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A New WSN Paradigm for Environmental Monitoring and Data Collection

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Abstract—Data collection of environmental phenomena has traditionally been a very manual process. Even the advent of electronic data logging instruments has not significantly reduced the workload for managing instruments in the field. Recently however, low-cost microcontroller systems with wireless connectivity, called wireless sensor networks (WSNs) have been developed. With the proliferation of low-cost sensing elements, WSNs should be transforming environmental monitoring, but certain shortcomings in the current WSN paradigm have conspired against widespread field deployment. These are: battery capacity limitations; specialised wireless protocols that exclude WSNs from direct integration into existing data networks; and closed rather than open and extensible designs. In this work we investigate the effectiveness of a new paradigm for remote data collection systems; employing alternative power sources to significantly extend the service interval, WiFi wireless communications to simplify remote management, and open-sourced design to enable customisation and extensibility. We conduct a direct in situ comparison of WiFi and similar ZigBee radios, evaluating signal range and battery utilization under various sensor and radio configurations.

Keywords—Wireless sensor network; environment; monitoring

I. INTRODUCTION

The collection of environmental data is a rapidly expanding undertaking. Increasingly, up to date information is being required for a range of environmental phenomena. This is a well recognised occurrence, Australia's State of the Environment recording that "Australia needs to apply a more systematic approach to environmental data collection and monitoring" (in NLWRA 2001; Beeton et al. 2006; Campbell 2006) [1]. Unfortunately, the systematic collection of data is no easy matter; and an effective mechanism is nowhere on the horizon. Revenga, Campbell, Abell, de Villiers and M Bryer; find that the collection of environmental data on any scale is problematic, with data gaps, because of limited sampling, being a real and ongoing issue [2]. The problem becomes even worse in "the global scale since in some countries, especially developing countries, there are as yet no bio-assessment data"[2].

The likelihood of a suitable solution to the global problem of inadequate environmental monitoring arising without a significant technical advance is very low.

II. MOTIVATION FOR CHANGE

Currently, the environmental data of interest is generally being collected through the use of standalone measurement devices and by utilising data logging instruments. This is a very laborious and repetitive undertaking. For example when undertaking water quality measurements, the practitioner is required to perform the following; 1) repeatedly travel to some field location to retrieve the collected data from a data logging device, 2) change or charge the batteries, and 3) conduct an inspection of the instrument, site and environs. Between times, the practitioner has no way of knowing whether the device is capturing readings correctly, or whether it has failed in service or whether some kind of unexpected event has taken place, which may invalidate the entire operation.

Clearly a great scope exists for improving data collection dramatically by automating this crucial process. Various attempts at providing a technological solution have been proposed in recent years, with wireless sensor networks (WSNs) being by far the most promising technology to date.

WSNs potentially provide automated remote sensing and monitoring capabilities for a variety of physical phenomena. The range of low-cost sensors which are available, include; 1) temperature, 2) barometric pressure, 3) humidity, 4) alcohol, 5) carbon monoxide, hydrogen, propane and methane gases, 6) optical dust, and 7) pH; three of which are shown in Figure 1.



Figure 1. Typical sensors: methane gas, barometric pressure, humidity

WSNs typically provide a small amount of capacity for pre-processing, and can deliver their collected data through various wireless protocols; including IEEE 802.15.4, ANT, and Bluetooth amongst others.

Various commercially manufactured and supplied WSN nodes (called motes), are available in the marketplace. These include; TelosB, MicaZ, SHIMMER, IRIS, Sun SPOT, and EZ430-RF2480/2500. Even though these systems generally offer a great deal of promise for automating the tasks of environmental monitoring, their rate of take-up and deployment in the field has been relatively slow. Various factors account for this slow acceptance, including; 1) use of unfamiliar or proprietary wireless protocols, 2) short battery life, 3) closed, un-customisable and un-extendable designs, and 4) relatively high installed unit cost.

These shortcomings of the commercial WSN motes are an inherent limitation of the prevailing WSN paradigm. While the devices are typically well-finished, and perform satisfactorily within their assumed design criteria, any implementation based

on these devices is bound to be constrained by the limitations of the paradigm. For example, the purpose designed enclosures, the on-board sensors, and the presence of internal batteries, are typical self-limiting factors found on a given mote. Even though aftermarket enclosures can be sourced and external batteries and sensors can be fitted; some modifications, such as changing the radio remain an impractical undertaking. Customising any mote derived from the prevailing paradigm is a clumsy process, and is arguably an implicit acknowledgement of the shortcomings of the paradigm itself.

In this research work, we challenge the prevailing paradigm and propose a far more accessible and easily used system. Our aim is to develop a suitable system which integrates existing commodity components in a cost effective manner; and provides a platform which has broad appeal, attractive to even the most cash constrained environmental practitioners.

III. DESIGN

In the following section we present the design of a slightly larger footprint, open-source hardware mote, based on common off-the-shelf commodity components (COTS).

A. Overall Structure

The foundation of our design is the Arduino Uno microcontroller platform [3]. This selection deliberately exploits the presence of a large body of technical literature and documentation and leverages the range of low-cost and widely available components.

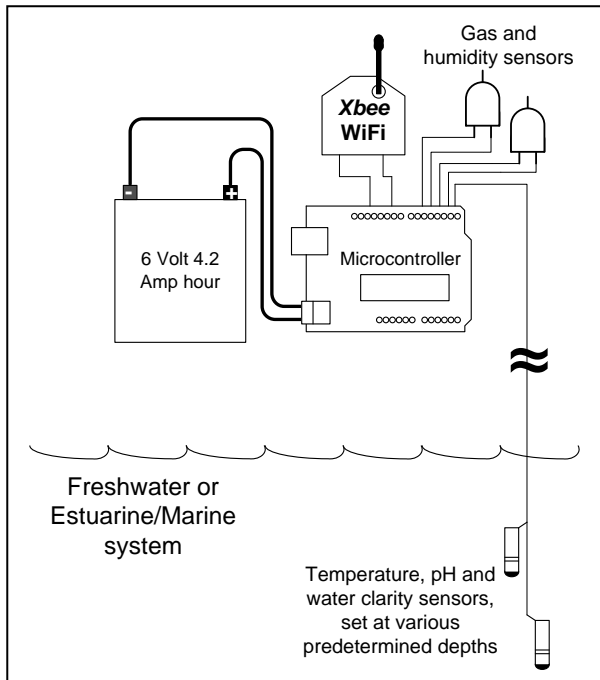


Figure 2. Layout of the various system components

These components include a variety of low cost sensors. Wireless connectivity is achieved by RN-XV WiFi XBee-socket compatible radios, enabling integration into existing

wireless networks through the use of the industry standard IEEE 802.11b/g protocols. In addition, we provide for dramatically extended service life through the use of sealed lead acid (SLA) batteries. The key departures away from the current unsuccessful paradigm for WSN motes are:

- The comparatively high capacity SLA battery, rather than low capacity, dual or quad AA battery packs;
- The use of the industry standard WiFi IEEE 802.11b/g radios instead of the usual IEEE 802.15.4 radios; and
- The use of open source hardware rather than closed proprietary hardware implementations.

In this research we implemented various WSN topologies in order to conduct a direct comparison between the dominant wireless types, and battery technology, and to investigate optimal WSN mote configurations. A simplified block schematic of the proposed wireless sensor network node design is presented in Figure 1. In this diagram we show the approximate relative sizes and positioning of the various components including; the Arduino Uno microcontroller, the sealed lead acid (SLA) battery, and gas, humidity, temperature and pH sensors.

B. Components

In this section, each of the major components of the mote is presented in further detail.

1) Wireless Radios

The radios chosen for the comparative testing (Figure 2) are Digi International Inc.'s XBee Series 2 Zig Bee IEEE 802.15.4 compliant radios (\$25.95USD), and the Roving Networks' RN-XV WiFi IEEE 802.11b/g compliant radios (\$34.95USD).

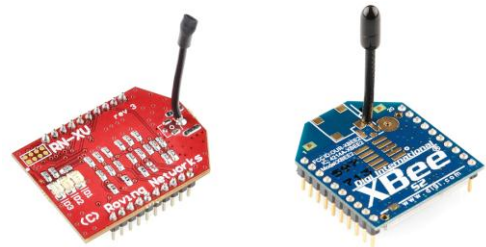


Figure 3. Roving Networks RN-XV and XBee Series 2 Radios

The RN-XV radios have the same footprint and are a drop-in replacement for the Digi XBee IEEE 802.15.4 radios. The RN-XV module has a wire antenna installed, though; chip, U.F.L., and SMA connectors are also available. The radio inside the module is the Roving Networks' RN-171 Wi-Fi unit. The radios are IEEE 802.11b/g compliant. They have an on-board TCP/IP stack and are WiFi Alliance certified for WEP, WPA and WPA2-PSK.

Because the RN-XV modules are socket compatible with the XBee units, direct comparisons are very straightforward, usually requiring only subtle changes and a recompile of the code [4]. However the interface boards employed in this work (voltage regulated Sparkfun XBee shields), expect a pull-up resistor on the Din pin. The resistor is present on the XBee but

not the RN-XV. Installing a 10kΩ resistor between the Din and Vcc pins on the RN-XV solves the problem when using the XBee shield [5]. Both radios operate in the 2.4 GHz range.

2) Sensors

The temperature sensors are a waterproof DS18B20 programmable resolution, 1-wire digital thermometer [6]. Each thermometer has a unique identifier, enabling multiple devices to co-exist on the same bus. Costs are \$9USD.

The humidity sensors are a HIH-4030. Current draw is very low at 200 μA. Cost of the sensor is \$17USD.

The MPL115A1 barometric pressures sensors measure a range of 50 - 115 kPa. At a once a second measurement cycle, the current draw is 10 μA. Cost of the sensor is \$25USD.

The MQ-4 methane, MQ-6 LPG, MQ-8 hydrogen sensors draw nearly 0.2 A. Costs are \$5, \$5 and \$8 USD respectively.

3) Battery

The batteries employed in the this project are the DiaMec 6 volt 4.2 ampere hour sealed lead acid battery [7]. The batteries are less than \$14USD each.

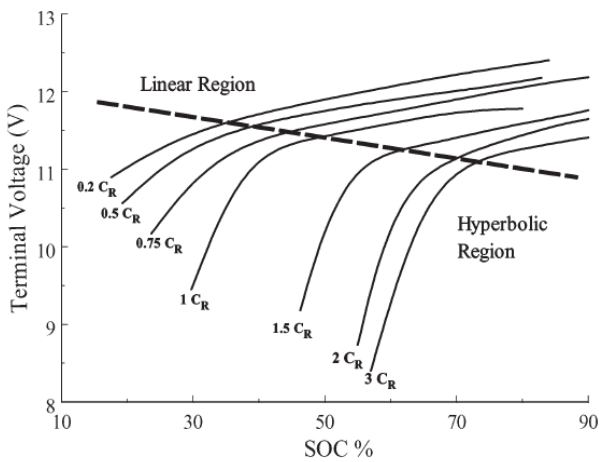


Figure 4. Load voltage of 12-V 17.2-Ah VRLA battery under different C rates versus SOC [8]

The discharge profiles of sealed lead acid batteries are well defined. Research shows (Figure 4) that the "terminal voltage curve of a battery measured under a constant current load discharge for different C rates has two distinct regions or slope inclinations over state of charge (SOC) and time" [8]. Where C rate (C_R), is the factor of current load in comparison to its maximum ampere-hour capacity Ah_{MAX} , as shown in (1).

$$C_R = \frac{I}{Ah_{MAX}} \quad (1)$$

As the state of charge on the battery is proportional to the output voltage, the state of charge of the battery can be approximated by monitoring the terminal voltage.

Referring to the manufacturer's discharge curve, a low discharge rate ensures extended linearity and a trustworthy correlation between voltage and stage of charge. From Figure

5, it is evidenced that maintaining the voltage above 6V at low discharge rates, ensures that the battery is well above the discharged state. Discharge tests carried out utilising various mote configurations, subsequently confirmed the very linear discharge curves for these batteries (Section V-2).

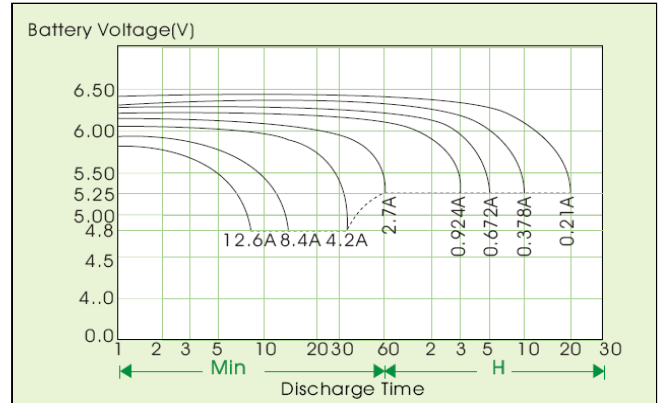


Figure 5. Manufacturer's discharge curves for batteries [7]

Maximising the service time of the Arduino based mote is achieved by adding solar panels to trickle charge the batteries in situ. The solar panels provide 100 mA at 12 V, and cost \$10USD. Supply voltage for the Uno is 6 - 20 V, with 7 - 12 V preferred.

4) Arduino Microcontroller

The Arduino Uno was deployed because of its wide market acceptance, well-understood open-source hardware design, and low unit-cost. The Uno's configuration is as follows:

- ATmega328, 16 MHz microcontroller ;
- 32 KB flash memory;
- 2 KB RAM;
- 14 digital input/output pins; and
- 6 analog input pins.

The Uno is programmed using an open-sourced integrated development environment (IDE), utilising a simplified C-like language.

C. Network Design

The two network topologies employed in this research are the ZigBee and WiFi star topologies. The ZigBee topology is displayed in Figure 6 showing the three categories of devices employed in this structure, the coordinator, the router, and the end devices [9].

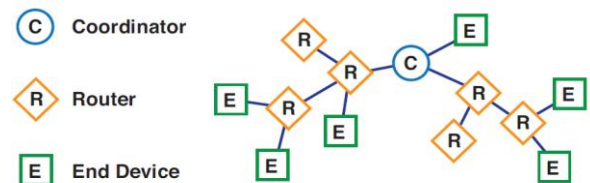


Figure 6. ZigBee network topology [9]

The WiFi topology is a standard star configuration, shown in Figure 7. A single base service set is employed with one base station (access point) and multiple end devices (Arduino motes with RN-XV radios). This topology is based on a centralised access point, which controls the membership and access to the network for each WSN mote.

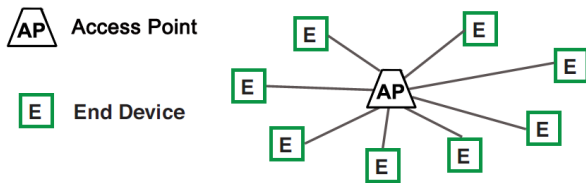


Figure 7. WiFi network topology

The access point also acts as gateway to any external network, such as the internet or organisational network as required. The access point (WiFi) and coordinator (XBee) are each supplied by mains power, as their service life in both instances is too short when supplied by battery power alone.

Other proprietary protocols with advanced self-healing topologies exist, such as Digi Mesh for XBee. Such protocols eliminate the need for an always-on coordinator and better supports the extremely large number of motes expected (>100s) under the prevailing paradigm [10]. However these topologies and protocols have no applicability to this research as the gateway nodes (coordinator and access point respectively) are never powered off and typical environmental installations utilize less than 20-25 motes, enabling the use of standard protocols such as IEEE 802.11b/g.

IV. IMPLEMENTATION

The test network was implemented on the central lake within the Joondalup ECU campus. The lake is approximately 120 meters in length, and 50 meters at its widest point. The lake is regularly monitored for water quality, with eutrophication and algal blooms being closely controlled.

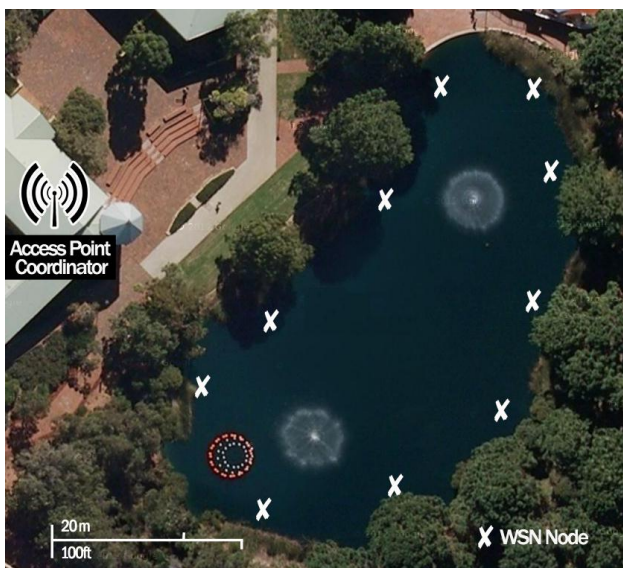


Figure 8. Overall sensor node layout at the lake

Ten active Arduino based motes were deployed as WSN nodes driving the waterproof temperature, humidity, gas, and barometric pressure sensors. In Figure 8, we show the location and overall sensor/mote layout of the environmental monitoring system implemented as part of this research work.

All motes are configured as router/end devices in the XBee environment, and as end devices in the RN-XV WiFi environment. Each mote is configured with two DS18B20 temperature sensors, and one of either a hydrogen, LPG, or methane sensor. Only three of the higher cost of humidity and two barometric pressure sensors are deployed, one of each at the end motes and extra humidity sensor on the middle mote.

The motes collect and forward the captured data to a coordinator node or access point, for the XBee and RN-XV WiFi configurations respectively. The access point is a Belkin F5D7230-4 Router / Access Point, supporting IEEE802.11b/g protocols. The maximum distance from mote to access point or coordinator is less than 100 meters.

V. TESTING

Various tests were conducted in order to determine power consumptions, battery discharge interval, and wireless range testing. Component costs were also determined. The results of these investigations are detailed below.

A. Power Supply Testing

A selection of tests was conducted in order to determine system service duration. The tests included:

- continuous operation, no transmission;
- continuous operation, continuous transmission;
- various duty cycles with wireless sleep mode when not transmitting; and
- various duty cycles with matching transmission time.

1) Methodology

The power consumption of the various components was verified by direct measurement under operating conditions. Current was drawn from an Agilent E3630A power supply. A selection of Arduino Uno R2s and R3s were deployed for the tests, demonstrating a maximum power consumption variance of approximately 2%. Throughout the tests we utilised the object code developed for driving the connected sensors. The tests were conducted in the first instance without the radios being connected, in order to assess the current draw for the Arduino and sensors alone. In the second phase, power consumption tests were conducted with the sensors installed and correctly configured; and transmitting the data. The consumption figures obtained from these tests mirrored the published power consumption figures very closely.

a) Arduino R2/R3 Power Consumption

Under normal operating conditions, the Uno draws approximately 47 mA.

Power draw when in sleep mode, and not using the USB and FTDI circuitry is under 10mA. [11]

b) XBee Power Consumption

The XBee Series 2 radios have a power consumption of approximately 40 mA under normal operating conditions. The powered-down sleep mode current draw is 1 μ A [12].

c) WiFi Power Consumption

The RN-XV radio has similar power usage as the XBee, except during transmission which requires 180 mA at 10 dBm. Digi publish a claim for potential battery life expectancy of more than one year with XBee radios, in contrast to battery expectancy of 1 week with WiFi [9]. In our tests it is clear that the power consumption of the XBee and RN-XV, while transmitting and receiving are of a similar order of magnitude. The claim that XBee radios are significantly more power frugal than WiFi radios cannot be substantiated. In order to achieve extended battery life, both the XBee and WiFi radios must be put into sleep mode for the majority of time, and only woken up when they are required to transmit data.

Devising sophisticated algorithms, which govern every aspect of the wireless sensor node operation, including: microcontroller and radio sleep patterns; and data collection and storage patterns; and data transmission patterns, is the key factor in extending battery service life in the field.

TABLE I. POWER UTILISATION FOR ALL COMPONENTS

Device	Power Consumption	
	Description	Power mA
XBee Series 2	Sleep mode	1
	Receive mode (/ boost mode)	35 / 40
	Transmit mode (/ boost mode)	38 / 40
Roving Networks WiFi RN-XV	Sleep mode	4
	Receive mode	40
	Transmit 10dBm	180
DS18B20	Temperature sensor	9.7
HIH-4030	Humidity sensor	0.2
MPL115A1	Barometric Pressure Sensor	0.005
Gas Sensors	Hydrogen sensor MQ-8	180
	LPG sensor MQ-6	170
	Methane sensor MQ-4	175
Arduino Uno R2	Microcontroller Operational	47
	Sleep mode	10

a) Sensor Power Consumption

The measured power consumption of the temperature sensors is approximately 7.1 mA per device. The power consumption of the gas sensors is nearly 0.2 A per device, a very significant current drain which is greater than the cumulative total of all the other devices.

2) Battery Discharge

The batteries were tested by deploying fully configured Arduino based motes (less gas sensors), and operating each at

full wireless transmission power from a DiaMec 6V battery. The motes were successfully operated for a period of over 40 hours, down to a final terminal voltage of 6V, on a single charge. A graph of the discharge over a 40 hour period is presented in Figure 9 below.

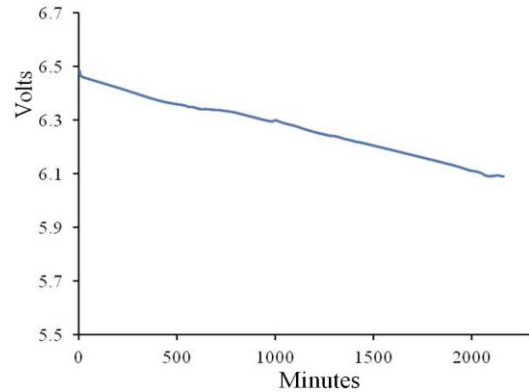


Figure 9. Battery discharge testing

B. Wireless Comparison

A selection of range tests were conducted comparing the operational ranges of the XBee Series 2 and the RN-XV WiFi 802.11b/g radios. All testing was conducted with the Arduino based motes measuring temperature and operating off the 6V DiaMec batteries. The tests included:

- ZigBee radio, point to point; and
- WiFi radio, point to point.

The results of the range testing are presented in Table II below.

1) XBee Line of Sight

The XBee Series 2 radio has a manufacturer's rating of 120 meters line-of-sight [5]. The XBees demonstrated an effective range in excess of 220 meters.

2) WiFi Line of Sight

The RN-XV radio has a manufacturer's rating of 100 meters line-of-site. A far greater range was achieved during testing; though the connection tended to become unstable beyond 150-175 meters. The domain host configuration protocol (DHCP) service providing the automatic IP address, which is hosted by the access point, also presented problems at the extended distances. The devices had difficulty regaining an IP address once a connection was lost above 150-175 meters. This effect was likely to be the result of a combination of factors, including: the prevailing noise floor, and the limitations of the commodity access point.

The XBee radios demonstrated a superior ability to recover from a break in transmission over the DHCP enabled RN-XV devices. In standard configuration the XBee also provided a greater workable range than the statically configured RN-XV. However additional tests conducted with high gain dipole (access point) and parabolic antennae (mote), demonstrated that IEEE802.11b/g can provide suitable connectivity at distances in excess of 2500 meters clear line of sight. This is

significantly further than Digi's published maximum range of 1000 meters for the XBee, and markedly strengthens the case for the new open-sourced environmental monitoring paradigm.

TABLE II. TRANSMISSION RANGE

Device	Overall Range	
	Description	Meters
XBee Series 2	Point to multipoint	200
	Point to point	220+
Roving Networks WiFi RN-XV	Point to multipoint (Static IP)	210
	Point to point (Static IP)	210
	Point to multipoint (DHCP)	158

C. Cost Comparison

The stated aim of exploiting the presence of low cost commodity microcontroller and radio devices was achieved by focusing on the open sourced Arduino Uno microcontroller platform. Several other microcontroller devices (such as the Arduino based Lillypad, Fio or Fretronics; or the Stamp modules, or the recently released Raspberry Pi) would also have served our purposes adequately, however the Uno presents several distinct advantages. These include the widespread availability of standardized components and the range of documentation and support. The costs of the commonly available WSN motes are listed in table III [13].

It is apparent that only a relatively small price differential exists between the bare motes supplied by the respective manufacturers. For various reasons the presence of on-board sensing elements on devices such as the TelosB, are of no practical advantage in environmental monitoring. 1) The Arduino motes can be deployed with sensors selected to suit the particular monitoring condition precisely. 2) Much more flexibility of operation is available with the externally attached sensing elements. 3) Rarely do the conditions require the sensing to be localised around the installation of any given mote. 4) The onboard sensing elements are often rendered unusable once the mote has been deployed in a waterproof field enclosure.

VI. CONCLUSION

In this paper we present the case for a new paradigm for wireless mote for environmental monitoring, based on common off-the-shelf commodity microcontroller components. This new paradigm presents a compelling, low threshold entry point into the sphere of fully autonomous, and self-managed environmental data collection systems.

The Arduino Uno can form the basis of such a paradigm; being widely available, having a large range of accessories, and supported by a very active development community. On the small to moderate scale monitoring operation of up to 20-25 motes, the most suitable network topology is the star. Either the IEEE802.15.4 coordinator/router/end point, or IEEE 802.11b/g WiFi (base service set) model is suitable. Advanced topologies, with self-healing features, do not provide any significant benefit at this scale. The well understood WiFi based systems

have additional benefits, being easily integrated into existing networks; and providing a convenience that is hard to match with other protocols. Finally; a change to larger capacity and cheaper SLA batteries, along with solar power charging units, enables the service times to be extended indefinitely, in a manner which is well suited to the collection of field data.

TABLE III. COST OF MOTES

Mote	Description
TelosB	US \$99 (no sensors), US \$139 (with sensors)
MicaZ	US \$99 per mote
SHIMMER	SHIMMER base boards are EUR 199, which includes base board, battery and enclosure.
IRIS	US \$115
Sun SPOT	3x base boards, 3x enclosures, 2x sensor boards and 2x batteries Development kit US \$750 / \$299 Educational
EZ430-RF2480/2500	The Z-Accel Demonstration kit for the EZ430-RF2480 series boards costs US \$99 per kit. (3x ZigBee motes)
Arduino Uno, ZBee / WiFi	US \$30 + \$35 Radio + \$10 Interface boards = \$75

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