Wireless Underwater Power and Data Transfer

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***Abstract*— This work investigates whether a contactless, wireless underwater coupling could be developed for underwater sensor networks. This requires the wireless transmission of power from the sensor hub to the transducer module, and the two-way wireless data communication between hub and transducer. Results from a trial deployment of systems with conventional waterproof couplings show that these are a major shortcoming of existing systems. Experiments are conducted which demonstrate that a Zigbee transceiver, operating in the 2.4GHz band, can communicate with low error rates up to 40mm at low RF power (-25dBm) and up to 70mm at higher power (-3 dBm) in seawater. Ranges are slightly higher in fresh water. Inductive power transfer, using a split transformer design, can transmit low power, in the 50-100mW range with efficiency of approximately 50%, demonstrating that wireless sensor couplings are feasible.**

***Index Terms*—underwater, marine, sensor network, wireless communications, inductive power transfer**

I. Introduction

Wireless Sensor Networks (WSNs) have been used extensively for terrestrial monitoring of the natural and built environment [1]. Such networks consist of a collection of sensor nodes which combine sensing transducers with a sensor hub that provides computation and data storage, power supply and wireless communications. System flexibility and modularity are improved if there are standard physical, electrical power and data interfaces between the hub and the sensing transducers [2]. IEEE has developed the IEEE-1451 series of standards for Smart Transducer Interfaces [3], although this standard has had very limited commercial uptake.

The goal of this project is to investigate whether a contactless, wireless underwater coupling could be developed for underwater sensor networks. This requires the wireless transmission of power from the sensor hub to the transducer module, and the two-way wireless data communication between hub and transducer. Both the host and transducer parts of the coupling would be in close physical proximity, with some form of mechanical connection joining the two sections. However, there is no penetrating electrical connection between the two halves of the coupling, enabling sensors to be disconnected and new sensors to be reconnected in-situ underwater. Figure 1 shows the proposed underwater coupling design based on inductive power transmission and *radio frequency* (RF) wireless data communication.

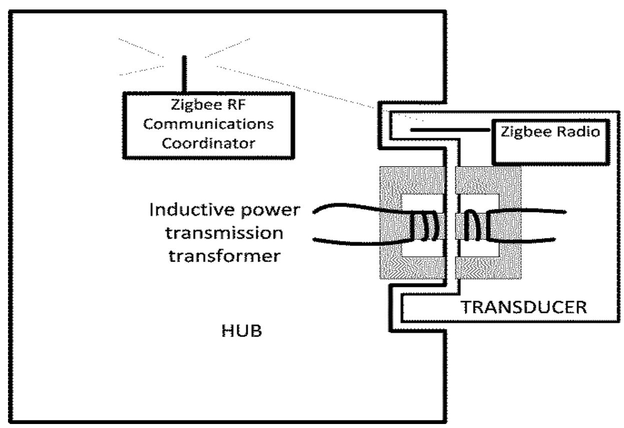

Fig. 1. Wireless Transducer Coupling Architecture

II. Lessons from SEMAT

This work is part of the *Smart Environmental Monitoring and Analysis Technologies* (SEMAT) project which aimed to investigate the design and use of low-cost, rapidly-deployed marine sensor networks [4]. A number of deployments for a few weeks at a time were used to test a series of sensor network designs which combined low-cost and adequate reliability and robustness. Of particular interest to this project are the results of a deployment of surface buoys, with suspended sensor strings, on Deception Bay, near Brisbane, Australia. The submerged sensors were built by modifying existing data loggers. The trial identified the following shortcomings:

1. Unreliable Sensors: 86% of the loggers failed during the one month deployment. The main reason was that the cables employed were not designed for underwater use. Cables either

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broke due to tidal and wave motion, or else they suffered damage to the insulation allowing water to leak internally down the cable into the sensors. Connections to some sensors were broken at the cable entry point.

*2. The design of the buoys disallowed 'hot swapping' equipment in the fiel*d. Devices such as sensors, antennas and processing components could not be swapped out in the field. This also prevented the replacement of damaged antennas and sensors in-situ during the deployment.

3. Not all of the equipment could be completely powered down in between duty cycles. This placed a constant drain on the power system of the buoys. On overcast days, some nodes' power supplies were exhausted and data communications with the land station was lost.

4 Biofouling of equipment affected measurement accuracy. This was most detrimental to the light sensors. The low-cost sensors used do not provide anti-fouling mechanisms such as wiper blades to disturb settled sediments [5]. Because of point 2 above, fouled sensors could not be swapped out.

5. The mooring system was not particularly robust. During the deployment, Deception Bay experienced unusual wave action (up to three metre waves). One node broke its mooring and washed ashore. Another buoy was struck by a boat.

6. There was insufficient data quality assurance and error alerting. This was a design problem that can be fixed by enhanced software on the sensor hubs.

7. Most of the electronics in the base station were redundant. This was due to a mismatch between an existing base station and the intelligent sensor nodes. This can be addressed by a custom land segment system design.

8. The buoy antenna height from the sea surface was too low. This led to future designs having the antenna raised to about 1m above sea level [4].

Of particular interest in this project are the first four items in the list. A sensor connection method using wireless power and data connections would assist in overcoming these shortcomings as follows (using the same numbering as above):

1. If the need for connectors which are sealed with waterproof screw couplings is removed, then the chance of water entry to sensors is greatly decreased, considerably reducing a major cause of node failure.

2. Wireless connectors allow components to be "hot-swapped", even underwater, so that faulty or biofouled sensors can be replaced or cleaned in situ.

3. Part of the wireless connector design could include the ability to power down components by stopping wireless power transfer.

4. Hot-swapping of underwater sensors which require cleaning from biofouling can be done in-situ.

Overall, the results from the SEMAT Mk II system deployment confirm the potential of wireless connector design, and this work evaluates possible technologies and circuits for each of wireless data communication, and wireless power transfer.

III. Using Zigbee for Wireless Underwater Sensors

There are several options for wireless transmission of data:

- The data could be modulated onto the inductive wireless power transfer system, in the same way that an Ethernet data stream is superimposed onto conventional mains power lines in the HomePlug home networking system [6].
- InfraRed line-of-sight communications could be used, making use of IrDA transceivers [7].
- RF wireless technologies such as Bluetooth, UWB Zigbee or WiFi could be used [8]. Zigbee is the most widely used wireless networking standard for communications between WSN nodes terrestrially, and Zigbee transceivers are low-cost and well understood, so Zigbee was chosen as the best RF communications candidate for these experiments.

Many wireless networking technologies operate in the 2.4 GHz band, which is used industrially for microwave food heating. This is due to the microwave energy being absorbed well by dipole relaxation of water molecules, while still having a reasonable penetration depth (in the order of 1 cm) [9].

There has been some previous work on the propagation of WiFi wireless networking systems underwater [10], which tested WiFi-enabled sensor nodes with power consumption of the order of 600mW in fresh water. They did not present data on the radio power, only on complete system power. Their experiments showed a very steep decline in packet loss between 150 and 180mm transmission distance – the packet loss rate was 0% at 150mm and 100% at 180mm.

Zigbee operates at significantly lower power than WiFi, and at a significantly lower data rate, and is generally a more suitable protocol for connecting sensor transducers. Additionally we are interested in propagation data in both fresh water and marine environments, so these experiments test both fresh and saltwater propagation. This paper specifically investigates the propagation of Zigbee wireless networking for short-range underwater communications.

The experimental setup uses two self-contained wireless sensor nodes. Each node is enclosed in a waterproof case and suspended in a water filled plastic tank. There is a variable distance between the two nodes. The suspended nodes are surrounded on all other sides by sufficient water to ensure that all transmission between the nodes is via the direct route through the water-filled space between the nodes.

The sensor nodes employed in the experimental set up are Jennic JN5139 sensor boards which combine a microprocessor and Zigbee transceiver on a single chip. The Zigbee transceivers are capable of operating at different power levels, and experiments are conducted at radio power levels of -25dBm, -17.7dBm, and -3dBm. The distance between the nodes varied between 0 and 280mm, and the packet error rate was measured. The experiments were conducted in both fresh water and in salt water with a conductivity of approximately 5 S/m. Figure 2 plots the results on a graph that illustrates the percentage *Packet Error Rate* (PER) 0-100% for Zigbee at different RF power levels in fresh and saltwater.

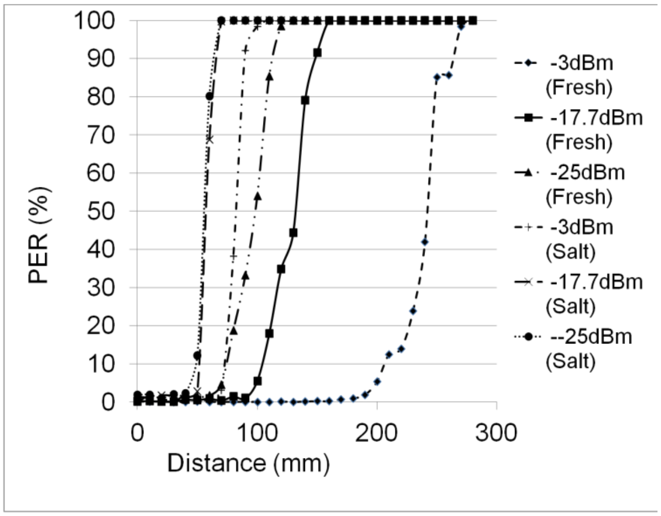

Fig. 2. Percentage PER 0-100% for Zigbee communications at different RF power levels in fresh and saltwater.

The results show that Zigbee wireless networking is capable of transmission through both freshwater and seawater. The reliable communication distance (nominally PER less than 10%) varies from 40mm at low power in seawater to 200mm at higher power in freshwater. In all cases, the transmission distance is compatible with high reliability communications across a wireless sensor coupling.

Additionally, the results show that high reliability communications is possible through water over short distances. This may be suitable in an application for communications between an underwater rover and a fixed sensor node, provided the rover's antenna is within 40mm of the node. As an additional benefit, the high attenuation beyond 300mm means that this wireless communication will be free of interference from other 2.4GHz RF sources in the vicinity. Any eavesdropping would only be possible in very close proximity to the sensor hub.

IV. Inductive power Transmission for Wireless Underwater Sensors

There have been several other reported uses of inductive power transmission for underwater systems. Bradley, et al, describes inductive power transfer systems that are used for recharging *Autonomous Underwater Vehicles* (AUVs) [11]. The general principle is the same as ours – a split transformer is used to transfer AC power from a dock to the AUV. However, the system is quite different in terms of the magnitude of the transferred power. Power transfer efficiency is around 80% for transfer at 200W, with quiescent losses (i.e., losses incurred when no power is transferred) of 15-18W. Since our system has a total power transfer typically less than 100mW, our system requires a different set of tradeoffs. Heeres, et al, describe an underwater power transfer system based on a coaxial transformer, designed for 3kVA power transfer [12]. Again, the scale of this system is considerably different to our system, designed for less than 100mW.

The systems that we are interested in have small, low-power smart sensors, which combine sensor, microprocessor and wireless communications. The power requirements of such a system are typically 50-100mW at 5V. The sensors do not contain a battery, although a capacitor can provide some short-term averaging of power consumption. Once a sensor reading is complete, power can be cut to the sensor. Similarly, the sensor should automatically "boot" when power is applied. It is therefore important that the system is able to transmit relatively low power values at reasonable efficiency.

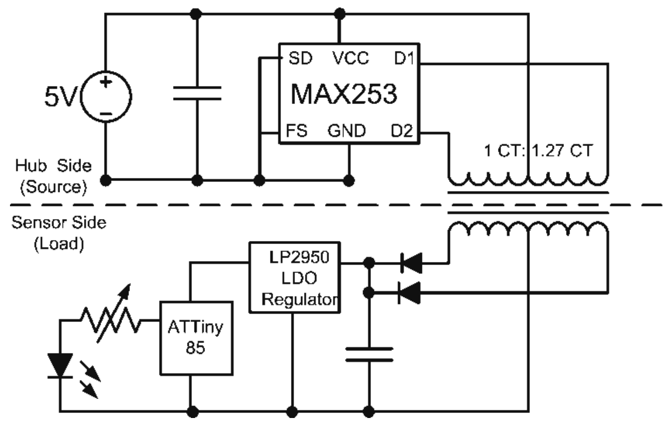

Fig. 3. Detailed Circuit Diagram

Figure 3 shows the detailed circuit of the system. The design uses an inductive DC-DC inductive power transfer system, consisting of a DC power source, connected to a switching DC to AC square wave converter, connected to the primary windings of a transformer. The secondary windings of the transformer are connected to a diode rectifier, a voltage regulator, and then the DC load. The experimental system uses a 5V DC voltage source, and a 5V DC secondary load consisting of an ATTiny85 microcontroller driving an LED (which simulates a typical smart sensor load). The key design challenge is to reduce the power conversion overheads, for example the power consumed by the inverter, iron and copper losses in the transformer, and AC-to-DC rectification losses.

The inverter (which acts as DC to AC converter) uses a commodity IC - a MAX253 power converter - which is specifically designed to drive a small centre-tapped transformer. The inverter's normal application is in providing isolated remote power delivery to communications transceivers. The switching frequency is fixed at 200kHz.

The small, custom transformer is built from an "E" style two-part ferrite core transformer. The transformer ratio is set to 30:38 or 1:1.267, resulting in a total primary inductance of Lp=2mH and a total secondary inductance of Ls=3.2mH using an EPCOS RM12 ferrite core of N97 material.

Normally, the primary and secondary cores would be wound coaxially on a single bobbin to increase mutual coupling. However, in order to split the transformer, the primary winding is wound on a half-sized bobbin that fits on one half of the core, and the secondary is wound on a second half-sized bobbin. The secondary side uses complementary half-wave rectifiers from the centre-tap transformer, and an integrated Low-Drop-Out voltage regulator, Texas Instruments

LP2950. The load power can be varied by a potentiometer controlling the current drawn by an LED load.

When the two halves of the transformer are coated in epoxy and mounted in opposite halves on a connector, there will be a gap between the two ferrite cores. The coupling factor, *k*, is the percentage of primary flux that reaches the secondary coil. This falls to 50% for a gap of 5mm, and at this point there is insufficient coupling to effectively transmit power. This means that the mechanical coupling design for an underwater wireless power connector must ensure that there is good alignment and close physical positioning of the two halves of the transformer using this "closely-coupled" inductive power transfer design.

A. Experimental Results

Tests were conducted to measure the efficiency of power transfer for the typical low power values associated with a sensor node. Power supplied by the source and delivered to the load was measured as the load current was varied. Table I shows the power transfer efficiency over a range of typical load power values. The experiments were repeated with the transformer underwater and there was no change in the power transfer efficiency. At load powers above 100mW, the low-power inverter circuit was unable to provide sufficient current, and a different inverter circuit would be needed.

TABLE I. INPUT POWER, LOAD POWER , POWER LOSSES AND POWER TRANSFER EFFICIENCY FOR THE INDUCTIVE POWER TRANSFER SYSTEM.

P_{IN} (mW)	P_{LOAD} (mW)	P_{LOSS} (mW)	Efficiency(%)
59.2	15.8	43.4	26.6
64.4	19.5	44.9	30.3
71.6	25.6	46.0	35.8
86.5	37.4	49.1	43.2
128.2	68.5	59.7	53.4
152.4	87.0	65.4	57.1

The power transfer efficiency for this inductive power transfer system reaches 57% for a load power of 87 mW. While this is not as high as efficiencies reported for kW levels of inductive power transfer, it is suitable for use with low duty cycle, low power sensors, whilst providing the ability to disconnect sensors in-situ underwater. The components are all inexpensive and easily available, so the system is compatible with low-cost marine sensor systems.

V. CONCLUSIONS

This paper described a series of experiments that have demonstrated the viability of underwater wireless data communication and wireless power transfer. Zigbee, operating in the 2.4GHz band, can communicate with low error rates up to 40mm at low RF power (-25dBm) and up to 70 mm at higher power (-3 dBm) in seawater. Ranges are slightly higher in fresh water. This is easily sufficient for practical connector design.

Inductive power transfer, using a split transformer design, can transmit low power, in the 50-100mW range with efficiency of approximately 50%. This is compatible with small embedded sensors. However, more work is required to improve the power transfer efficiency. Future work involves using the experimental underwater wireless communication and power transfer described in this paper towards the design of a physical connector. This would provide the ability for an aquatic sensor network to hot swap equipment underwater (or out in the field) without the risk of water ingress.

ACKNOWLEDGMENT

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