 Chemical MEMS sensor](image)

Having surveyed sensor types, we now turn our attention to how WSNs may be powered, the ease of which is a critical enabler for viable WSNs.
2.2 Power Sources and Harvesting

Power sources are usually split into primary and secondary cells, where the difference is that primary cells cannot be recharged, by design, whereas secondary cells have a need for regular charging. Key parameters of primary and secondary cells include capacity, temperature range, current drain level and self discharge characteristics. Alternatively, there is also a storage method based on capacitors, called super-capacitors. Whilst these are strictly not power cells, they are useful energy stores. A potential future energy source is fuel cells, if they could be made small and safe enough for more applications.

Where secondary cells are used, the charging source may come directly from the cell’s working environment. The most well-known example of this is probably the harvesting of solar energy to charge a battery. However many other energy modes are available for harvesting and scavenging, such as vibration, wind power and thermal energy.

In this section we look at

- Primary cells
- Secondary cells
- Super-capacitors
- Fuel cells
- Energy harvesting methods

2.2.1 Primary cells

If average energy requirements are low, a primary battery might provide an adequate source of lifetime power for a remote sensor, although this is unlikely to exceed 10 years.

Various cell chemistries are potentially of interest depending on the cell capacity, operating temperature range and discharge currents required\textsuperscript{22}. For low-power-consumption sensors with short operating life requirements, ZnO\textsubscript{2} (Zinc-Air) cells offer high power densities, but the short life of these cells (typically 50\% self discharge after 4 weeks once activated), means they are not attractive for long term deployments. The energy density of LiSOCl\textsubscript{12} (Lithium Thionyl-Chloride) is the highest of the other typically available commercial cells and a commercial D cell gives approximately 4 J/mm\textsuperscript{3}. To put this into context via a real world example, six years ago Plextek designed a narrowband transmitter unit for the remote meter reading of gas meters powered by a single LiSOCl\textsubscript{12} D cell with an operational life of 10 years.

Smaller cells and other chemistries tend to have lower energy densities, but could well be cost effective for low power, low duty cycle applications. Table 2-2 gives some typically available cell examples, where it can be seen that the practical volumetric energy density (Wh/cm\textsuperscript{3}) does not vary widely across these types. Whilst larger cells have a higher ratio of active constituents to casing material, larger cells often require more volume for safety devices and mechanisms. Apart from the ZnO\textsubscript{2} cell, all the other types are potentially usable for longer term (5+ years) powering of sensors. Some products using LiSoCl\textsubscript{12} claim up to 20 years lifetime.

\textsuperscript{22} see e.g. http://www.mpoweruk.com/chemistries.htm
### Table 2-2 Examples of cell energy densities, typical numbers for today

<table>
<thead>
<tr>
<th>Cell Type</th>
<th>Typical Capacity (Ah)</th>
<th>Approximate size (mm)</th>
<th>Approximate Volume (cm³)</th>
<th>Maximum energy density (Wh/cm³)</th>
<th>Typical Temperature range</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC13 ZnO₂ 1.4V</td>
<td>0.28</td>
<td>7.9 dia x 5.4</td>
<td>0.26</td>
<td>1.5</td>
<td>-10 C to +55 C</td>
</tr>
<tr>
<td>CR2032 lithium 3V</td>
<td>0.24</td>
<td>20 dia x 3.3</td>
<td>1.0</td>
<td>0.72</td>
<td>-40 C to +60 C</td>
</tr>
<tr>
<td>AA Alkaline 1.5V</td>
<td>2.9</td>
<td>14.5 dia x 50</td>
<td>8.2</td>
<td>0.53</td>
<td>-20 C to +55 C</td>
</tr>
<tr>
<td>D LiMnO₂ 3V</td>
<td>11.1</td>
<td>34 dia x 60</td>
<td>54</td>
<td>0.61</td>
<td>-40 C to +70 C</td>
</tr>
<tr>
<td>D LiSOCl₁₂ 3.6V</td>
<td>19</td>
<td>34 dia x 60</td>
<td>54</td>
<td>1.26</td>
<td>-55 C to +85 C</td>
</tr>
</tbody>
</table>

**Effect of current drain**

Many RF communications standards such as GSM, Bluetooth etc are bursty in nature and consequently can have relatively high peak to mean current ratios when active, because of the current drawn during the RF transmit burst. The internal impedance of a cell varies across chemistries, but is generally inversely proportional to the cell capacity. With small cells and/or high peak sensor current requirements, there is often the need to use extra electronics to be able to deliver the peak current which can sometimes significantly increase the space and cost requirements.

To achieve several years’ operational life from a primary cell, a remote sensor must typically employ duty cycling with good power management design and excellent standby state leakage current. For example to get five years of operation from a CR2032 coin cell requires the average current drain to be less than 6 µA. With smaller and smaller silicon geometries, meeting the low active state current targets becomes easier, but meeting the low leakage current requirement can be difficult as the leakage increases inversely with silicon feature size and so sometimes extra power management and/or system design is needed.

**Primary cell developments**

It is reasonable to assume that manufacturers will continue to make small improvements, year by year, in achievable cell capacity for all of these cell types, but for these mature chemistries the trend is likely to be only a few percent per annum.

The development of new chemistries and technologies for batteries is generally a long process and it typically takes several years from initial prototypes to commercial production release.

There are potentially significant improvements in cell capacities to be gained by the use of nanostructures in the cell design as these can dramatically increase the active areas, but there are no estimates of when this may be realised.

### 2.2.2 Secondary Cells

Lithium Ion and Lithium polymer types are the types most commonly used today in portable electronics. They have a discharge temperature range typically from –20 C to +60 C but a charging temperature range of only 0 C to +45 C.

One of the potentially significant limitations for almost all commercially available secondary cell chemistries is the limited operating temperature range, particularly for charging, where the maximum temperature is typically limited to +40 to +45°C. Relatively limited cycle life is also potentially an issue; most chemistries are only rated for several hundred cycles. For these reasons super-capacitors (section 2.2.3) may be a more attractive solution for long term deployments.

**Secondary Cell developments**
Manufacturers are continually improving the capacity of Lithium Ion and Lithium Polymer cells at a present rate of around 5% per annum through minor chemistry and processing improvements. The assumption in industry appears to be that this will continue, or will fall off given this is a fairly mature technology.

There are new variations in Lithium-based chemistries that have just become mainstream during 2007 and which have slightly higher terminal voltages (typically 4.36 V compared to 4.2 V for established Lithium Ion and Lithium Polymer). These will initially give around 10% better energy density and manufacturers are also likely to continue to improve this at around 5% per annum.

As with primary cells, there are potentially significant improvements in cell capacities to be gained by the use of nano-structures in the cell design, but predicting if and when these will be commercially successful is equally problematic.

There are also chemistry variations in development that promise to deliver cycle life closer to 1000 cycles\(^\text{23}\). There are also early research projects that could potentially offer very significant improvements in energy density but which presently seem unlikely to come to fruition within the project timescale\(^\text{24}\).

### 2.2.3 Super-capacitors

Super-capacitors are extremely high capacitance capacitors that can be used as energy storage devices. Temperature ranges are typically –40 C to +70 C and some types can be charged and discharged rapidly thousands of times, so they are attractive to use in conjunction with energy harvesting technologies. Capacitances vary, depending on the physical size and application, from tiny surface mountable 0.07 F types (5mm diameter x 1.4 mm) through to hundreds of farads for vehicle/industrial applications\(^\text{25}\).

Once again nanotube technology holds the promise of significantly higher energy densities for super-capacitors, but in this case is at least 5 years away\(^\text{26}\).

### 2.2.4 Fuel cells

Fuel cells have been successfully used for several years, perhaps most notably in spacecraft. There are several types of fuel cell, with the direct methanol fuel cell (DMFC) being the one most likely to be ultimately used for small portable devices like mobile phones\(^\text{27}\).

Micro-scale fuel cells for portable electronics have been continually ‘just around the corner’ for several years already and it is likely to be several further years still until manufacturing costs fall to levels where they will become mass-market products\(^\text{28}\).

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\(^{23}\) [http://www.eetimes.com/showArticle.jhtml;jsessionid=20SZ5GPC1VXFYQSNDELPSKHSCJUNN2JVN?articleID=197003851](http://www.eetimes.com/showArticle.jhtml;jsessionid=20SZ5GPC1VXFYQSNDELPSKHSCJUNN2JVN?articleID=197003851)

\(^{24}\) [http://www.brown.edu/Administration/News_Bureau/2006-07/06-022.html](http://www.brown.edu/Administration/News_Bureau/2006-07/06-022.html)

\(^{25}\) e.g. [http://www.maxwell.com/ultracapacitors/products/small-cell/pc-5.asp](http://www.maxwell.com/ultracapacitors/products/small-cell/pc-5.asp) and [http://www.innoresearch.net/reports/ULTRACAPACITORS.htm](http://www.innoresearch.net/reports/ULTRACAPACITORS.htm)

\(^{26}\) [http://www.boston.com/business/technology/articles/2006/06/26/mit_research_may_spell_end_for_the_batt](http://www.boston.com/business/technology/articles/2006/06/26/mit_research_may_spell_end_for_the_batt)


\(^{28}\)
The main attraction of fuel cells compared to batteries for portable electronics use is their significantly higher energy density, initially probably only a factor of 2 higher, but ultimately maybe by as much as a factor of ten. Costs are expected to remain significantly higher than batteries for many years, so their use for low cost, remote sensor applications is likely to be limited. There are also still concerns about waste heat (DMFCs generally operate above 50°C) and cell contamination with small fuel cells used in consumer products, the latter being a concern for reliability in long term deployments.

Reliability and safety thus remain the prime barriers for wider fuel cell deployments.

2.2.5 Bio-fuel cells

This is very early stage technology, but there have been some developments, including some that ultimately might be able to use the small amounts of free hydrogen in the atmosphere to generate small amounts of electricity.29

2.2.6 Energy scavenging/harvesting

Most of the following power generation methods are likely to need to be used in conjunction with secondary batteries or super-capacitors to store energy for use at times when the harvested energy source is not available. In some applications, a battery may not be required if the sensor activity is mechanical event driven or flow driven.30

Solar

Solar systems need some degree of installation to ensure optimum orientation, particularly at UK latitudes. Currently the best silicon solar cells offer efficiencies in the mid 20% range, with low cost commercial cells being significantly lower than this. Solar cells are currently in short supply and prices are typically around $1.5/W. Demand for solar cells is growing rapidly, hence start-ups and major corporations are investing heavily in solar cell manufacturing plants which should result in significantly lower device costs in coming years.31

Emerging technologies are likely to improve efficiencies and/or lower production costs.32 As average sensor power requirements fall, the use of solar cells as a potential power source for indoor environments will become more viable.

Wind

As for solar cells, wind power requires installation and maintenance and is hence likely to remain a practical option only for larger sensors. Micro versions of wind generators are being developed that will have potential uses for powering sensors associated with gas flow systems, for example in the oil and gas industry.


30 http://sciencreview.berkeley.edu/articles.php?issue=12&article=smallenergy
31 http://www.sanyo.co.jp/koho/hypertext4-eng/0612/1219-1e.html and http://pesn.com/2007/05/02/9500469_RSI_Silicon_wins_MIT_contest/
33 http://www.g24i.com/faqs.html and http://pesn.com/2007/05/02/9500469_RSI_Silicon_wins_MIT_contest/
Water/liquid turbine

Small hydrodynamic generators for use with water and other liquids which generate around 100 mW exist now and could potentially be used in liquid flow sensor applications like pipeline monitoring, shower flow rate sensing etc.\textsuperscript{34}.

Vibration/Mechanical

EnOcean already have a range of low power RF transmitters that utilise their own electro-dynamic generator\textsuperscript{35} or solar energy sources. Kinetron\textsuperscript{36} have a range of micro-generators which are useful where motion is constantly or intermittently present, such as body worn sensors. Vibration energy harvesters already exist as components, including ones optimised for 100 and 120 Hz vibrations derived from mains powered equipment\textsuperscript{37}. Alternatively, Figure 2-20 shows a vibration sensor on a pipeline, from Perpetuum.

![Figure 2-20 Installed vibration sensor on a pipeline motor, from Perpetuum](image)

Miniaturised versions of both electromagnetic and piezo based vibration powered generators are being developed with a view to powering remote sensors which only need average power in the tens of nW to tens of uW range\textsuperscript{38}.

\textsuperscript{34} http://www.kinetron.nl/cms/publish/content/downloaddocument.asp?document_id=4
\textsuperscript{36} http://www.kinetron.nl
\textsuperscript{37} http://perpetuum.isonlinehere.com/resource/PMG17-100_dsheets.pdf
Thermal

Thermo-electric generators (TEG) utilising the Seebeck effect have been around for many years. The amount of electricity that can be generated depends on the available area of the hot and cold surfaces and the temperature difference between the surfaces. As the average power requirements for sensors fall, utilising TEGs as a power source may become a viable option in some situations. Researchers at IMEC in Belgium have demonstrated a prototype wristwatch-sized body heat powered TEG which generated approximately 100nW.\textsuperscript{39}

2.3 Sensor interfacing and calibration

Having looked at sensor elements and power options, we now look at the next step towards making a wireless sensor network.

There is a large gap between, on the one hand, producing a sensing element and, on the other hand, of successfully deploying that element in a network. In practice, the two major problems are:

- Firstly the lack of a standard sensor interface and
- Secondly that networking knowledge lies outside of the majority of sensor manufacturers’ core competences.

The knowledge that this was the case and that it was holding up the industry was what drove the creation of the IEEE1451 standard for smart sensors.

![IEEE 1451 functional diagram]

IEEE1451 specifies electronic data sheets and wired/wireless communications for sensor networks.

Electronic data sheets are contained within the smart sensors and define the sensors’ networking interface, its sensor type and its calibration data. This is shown in Figure 2-21 where sensors (called transducers or XDCRs) with analogue or digital inputs and outputs (I/O) – and even a sensor whose output format is not known to the user – are linked to their specific TEDS. In this way each sensor has a known interface and stores its own specifications meaning that the user need no longer know the lowest level details of the sensor and network implementation. It is easy to see why sensors conforming to IEEE 1451 are referred to as smart sensors. The interface to the sensor module (STIM) is a digital interface defined by IEEE 1451. Later sections of IEEE 1451 (1451.3/4/5) provide for the interface to the wider network to employ various forms of wired or wireless link.

The wireless parts of IEEE1451 (1451.5) simply reference the use of existing wireless networks, presently including 802.11, 802.15.4/ZigBee and Bluetooth. One of the strengths of IEEE 1451 is that the sensor network may be grown by enlarging the host network (Ethernet, 802.11 etc) rather than having to extend bespoke sensor links.

A large-scale confirmation of the usefulness of IEEE1451 is shown in its adoption by the SensorNet40 project in the USA. This project aims to link up sensors over the whole country, see Figure 2-22. IEEE1451 is used at the lower levels, plus SensorML is the higher standard language used in order that sensor data can easily be handled by web applications. The aim of SensorML is broadly analogous to the familiar HTML standard for specifying web pages. Both the IEEE1451 and SensorML standards remove barriers for the use of sensors by industry.

In summary the usefulness of IEEE1451 is that it creates defined sensor interfaces where presently none exist, it includes sensor data in an embedded manner and it connects easily to existing wired and wireless local area networks. An IEEE1451 wireless sensor network clearly possesses infrastructure, a point which we shall pick up later in chapter 3.

40 www.sensornet.gov
Figure 2-22  Many sensors, many networks from SensorNet using 1451 and SensorML (Sensors Magazine)
2.4 Application Examples

We next provide three application examples for WSNs and an example of equipment presently available from suppliers. The application examples cover:

- Environmental and infrastructure monitoring for transport
- Oil platform process monitoring
- Smart buildings.

These examples are useful context for both the technology and the market discussions which follow in later chapters.

2.4.1 Transport Environmental & Infrastructure Monitoring

An example of a major activity currently in progress which is looking to implement a large-scale sensor network is the EPSRC / DfT ‘MESSAGE’ project - Mobile Environmental Sensing System Across Grid Environments 41.

This is a £3.5m three-year research project started in October 2006 and is funded jointly by the UK Engineering and Physical Sciences Research Council (EPSRC) and the UK Department for Transport (DfT). The project team, lead by Imperial College London, includes researchers at Universities of Cambridge, Leeds, Newcastle and Southampton. The project also has the support of nineteen non-academic organisations from public sector transport operations, commercial equipment providers, systems integrators and technology suppliers.

The project is developing and demonstrating the potential of diverse, low cost sensors to provide data for the planning, management and control of the environmental impacts of transport activity at urban, regional and national level. This includes their implementation on vehicles and people to act as mobile, real-time environmental probes, sensing transport and non-transport related pollutants and hazards.

Three sensor platforms will be developed as part of the project, including a “smart-dust” network using ZigBee (see section 3.2) motes, a network that utilises both Wi-Fi (IEEE 802.11.g) and WiMAX (IEEE 802.16) technologies for communications and positioning, and a set of novel sensor designs. All platforms will integrate with a common data processing system.

This project links to other wireless sensing research, including the EPSRC ‘WINES II’ project (Wired & Wireless Intelligent Networked Systems), looking at deploying sensors to monitor infrastructure integrity in the London Underground (see Figure 2-23), water and major bridge infrastructure 42, and the National Transport Data Framework project, which is looking at building an integrated and coordinated data repository of transport-related data, including sensor data from highways and transport systems 43. WINES II sensor network field trials include monitoring on the London Underground, Prague, Barcelona and Madrid metros, the UK Humber Bridge and infrastructure sites of Yorkshire and Thames Water.

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41 http://research.cs.ncl.ac.uk/message/
42 http://www.rsd.cam.ac.uk/events/horizon/horizondocs/sw/2.3-Soga.pdf
43 http://www.ntdf.org.uk/
The overall objective of these investigations is to clarify the practical issues of using wireless sensors in real work environments.

### 2.4.2 Oil Platform Process Monitoring

Emerson Process Management in the US has recently successfully used its wireless products on the Statoil Grane offshore oil platform, to provide monitoring of wellhead and heat exchanger pressures. The Grane platform is located in the Norwegian sea of the coast of Bergen, Norway. Emerson offer a range of industrial process sensors for monitoring level, temperature and pressure, under their ‘Rosemount’ family, see Figure 2-24 and Figure 2-25. These use 802.15.4 wireless and wireless-HART standards, with each sensor powered by a replaceable lithium thionyl chloride battery. A five year sensor battery life is claimed with a one minute transmit rate.

The sensors operate as a self-organising mesh network and link to one or more wireless gateway devices. Gateway devices are not battery powered, but require 24v dc from a local supply.

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The SmartWireless network installed on the Grane platform employs 22 sensors that replace traditional manual pressure gauges. The wireless gateway was mounted outside of the main wellhead area, at an elevated location so that it could oversee the working area.

The installation and operating experience has been reported to be good. The crowded wellhead, which includes metal pipe work, metal walkways above and below, together with other metal obstructions, presented a challenging environment, but as new devices were added, sensors were reported as quickly and easily joining the mesh. Signal strength and consistency during the operational period were reported as being excellent.

The benefits of the WSN include continuous monitoring, in contrast to previous daily manual visits to the wellhead to take gauge readings. Continuous monitoring also allows staff to identify unusual conditions earlier and take action as needed to avoid more serious problems developing. Fast installation for adding additional wireless sensors is also cited, compared to up to two days where a wired sensor is used.

2.4.3 Smart buildings

Wireless sensors can reduce installation costs by up to 80% compared to wired sensor installation. This is particularly of benefit in applications in commercial buildings, both during new build and during upgrade to existing properties, when commercial building owners and inhabitants do not want problems of dust, paint, wires and contaminants (e.g. asbestos) to achieve more energy efficient ‘green’ buildings. WSN installations generate almost none of these.

According to ONWorld\(^45\), commercial buildings consume 20-40% of primary energy use and account for as much as 25% to 60% of all electricity used. Buildings account for 38 percent of CO2 emissions in the United States and over the next 25 years CO2 emissions from buildings are projected to grow faster than any other sector. Lighting, heating, cooling, and ventilation make up 57% of primary energy.

Therefore there is good incentive to improve the usage efficiency of lighting, heating and ventilation systems, both in terms of operational cost benefits to the owner and tenants, and in reducing the environmental impact. This can be achieved by making control and sensing more localised (requiring more sensors), by making individual sensors more intelligent, and by allowing many sensors to be monitored in an integrated manner as part of a more centralised control system. Many traditional building controls companies, as well as new entrants, see intelligent ‘automation’ of buildings as a leading application area which can benefit from wireless sensor networks.

An example is German company EnOcean\(^46\). Based on their range of battery-less sensors, energy


\(^46\) [http://www.EnOcean.com](http://www.EnOcean.com)
scavenging and radio modules, EnOcean provide systems integrators with the elements needed to build wireless sensor systems, particularly for the building and home automation markets. The system is based on operation at 868MHz, with typical operational ranges of 30m indoor/300m outdoor. Proprietary protocols and use of very small amounts of data provide energy efficient data bursts at 120kbit/s to allow battery-less operation.

EnOcean focus on the control of:

- Lighting
- Shading
- Presence detection
- Window monitoring
- Room temperature sensing
- Integration with other building sensors and monitored data

Figure 2-26 illustrates two devices, a solar-powered magnetic actuator for window frames, and a switch actuator for lighting control, powered by electromagnetic energy scavenged from the mechanical operation of the switch, i.e. the movement caused as the user presses the switch. The EnOcean wireless system is proprietary at 868MHz, rather than being 802.15.4 based, in order to get the absolute lowest power consumption for battery-less systems. 802.15.4 was designed from the outset to be battery powered.

![Figure 2-26 Wireless battery-less magnetic contact and switch actuators from EnOcean](image)

EnOcean cite of the order of 10,000 building applications installed since 2003, many in Germany but also in other European countries including the UK, plus Canada and Brazil. As an example, the UNIQA Tower in Vienna provided particular challenges for a conventional approach, with exterior and interior walls of glass (making cabling problematic) as well as requiring flexible room use. EnOcean provided 350 wireless temperature sensors and 100 receivers to assist room temperature control, installed in a cost efficient and visually acceptable manner.

Siemens Buildings Technology Inc. is another example of a building automation WSN provider, offering their ‘Apogee’ system using technology based on EmberZNetPRO from Ember Corporation, see Figure 2-27.

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Figure 2-27  Example of Siemens Apogee Wireless Room Temperature Sensor

The system operates at 2.4GHz using the 802.15.4 radio standard, with wireless room temperature sensors employing a 3.6V lithium battery with a nominal 5 year life, depending on configuration. Sensors communicate directly with local ‘Field Level Network Transceivers’, which then network together in a mesh configuration to link multiple sensors. Siemens Buildings Technology Inc. also provides a good example of an established sensors and control systems supplier that is developing their capability and product range to enhance the capability of their current systems.

Home Automation

In contrast to automation of commercial buildings, we note that the home automation market is progressing relatively slowly by comparison, with the market currently being more product-led than system-led. There is less evidence of the market being enabled by major stakeholders and end-users (house-builders, local authorities, building regulations bodies), but this may change in future with an increasing awareness and focus on environmental requirements and energy efficiency. zigbee is the radio system popular within US homes, which is less power hungry, but less capable than ZigBee.

2.4.4 Supplier Example

Having considered WSN applications, it is useful to next consider WSN supplier capabilities.

Sensicast/Adaptive Wireless Solutions provides an example of a complete WSN system supplier with real-world experience of sensor networks in industrial applications. Sensicast are typical of a smaller but well-established systems supplier in the WSN value chain (chapter 5) with a range of modules to build structured WSNs - gateways, routers, interfaces & sensing nodes, see Figure 2-28. Nodes are normally battery powered with system monitoring/management designed in, with the use of PC-based application-level software. The frequency used is 2.4GHz, using the 802.15.4 radio standard but with proprietary protocols.
Sensicast have implemented WSNs in a range of applications which provide further examples of current WSN usage. These include:

- **Steel works temperature monitoring**
  A US steel mill required rapid sensing of the water jacket of an arc melting furnace, to prevent melting of the furnace wall in a very short time should the furnace arc become mis-directed. This occurs around 8 times per year at a cost of around $42,000 in lost production. Sensicast deployed wireless sensing nodes to monitor the water jacket temperature and alert for hot-spots, integrated into the plan control system (this is an example of a very short latency requirement, where wireless sensors are active a significant percentage of the time). The payback period for the system was estimated by Sensicast at under 4 months.

- **UK hospital pharmacy and remote store temperature monitoring (10’s nodes)**
  A UK hospital required monitoring of both a pharmaceutical clean room and a second storage site located 350m away, to ensure appropriate storage temperature conditions to meet FDA requirements. Wireless sensors were used in a mesh configuration, both within the main site and to link the remote refrigeration site via an intermediate mesh node on a building roof. Benefits were speed and low cost of installation compared to alternative approaches, and practical integration with a existing wired FMS (Facilities Management System).

- **Data centre environmental monitoring in the Gulf states (200 nodes)**
  Temperature and humidity monitoring in a large data centre was needed to provide rapid alerts in the case of cooling failures to the network equipment racks to reduce facility downtime and risk of equipment damage. The complexity and cost of installing wired
sensors across three buildings and multiple floors was the leading reason to adopt a stand-alone wireless solution.

2.5 Case study – designing a real-world test bed

Building upon our earlier commercial examples, this section describes the real world design and deployment of a more forward-looking wireless sensor network, which is work in progress at the time of writing. Our interest here is more in the process of design and deployment rather than the ultimate end use. Nonetheless a real-world case study makes the process easier to understand, and this case study naturally leads us into having to consider personal privacy and security. After introducing the case study we will go into some detail over the selection process used to decide which commercial wireless sensor nodes to use in the project, i.e. which hardware and which software. This will introduce some new concepts and problems specific to WSNs, which are then clarified in later chapters of this report.

2.5.1 The application – a student class project in augmented social networking

In the research and industrial communities, there has been much interest in wireless sensor networks over the last decade or so, and the interest is increasing as wireless sensor hardware and software toolkits become increasingly available. However, there are still many challenges in physically deploying and using a wireless sensor network.

Here we describe the experience, so far, of deploying a wireless sensor network at the School of Computer Science at the University of St Andrews in the UK. In fact this program is part of a larger, heterogeneous wireless test-bed. The area of the planned wireless sensor network deployment is shown in Figure 2-29, although node locations are not marked since they are not yet known. However, the initial locations are likely to be university owned buildings. In the figure, the black shaded buildings are the university buildings and they are located throughout the city so allowing a good citywide coverage by deployment in university-owned buildings alone. Deployment possibilities in non-university buildings are currently being explored in order to extend the depth and breadth of the eventual sensing coverage of St Andrews.
So, if various sensor gateways are deployed around the University, and eventually the whole city, and if students carry personal wireless sensor nodes, they could then track other students’ movements in a coarse-grained manner. The degree of coarseness will be determined by the density of gateway devices.

The initial function planned for the test bed is ‘encounter tracking’ – to simply record when devices see each other. In order to investigate the use of this function, a student class project has been set-up to make use of the sensor information collected by the gateways and to interface this information to the ‘real-world’. The particular interface chosen is a popular web-based social networking system called FaceBook\(^49\). The students will track encounters, and build a social networking application augmented with location and person-person proximity/encounter information. This will allow them to investigate social group dynamics. The students must consider aspects wider than simply the sensor network information. For example, they might try to make observations such as models for mechanisms of behaviour within group interactions.

### 2.5.1.1 Privacy and security implications

Clearly, this has definite implications for personal privacy and security, and the students will investigate this wider aspect. Indeed, within ‘people-centric’ sensing applications, personal privacy and security issues are key considerations, including the location, use, storage and availability of personal information.

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\(^{49}\) [http://www.facebook.com](http://www.facebook.com)
This particular use of sensors is very topical. It is very likely that much sensor information within the built environment will have some relationship to the presence (or not) of people within specific areas. Potential problems arise since inferences may be drawn from such data, which may violate privacy. This may include violation of privacy in various ways that are not currently possible. Moreover, this can be the case even when the data being transported over the network does not have a direct link to any personal identity. For example, consider a building monitoring and management system that records usage of power or light in offices. This may allow an observer of that data to make accurate inferences of who was and was not in their office at certain times. This may not necessarily be desirable in all circumstances by the occupiers of those offices. On the other hand, the same information could be used to improve building security and safety applications, if used in the correct manner.

Returning to plans for the immediate test-bed, by using FaceBook users can control their own privacy through the normal privacy setting present in their FaceBook profiles without having to invent privacy models of their own. This is shown in Figure 2-30.
2.5.2 Considerations and constraints on the network

In the university work there exists a different goal and outlook to that of a commercial deployment, although the results of such university research work typically influence subsequent commercial implementations. So before describing the network design in detail, it is instructive to keep in mind the considerations and constraints, which will be particular to the specific research context and that will have shaped the design, planning and deployment decisions.

For each of the areas listed below, we highlight the differences and linkages between research and industrial aims, from the point of view of the designers.

- **Incremental scaling of deployment.** In contrast to, say, the deployment of wireless sensors in a ‘new building’ project where the sensors are likely to be embedded, we must necessarily plan for an incremental deployment and scaling of our network.
  
  Initial research explorations will be to gain experience with the hardware and software chosen. Also, the network will start off with a small number (e.g. perhaps only 6 to 12) of sensors and then it will be considered how these numbers will increase over time. So the sensor network will grow organically. In a building project, all the devices in the wireless sensor network are more likely to be deployed, commissioned and tested together and the network may not be required to scale beyond its initial deployment (because, for example, it is unlikely that the building will be enlarged). However, it is quite possible that a commercial installation will have incremental scaling needs.

- **Heterogeneity of hardware deployment.** If we again consider our new building example, it is quite possible that the heterogeneity of the types of devices deployed is quite limited.
  
  Specific applications, such as climate/environment management, safety, etc., may have need for only one or two types of sensor and this fact will be known in advance. In contrast, with a
research platform, serving perhaps many projects, looking at many aspects of the wireless sensor platform – from applications, to communication protocols to systems environments – there is likely to be a diversity of hardware. Indeed, in a Computer Science research context, a diversity of hardware may be considered very beneficial in order to achieve a rich environment in which to explore the information harvesting, data processing, data dissemination, communication and application interfacing issues that occur in sensor networks.

• **Diversity of applications.** With our new building example, it is quite likely that the applications are fixed when the building is designed and planned, and once commissioned, those same applications remain static in their operation throughout the lifetime of the building, and so of the sensor network.

In this research scenario the applications will change as the research moves forward and with work on different projects, and indeed it could be that the sensor network has to provide an environment for more than one application simultaneously. Also, it will need a control & management channel for allowing re-tasking of the devices as required for different experimental purposes.

• **Network stability and load.** In the new building, careful design and engineering consideration will have been given to the devices deployed, the likely topology and level of load in the network.

These considerations will be used to build a network design and operational configuration that is likely to lead to stable operation and predictable characteristics. Meanwhile, in this research scenario there is likely to be development and testing of new systems software, communication protocols and system architectures, so the network stability cannot be guaranteed. Additionally, in case the experimentation work results in system-wide states or device states that are undefined and hard to recover, there will need to be some sort of out-of-band (OOB) control & management channel (i.e. a secure ‘back door’) to the sensor devices so that there is a way of communicating with the devices and effecting control operations even when the device’s radio system is not useable.

So, overall, it could be argued that considering a research-oriented test-bed as a case study presents a set of scenarios for the wireless sensor network that really tests its capability, in a much more challenging manner than one might find in a commercial deployment.

### 2.5.3 Sensor network hardware

A bottom-up approach was taken in building the network, for practical reasons. It began by considering the hardware devices desired to be used and listing some non-technical requirements. None of the listed requirements below are essential but they all add to making devices more desirable for a deployment situation for research use and indeed for commercial use.

1. **Cost.** The devices should have relatively low cost.
2. **Availability.** The devices should be easily available, and continue to be so.
3. **Unlicensed usage.** The devices should be useable without requiring any form of licensing, e.g. for use of the RF spectrum, or for the use of firmware/software which is used or modified during the course of our work.
4. **Ease of use.** The devices chosen must be easy to program and must have software toolkits and/or APIs readily available.
5. **Recoverability.** If a program downloaded to the sensor device causes the device to enter into an undefined/unrecoverable state, there should be a mechanism available to restore it to some
well-defined state from where it can once more be used, e.g. restore to ‘factory default’ conditions.

6. **Used by other researchers.** It would be highly beneficial to use devices that are already in use by other researchers, so that each can draw on other people’s experiences, shared knowledge of operation and troubleshooting, and any shared code-base that may exist.

7. **Interworking and gateways.** It should be easily possible to allow interworking of the sensor devices with other convenient network technologies, e.g. Internet Protocol (IP) gateways for sensors allowing interaction between the Internet world and the world of the sensor network.

With this in mind, it was chosen to use a selection of hardware produced by the company Moteiv\(^{50}\). Moteiv’s Tmote family of hardware is based on 802.15.4 radios\(^{51}\).

The hardware devices chosen are as detailed below. There are basically three devices

- A Sky device which is a bare-bones radio transceiver with sensor options
- An Invent device, a Sky packaged with sensors and made to be carried by people
- A Connect device, which acts as the wired half of the gateway between Ethernet and 802.15.4

Let us look at these basic WSN components in more detail.

The Tmote Sky has no sensor pack and is the device intended to be used as an 802.15.4 base-station. It contains a low power microcontroller, and a 2.4GHz IEEE 802.15.4-compliant radio. An optional suite of sensors is available to fit to the Sky. It can be powered via USB or by 2x AA cells. The Sky is shown in Figure 2-31.

\(^{50}\) [http://www.moteiv.com/](http://www.moteiv.com/)

\(^{51}\) 802.15.4 and all the other technical aspects in the case study are covered in detail later in this report. Additionally we refer the reader to the glossary of abbreviations in an appendix to this report.
The Tmote Invent, Figure 2-32, includes the Tmote Sky module plus integrated light, temperature, acceleration, and sound sensors, and a rechargeable battery. The Tmote Invent is designed to be carried around by users.
The Tmote Connect is a gateway appliance for directly connecting Tmote wireless sensor modules to a wired local area network. It has no radio, but supports 2 Tmote Skys via wired USB connections\(^{52}\). Each Tmote Sky module connected to a Tmote Connect can be remotely administered through a web-based graphical user interface.

\(^{52}\) The Tmote Connect is actually a Linksys NSLU2 Networked Attached Storage (NAS) Device (i.e. an inexpensive compute node with an Ethernet port and 2 USB ports, running Linux), with the Tmote Connect Software installed.
2.5.4 System software

There is a choice of operating system software, which can be used with the Tmote Sky and Tmote Invent devices. The ‘official’ supported platform is TinyOS\(^53\). This was originally developed at Stanford University, but is now an open-source project with many contributors worldwide. Indeed, TinyOS has a large user base, and has a conference called the TinyOS Technology Exchange (TTX).

The other main option is Contiki\(^54\), developed at the Swedish Institute of Computer Science (SICS), which is also an open-source OS. This is also in widespread use, but mainly in Europe.

St Andrews has, for now, opted for TinyOS, as the Tmote Sky hardware (from its Telos origins) and the TinyOS have a longer history of being used together.

2.5.4.1 A real-world problem

It was decided to purchase the Moteiv hardware in February 2007. Various delays, at the supplier in the US, then at UK Customs, meant that the devices were not delivered until September 2007. On 16 October 2007, very surprisingly, the company that now owns Moteiv, Sentilla, issued an End of Life (EoL) notice on all the Moteiv products\(^55\), including all those listed above for the sensor network deployment.

While this in itself is not a ‘show-stopper’ it does highlight a practical reality of sensor network hardware – the hardware could well outlive the company that makes it. So mission-critical systems which are based on the use of sensor networks need to consider carefully the contingency plans for dealing with such situations. Such contingency plans need to consider every aspect of impact of the deployed devices, including maintenance of the existing deployed base (hardware and software), possible sources of replacement/alternative devices, and operation and management of a network with a mix of legacy devices and new devices.

2.5.5 Basic system configuration

The basic system configuration is actually very simple. A single Connect device is connected using Ethernet to the existing wired network running TCP/IP. A single Sky device is connected to one of the USB ports on the Connect.

This arrangement effectively forms a gateway between TCP/IP over Ethernet and the networking implementation over 802.15.4 on the Sky device. The Sky device can thus detect and transfer data to/from other devices (either other Sky devices or Invent devices) within radio range. Initial tests within one of the two Computer Science buildings in St Andrews suggests that effective radio range within a building is approximately 10m radius between devices. This basic configuration will be installed in various sites within the School. By March 2008, the expectation is to have installations in other University sites in St Andrews (e.g. Student’s Union, University Sports Centre and Gymnasium), connected via the University Ethernet backbone.

It is also expected to have installations in one or more local businesses, but it is not clear yet what the wired connectivity for those Connect devices will be – they may be isolated. In some cases, there may be an existing ADSL/broadband connection that could be utilised, but the other option being considered, especially if the gateways are isolated, is to use the Invent devices, which are carried by people, as ‘data mules’ in a delay tolerant network (DTN) scenario. That is, isolated

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\(^53\) [http://www.tinyos.net/](http://www.tinyos.net/)
\(^54\) [http://www.sics.se/contiki/](http://www.sics.se/contiki/)
\(^55\) [http://www.sentilla.com/moteiv-endoflife.html](http://www.sentilla.com/moteiv-endoflife.html)
gateways always collect data from encounters with other devices. Subsequently and opportunistically they would (attempt to) download such data to passing Invent devices. At the next suitable encounter, those Invent devices could then upload the data to a non-isolated gateway. In this way the Invent devices act like couriers, or data mules, and ideally the data eventually reaches the destination. Of course there is a probability that isolated nodes may never encounter a suitable opportunity to pass on their data, so ultimately the reliability and generally the latency of this approach is poorly defined.

Having introduced many WSN aspects in this section, we will now look at the areas in more detail in the remainder of the report. We begin by more clearly defining the different technologies involved, before moving to look closely at network architecture. Here we will note major capability splits between:

a) Networks which have infrastructure compared to those which are infrastructure free, and

b) Networks where all nodes are equal compared to those where they are not.