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A demonstration of wireless sensing for long term monitoring of water quality

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Abstract
At a time when technological advances are providing new sensor capabilities, novel network capabilities, long-range communications technologies and data interpreting and delivery formats via the World Wide Web, we never before had such opportunities to sense and analyse the environment around us. However, the challenges exist. While measurement and detection of environmental pollutants can be successful under laboratory-controlled conditions, continuous in-situ monitoring remains one of the most challenging aspects of environmental sensing. This paper describes the development and test of a multi-sensor hetrogenous real-time water monitoring system. A multi-sensor system was deployed in the River Lee Co. Cork, Ireland to monitor water quality parameters such as pH, temperature, conductivity, turbidity and dissolved oxygen. The R. Lee comprises of a tidal water system that provides an interesting test site to monitor. The multi-sensor system set-up is described and results of the sensor deployment and the various challenges are discussed.

Key-words; multi-sensor system, real-time monitoring, water quality, biofouling

I. INTRODUCTION

Environmental and water quality monitoring is key to measuring and understanding the chemical and biological quality of water and for taking reactive remedial action as appropriate. Over the coming years, monitoring of water bodies will increase within Europe, in order to comply with the requirements of the Water Framework Directive (WFD, Council Directive 2000/60/EC), [1-5] and globally owing to pressure from climate change. The establishment of high quality long-term monitoring programmes [6] is regarded as essential if the implementation of the WFD is to be effective [1, 7]. The ideal monitoring system of the near future might consist of a network of sensors deployed at key locations, capable of autonomous operation in the field for a year or more. [8-12]. Valuable insights have been given by Voigt and co-workers on how power management can enable longer deployment time. [13] The data from the monitors are communicated by wireless technology for processing and interpretation.

Summary of the research challenges

Although some elements of this ideal system are in place, ongoing research and development is required. The challenges are in overcoming the need for maintenance of sensors, the provision of a power solution to enable long-term deployments and in the development of robust sensors that can operate in aquatic environments. Table I outlines challenges and some solutions in meeting the needs of the users.

A. The Project

This exciting demonstration project represents an important collaboration between research centres, SME and local authorities with technical and analytical expertise to deploy, maintain and evaluate a series of multi-sensor systems to assess the effects of long-term sensor deployment on water quality monitoring systems and sensor data. In this process we collected a continuous data set of environmental and water quality variables from a number of sites to provide the necessary degree of spatial and temporal granularity of data.

B. User Requirements

As a result of consultation with potential users of sensor-based monitoring technology, a list of needs of users of water monitoring systems was developed and is shown in Table I.This process of engaging with users, involved a number of meetings with different user groups to allow them to state their needs regarding monitoring. While many systems have been developed in the laboratory, they may not have been fully validated in the field. The long-term deployment of multi-sensor systems in the field is faced with many challenges (table I). Besides fouling, on-line calibration of aquatic sensors, methods to reduce sensor drift, wireless technologies implemented and data aggregation are of high importance for remote sensors [12].

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TABLE I
DESIGN FEATURES OF A MONITORING SYSTEM AS IDENTIFIED BY USERS, THE CHALLENGES AND SOME SOLUTIONS

DESIGN FEATURE	COMMENT	CHALLENGE	SOLUTIONS
Robust sensors, monitoring module and ruggedisation	Sensor maintenance and housing are a major factor.	Sensor materials can be weak and susceptible to fouling or breakage.	Select good quality well validated sensors/
Low Cost	Cost will depend on networking requirements (real-time alerts or manual data collection) and sensor type.	Bringing the cost of sensors down to enable a low cost of ownership of the network.	High volume production driven by need, will bring the cost down.
Low Battery Maintenance	Battery life will depend on the sensor(s) type and monitoring frequency	To provide adequate power for long-term deployment.	Power harvesting approaches are becoming widely used e.g. solar panels.
Real-time data gathering from remote locations to a central server	Options available, depends on terrain – GSM/GPRS and WiMax.	The sampling locations are sometimes remote.	Employ drive-by or near-real-time data collection options.
Programmable sampling periods (continuous to days)	Will affect battery life.	To identify frequency of sampling needs.	This is driven by user needs.
Presentation and ease of handling data	Report generation and trending would be standard. Data will be presented in a format that can be readily imported to other systems.	To simplify the data collected for the user needs in relation to reporting requirements.	Use easy to understand web-based templates with visual representation of data.
Portability	Necessary for rapid re-deployment of sensor(s) from one sampling site to another.	Some autonomous sensors require a battery that adds additional weight to the device. However, this will restrict the size of battery to be used and hence the operating lifetime of sensor(s).	Employ robust systems & systems that provide sufficient data. No need for a full sensor suite in all situations.
Variable sampling frequency	To include a trigger mechanism which would change frequency of monitoring upon a change in weather conditions.	Depending on location the power needs may limit frequent sampling or there may not be access to wireless communications for immediate data download.	This is driven by user needs and will be user specific.

II SITE DESCRIPTION

A number of sites along the River Lee, Co. Cork, were selected which would be representative of the complete length of the river from estuary to source.

The SmartCoast demonstration looked at monitoring typical water quality parameters by deploying sensors, which:
- Measured water quality parameters;
- Collected and managed data;
- Communicated the results; and
- Activated responses.

The five monitored sites on the River Lee, extended from the Inniscarra reservoir to the Tivoli Docks in Cork city. These sites were selected as they represented a range of site types with different technical challenges and were scientifically interesting. The five sites are shown in Figure 1, and include:
- Inniscarra Reservoir (two sites);
- Lee Road;
- Lee Maltings; and
- Tivoli Docks.

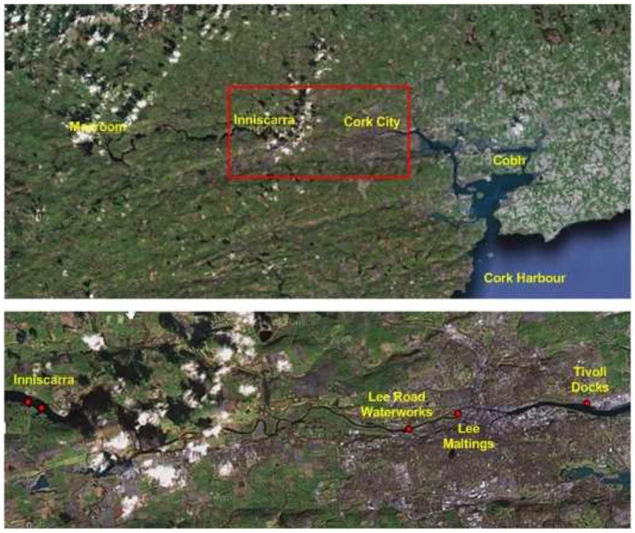

Figure 1. Locations of deployment sites for sensor systems

A variety of different sensors appropriate to the site and its particular deployment characteristics were deployed, such as ability to carry out sensor and system maintenance, access to power supplies, security of location and physical access characteristics. For instance the base station and pumphouse multi-sensor system were sited in a secure location, protecting the equipment; mains power was available (enabling high power consumption sensors to be utilized), and any system failures could be checked promptly.

The instruments were mounted on a combination of inshore sensor buoys complete with solar panel and power pack, as well as a variety of bank mounted systems with a variety of sensors and telephony systems

III TECHNOLOGY DEMONSTRATOR

The technology demonstration in May 2008, involved the integration of a group of water quality sensors into a distributed communication network, through interfacing them with the PSoC Plug and Play system, with Zigbee telemetry, capable of transmitting the data to the SmartCoast server, which processed the data for transmission to the web. The demonstration of a truly heterogeneous water quality monitoring networked system was one of the first of its kind in Ireland and showed how data could be collected from a number of locations and viewed in real or near real-time.

A. Sensor Interface

Sensor interface infrastructure (incorporating Programable System on Chip - PSOC technology) and data telemetry systems compatible with the Zigbee data transmission system were developed to enable data acquisition and dissemination. These were developed to be modular and versatile in the range of implementations they are capable of and implemented in single and multi sensor versions as appropriate and required by the deployment site requirements, through Tyndall “Stacking” technology [14].

A key component of the wireless sensor system is the implementation of intelligent sensors incorporating TEDS (Transducer Electronic Data Sheet), which allow the sensor to identify and describe itself to the control unit within the transceiver system. The TEDS is a machine-readable specification of the characteristics of the sensor, with the intention to easy sensor installation and replacement. This allows TEDS-enabled sensors to be interfaced with the systems in a Plug and Play fashion. This TEDS implementation is based on the IEEE 1451 standard and the sensor interface can be dynamically configured by the system allowing for: sensor modularity and compatibility, sensor aggregation, sensor inter-operability, sensor fault tolerance and dynamic calibration.

The PSOC system is used to create a generic sensor interface. It accommodates the output magnitude from the sensors and processes the data in order to make it generic for the communication and processing unit of the system.

The flexibility of the PSoC is shown and evaluated in aspects such as:
- Sensor Plug and Play:
- Standard I2C Bus:
- Multi-sensor interoperability: and
- Dynamic software configurable sensor conditioning:

In terms of power consumption, the goal is to minimize system power as much as possible. In order to achieve that, various solutions were evaluated. For instance duty cycling of wireless sensor nodes with long SLEEP times minimises energy usage. A case study of a multi-sensor, wireless, building management system operating using the Zigbee protocol demonstrates that, even with a 1 min cycle time for an 864 milli-second ACTIVE mode, the sensor module is already in SLEEP mode for almost 99% of the time. For a 20 minute cycle time, the energy utilisation in SLEEP mode exceeds the ACTIVE mode energy by almost a factor of three and thus dominates the module energy utilisation thereby providing the ultimate limit to the power system lifetime [15]

Table II.
TYNDALL MOTE POWER CONSUMPTION ANALYSIS

	Voltage (v)	Power Consumption (mW)	Time (sec)	Energy Consumption (mJ)	Ratio Duty Cycle (%)	% Energy Consumption
Active sensor and Radio	3.0	96.2	0.039	3.75	0.065	53.6
Sleep	3.0	0.054	60	3.24	99.93	46.4
Average	3.0	0.116	60.039	6.99	100	100

Table II provides detailed data of the calculated energy utilisation for the wireless sensor in both ACTIVE and SLEEP mode. The wireless system undertakes a full operation of sampling, processing and transmission in 864 ms. It is interesting to note that, although the transceiver has by far the largest power consumption, in this application, and contrary to the general opinion, some of the sensors dissipate significantly more energy than the transceiver.

To this end power saving strategies have also been implemented in the PSOC sensor interface including:

- Duty cycling low power operation modes of the PSoC: The PSOC is programmed into its lowest power consumption operation mode whenever the main processor requests, specifically, under slots of time in which the sensors are not being used;
- Optimising power consumption of the PSOC for each interfaced sensor: The PSOC software, or drivers to implement the plug and play and standard output data format, requires internal PSOC hardware configuration and software algorithms.; and
- Changing and switching of different operation modes of the PSoC: The Interface layer has to be able to switch back and forward between operation modes, consuming substantially different levels of power.
-

B. ZigBee Telemetry Layer.

The original Tyndall ZigBee revision 1 module was designed in 2004. Since then the module was used successfully in a variety of projects. However, areas for improvement of the module were identified to enhance its performance as a tool for monitoring water quality as part of a sensor network based WFD solution. For this reason, a redesign of the board was instigated to meet the demand for longer range of RF transmission with the original module, as well as other improvements. To increase the RF range of the module, the RF section of the circuit was carefully redesigned. To meet the low power consumption requirements of the deployment scenario envisaged, the communications mechanism being implemented in the system is Zigbee standard based. This enables ad hoc mesh networks of sensor systems to be implemented giving the required granularity of sensor information (spatially and temporally). The Zigbee standard enables low power consumption data transfer for Wireless Sensor Networks using the 2.4 GHz ISM band, at data rates of 250 kb/s.

The final enclosure is IP68 waterproof rated with appropriate sensor connectors.

Figure 2: Multi-sensor interface board with sensors

C. Sensors used

Off the shelf sensors from Global Waters were used to verify the performance of the multi-sensor system during the field trials:

WQ101 Submersible Temperature Meter;
WQ201 Water pH Meter;
WQ301 Water Conductivity Meter;
WQ401 Dissolved Oxygen Sensor;
WQ701 Water Turbidity Meter; and
WL400 Water Level Meter.

The multi-sensor system deployed (Figures 2 & 3) in the River Lee as part of the field trial was composed of:

- Generic interface board;
- Generic sensor interface or PSoC;
- ZigBee communications and processing platform; and
- Ruggedised casing.

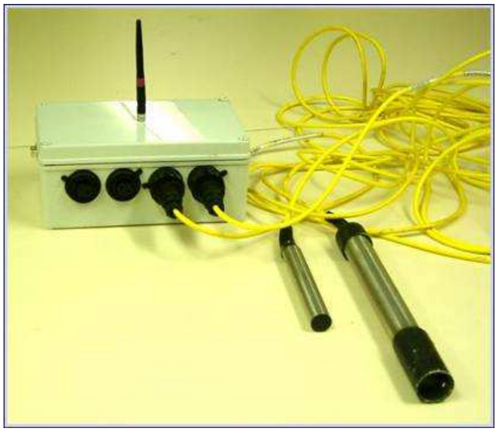

Figure 3: Sensor system ready for deployment

The interface board (Figure 2) was designed to be used in conjunction with the PSOC (the PSOC is mounted into the generic interface board and acts as a driver to interface with the sensors) and ISM band telemetry system to provide full control of the sensors, allowing for an on/off supply cycle, and therefore power management, and sensor plug and play connectivity. Thus, the smart interface board is required to supply the sensors with the appropriate voltage levels, to create a generic sensor interface, provide support for as many sensors as possible, and interface with the processing unit and wireless communication platform. The Plug & Play capabilities described in the previous section enabled by the developed Wireless Sensor Network (WSN) platform allow for the integration of any commercially available water quality sensors.

IV. SENSOR MAINTENANCE & BIO-FOULING

Sensor maintenance occurred regularly throughout the course of the field trial, with the length of time between sensor maintenance visits decided by sensor data readings observed on the project website and by the time of the year. Maintenance involved the removal of the sensors from the River Lee. Sensors were then gently cleaned and sensor readings were checked against available standard laboratory methods before being returned to the deployment site.

Biofouling can be defined as the undesirable accumulation of microorganisms, plants, algae, and/or animals on water-exposed surfaces. The effects of biofouling (see Figure 4) were noticeable within days of deployment and the sensors required regular maintenance during deployment.

Figure 4: Photographs of a fouled (top) turbidity sensor and (below) after cleaning the same sensor.

Biofouling can decrease the operating lifetime of sensors in the field and introduce a degree of error into the collected data. Frequently used mechanical methods of biofouling removal are not ideal for application in sensing – where power consumption is a limiting factor in deployment of devices for extended periods of time in the field. The antifouling research carried out at the NCSR involved the following:

1. Establishment of the nature of the biofouling process;
2. Development of mechanisms to test the degree of biofouling;
3. Design and development of novel materials that can be used on optical sensors and sensor platforms to reduce the effect of biofouling;
4. Testing of novel materials in the laboratory and in the field; and
5. Applications of materials to sensors.

Initial results in the laboratory indicated that by preventing the initial bacterial attachment to surfaces greatly reduces the impact of biofouling. This research is on-going.

Trends were observed in the data collected using the multi-sensor system arising from tidal changes, temporal variations and fouling of the sensors (see Figure 4). Fouling is a problem associated with all deployed aquatic equipment and over time is visible in a reduction of sensor performance and the smoothness of sensor readings as shown in Figure 5.

V RESULTS

A. Trend Observation

Over the course of the deployment, trends were observed in the data collected arising from tidal changes, temporal variations and fouling of the sensors. Figure 6 shows a time series over a three week period showing water level (feet) (red line), conductivity (mS) (green line) and turbidity (NTU) (blue line). It is important to note the relationship between the temporal changes in parameters, for instance, as one would expect in an estuarine environment there is a relationship between conductivity and water level.

When the tide is low there is a low level of saline water intrusion in the river and therefore the conductivity level falls, on the other hand, when the tide rises the water coming from the sea increases the conductivity as the salinity of the water changes.

A relationship was also seen between water temperature and a change in water level. Figure 7 shows changes in water level, temperature and ambient temperature over a two and half week period. This relationship is evident when the tide is low because the temperature rises as there is less inward tidal movement of the cooler sea water and the influence of warmer river water which is flowing outwards towards the sea.

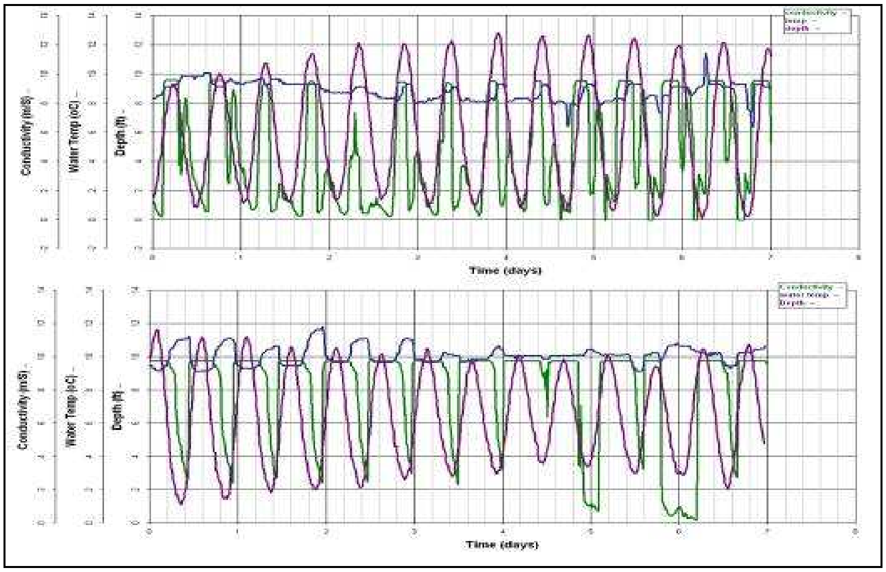

Figure 5 Changes in temporal water quality parameters in the River Lee, prior to (top) and after (bottom) sensor cleaning.

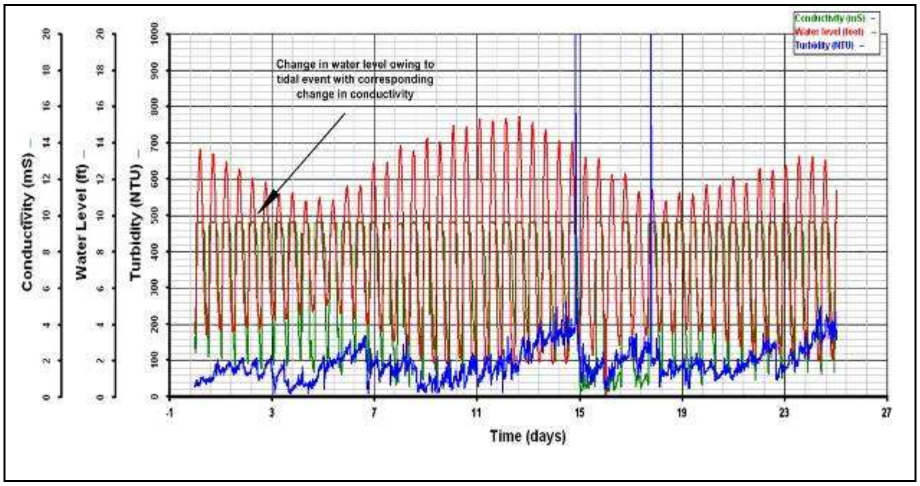

Figure 6 Change in conductivity (mS) and turbidity (NTU) with water level (feet) over a 24-day period.

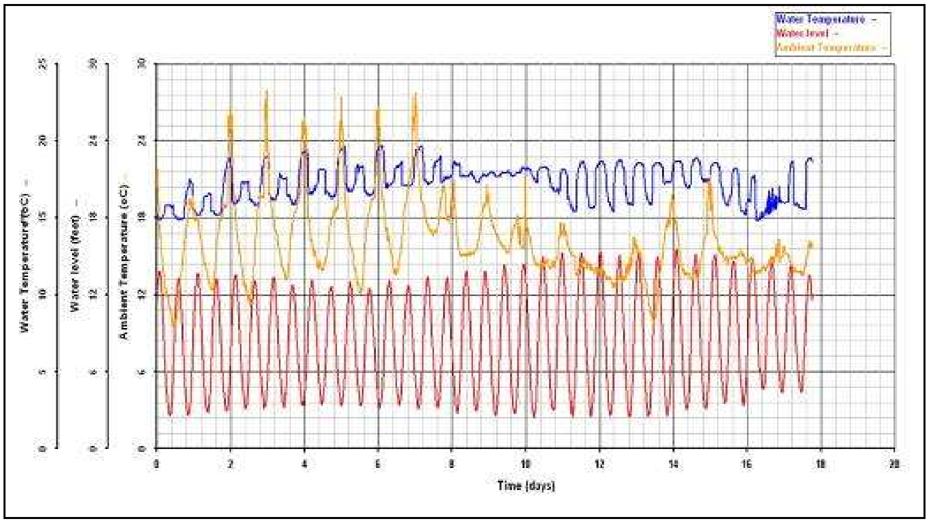

Figure 7 Changes in water temperature (ºC), water level (feet) and ambient temperature (ºC) over time.

B. Multi-sensor System Performance

Over the course of the deployment, certain sensors exhibited readings and values that would not have been originally expected. While the verification of the reliability of the off-the-shelf, third party sensors used in the deployed multi-sensor system was outside the scope of the project, it was assumed that they performed to their stated specifications. Over time the optical turbidity sensor readings degraded, possibly owing to biofouling and the data collected was not consistent with the levels that would have been expected. When this occurred, sensors were cleaned and checked to examine whether further maintenance was required or if there was a problem with the multi-sensor system.

VI CONCLUSIONS AND RECOMMENDATIONS

The capability and capacity building in SmartCoast meant that the project team gained knowledge in a number of key areas:

- Current monitoring status in Ireland and globally;
- Needs of the user;
- Issues relating to long-term monitoring;
- Communication capabilities currently available and communication needs;
- Data value, collection, interpretation and reporting; and
- Gaps in the area of water quality monitoring in Ireland.

The SmartCoast Project has highlighted the potential of wireless sensor systems, enabling the scientist to observe and monitor environmental variables of interest. Data from monitoring stations can be analysed and communicated by wireless technology, for statistical processing and interpretation by expert systems, from the office. The capability of the developed SmartCoast multi-sensor system to continuously sample and communicate up-to-date information, will enable monitoring costs to be reduced, while providing better coverage of long-term trends and fluctuations of parameters of interest. It is envisaged that the deployment of sensor systems similar to SmartCoast will allow a new approach to study the environment, new field methods to be conceptualised, and new solutions to scientific problems. Funding agencies should establish collaborative research efforts in areas of sensor development and related areas of work and facilitate the field testing of sensors over long periods of time. The ideal monitoring system of the near future might consist of a network of sensors, deployed at key locations, capable of autonomous operation in the field, for perhaps a year or more. Currently, the building blocks necessary to achieve the ideal scenario, of the measurement of multiple water quality parameters, simultaneously, in real-time are available. However, we need to improve the quality of some of our more sophisticated sensors for nutrients, while using the simpler devices in clever ways in embedded networks.

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