SPE 99849

Wireless Condition Monitoring

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This paper was prepared for presentation at the 2006 SPE Intelligent Energy Conference and Exhibition held in Amsterdam, The Netherlands, 11–13 April 2006.

Abstract

A 130,000-ton oil tanker might be a surprising place to find cutting edge wireless technology, but on BP's Loch Rannoch the world's first maritime "mote" network was developed to prevent critical machinery breakdowns before they happen. Standard monitoring practice is manual and time-consuming, an innovative solution developed by a BP-led team of BP, Intel, Rockwell and Crossbow applied leading edge sensory network technology to create the world's first mote network onboard an oil tanker. Rotating machines begin to vibrate imperceptibly as bearings wear and shafts become mis-aligned. Accelerometers placed on critical machinery capture equipment vibration, the data is passed wirelessly through a mesh-network to a datalogging computer so that machinery status can be monitored every day rather than manually every six weeks. —helping improve preventative maintenance and safety!

Given the large number of rotating machines on modern oil tankers, it is not feasible for the crew to take readings more than every six weeks using hand-held dataloggers. Faults can develop up to six weeks before detection. Some machines require engineers to take measurements in confined or awkward spaces; wireless sampling removes this safety risk.

30 motes were installed in engine room locations logging vibration signals from 98 accelerometers for 5 months. The wireless, battery-operated motes allowed for rapid installation (17 hours) where traditional wired solutions were not feasible. Motes enable much more frequent sampling (every 6-18 Hours), increasing the quality of predictive analyses and enhancing our ability to spot machine defects early on before serious damage.

Loch Rannoch is an example of how the FIELD OF THE FUTURE programme develops technologies to improve management of BP's assets.

This paper describes the challenges faced in modern day operations and how BP is beginning to face these challenges with modern mesh sensor net technology.

1 Uptime, Optimisation & Safety

1.1 Challenges

Modern Upstream & Downstream operations face challenges of increasing the uptime of equipment, optimising processes and increasing safety. Meeting these challenges increases the need to understand the physical environment and parameters of our operations to new heights.

As we move towards a vision of the real-time enterprise it becomes increasingly apparent that a predictive rather than reactive regime will be required which fuels the need for much more data about our physical operations. The barrier to getting more data is that tradional wired sensor solutions are costly in terms of both money and time. It is not uncommon to see costs of $125/metre for cabling and months of elapsed time for a management of change process to get a sensor functioning.

The rapid changes in digital and sensor technology are beginning to show how enterprises can acquire plant data quickly, reliably and inexpensively

1.2 Technology

Late in 2003, whilst searching for ways that existing sensor technology could be read wirelessly by hand held devices BP discovered Mote technology and immediately saw the value that this technology could bring.

Probably the first thing to explain is that Mote is not an acronym but derives from old English for speck or particle, as in dust motes. Kris Pister, CTO Dust Networks, who coined the phrase when commenting that devices would be so small they would be like dust. So what is a "mote", what's the big deal?

- The core of a mote is a small, low-cost, low-power computer (microcontroller). All of the motes available today use 8bit processors with between 128-512kbytes of flash memory to store programs.

The processors will typically consume around 5-15 milliamps in use and around 20 microamps in sleep mode. Through a sensor interface (A/D) the computer monitors one or more sensors. Typical sensor applications are for temperature, light, sound, position, acceleration, vibration, stress, weight, pressure, humidity, etc. Whilst no doubt there are applications for motes without sensors, the industrial applications we can see for motes all require sensors

- The computer is integrated with a low power, low cost radio that allows it to connect to other motes and gateways. The radios typically use the unlicenced 433, 968 or 2.4 GHz bands. The low power of the radios (milliwatts) allows them to communicate up to around 50 meters. The distance that the Motes can communicate is a function of power consumption, size and antennae design. Typical throughput is between 40k-250kbps depending on frequency.

- Typically motes will run on batteries as an energy source but can be augmented by Solar or other energy harvesting techniques or even connected to grid power (although this is rare)

All of the above is typically packaged into a small and low cost integrated device. Fig 1 shows the MicaDot motes from Crossbow Technology Inc. in relation to a US quarter. The way that motes establish a network between themselves is what sets this type of wireless sensor acquisition apart from more traditional methods. Their unique networking characteristics are as follows;

Photo: Courtesy of Crossbow Technology Inc.

Fig 1

- Each node is autonomous and does not require to be configured by an operator.

- Each node, when powered up, will execute a discovery process to learn which other motes are within radio contact. Through monitoring signal strength and signal quality each mote will discover the "nearest" mote to communicate with.

- Motes will have been programmed to deliver sensor data to a gateway in the network, they will through learning the mote topology achieve the lowest cost routing to that gateway where cost is a proxy for power consumption.

- On wake up Motes will evaluate "nearest" neighbours for signal strength and signal quality and will re-configure routing automatically if parameters change.

- Where motes cannot directly "see" the gateway they will hop data through other motes keeping the number of hops to a minimum.

- Motes have a "sleep mode" which is an ultra low power mode where they listen and can be awoken by beacon signals.

In effect the motes create a mesh network that constantly re-evaluates and reconfigures for optimum connectivity. It is this feature that makes these devices so exciting for our industry.
Fig 2 shows a schematic of a mesh network with the primary routes denoted by the blue connections and the secondary, backup routes in red. Secondary routes will be used when signal quality or strength for primary links dips below a given threshold

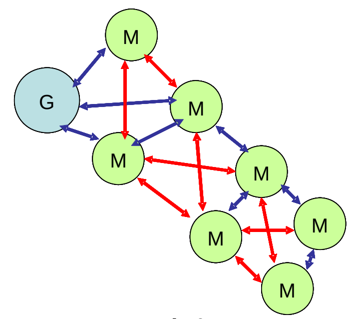


Fig 2

2 Background

Whilst understanding how mote technology could change the way we acquire data from our plant it was far from obvious how whether these devices would work in the harsh industrial environments in upstream or downstream. The devices were bare board printed circuit boards with little more than a short piece of wire acting as the antennae. It came as no surprise to learn that all the sales of motes were to research laboratories. If motes were to make a difference at BP we needed to demonstrate that they would work not only in extremes of temperature and vibration but also in the high metallic environments found in refining and upstream operations.

We typically operate in environments that are zoned to ensure that electrical equipment is certified that it can be used in potentially explosive atmospheres. Getting electrical equipment certified is both time consuming and costly and is a generally a significant barrier to prototyping in these areas. In searching for locations to trial this technology we surmised that the engine room of a ship offers much if not a more challenging environment without having the requirement for certified equipment. With this in mind BP Shipping offered the use of the *Loch Rannoch* (Fig 3 & 4) to be used as a platform for the trial.

Fig 3

The *Loch Rannoch* was designed and built to act as a shuttle tanker for the Schiehallion oil field, west of Shetland. The *Loch Rannoch* is over 1200 feet long and can transport

850,000 barrels of oil. The steel construction of the *Loch Rannoch,* was expected to pose many challenges to the use of wireless technology.

Rather that just deploy motes to test the radio communications we decided to look at a real-world application to apply in the trial. In consultation with BP Shipping we decided to apply the trial to collect vibration spectra from a variety of rotating machines for equipment condition monitoring. The trial was designed to deploy motes connected to accelerometers to collect signature vibrations from rotating equipment. This condition monitoring data was to be collected by a Rockwell application and transmitted on a regular basis to Rockwell, which holds the condition monitoring contract with BP Shipping. Vibration monitoring is one of the most challenging applications for Sensornet technology.

Fig 4

Crossbow Mica Motes, Intel Stargates and Rockwell Accelerometer technology was selected for inclusion in the pilot.

3 Scope & Purpose of Trial

The technology was deployed to test the following;

- ***Ability of Wireless Mote Technology to operate in areas where there is high RF noise***. The *Loch Rannoch* has high-powered Radar, HF communications equipment and was expected to create high ambient RF when the main engines and diesel generator were on-line.

- ***Ability of Wireless Mote Technology to operate in areas with high physical vibration.*** The *Loch Rannoch* provides a mechanically hostile environment, for example the bow thruster area is about as severe an environment that the Motes will encounter.

- ***Ability of Wireless Mote technology to operate in an "occasionally connected" mode.*** The *Loch Rannoch*, in common with many commercial ships is constructed from steel and is likely to prevent communication between motes in different compartments. During a voyage the compartment doors are regularly opened and closed giving the mote network an opportunity to synchronize and transmit data to the central Stargate (gateway device).

- ***Ability of a medium sized mote network to reliably capture data from analogue sensors and move the data to a central location.***

The development of an operational wireless condition monitoring network was not within the scope of the trial.

3.1 Success Criteria

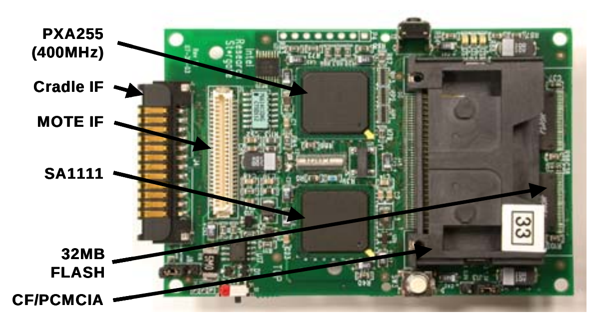
- Works well in areas with high ambient and or transient RF.
- Works well in harsh physical conditions, i.e. Heat, vibration, salt water.
- Able to operate in an "occasionally connected "mode.
- Able to reliably capture data from multiple high-frequency analogue sensors and move the data to a central location using a multi-layer architecture.
- Ability of the system to accommodate the possible failure of a sensor or mote and continue to capture data with remaining operational components.

4 Technologies Used

4.1 Motes

The Motes used in the trial were Crossbow Mica2 with MDA240 analogue/digital conversion interfaces. The Motes were powered by 4 D cell batteries inside a Steel enclosure (see Fig 5). The cables from the transducers were terminated on the MDA240, each mote collected data from a maximum of 6 transducers, although it could physically cope with 10 transducers. Motes were mounted close to machines being monitored with cable ties. The radio on the mote is software tunable and for the trial the 900 MHz radios were re-tuned to the 868 MHz band to remain within the UK unlicenced radio spectrum.

Fig 5

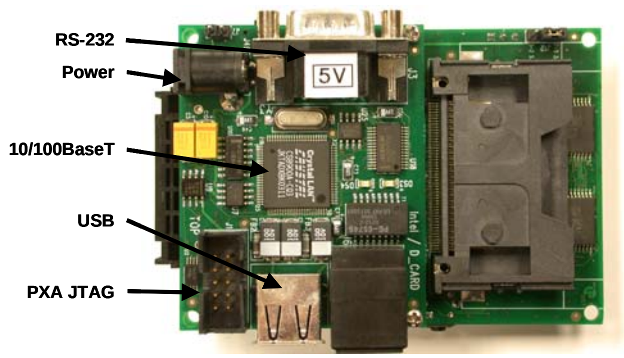


Stargate – Top View

Fig 6

4.2 Stargates

The Stargate (Fig 6 & 7) is a general purpose *microserver* platform designed by Intel and manufactured by Crossbow. It was originally developed for a broad array of advanced development applications including sensor networks, ubiquitous computing and robotics. It provides the power and features of a low-end PC in a palm-size device that can operate from a battery or external power. The core of Stargate is a 400MHz Intel Xscale PXA255 processor with 64MB of RAM and 64MB of onboard flash. Peripherals include 1 PCMCIA port, 1 Compact Flash (CF) port, Ethernet, RS-232, USB and optional Bluetooth support. The Stargate also has a



Stargate – Underneath View

Fig 7

built-in connector for the Crossbow MICA2 series motes. The PCMCIA/CF ports allow for the addition of a wide variety of expansion cards, including wireless Ethernet, cellular & GPRS modems and additional secondary storage. The Stargate runs the Linux operating system (version 2.4.19) and supports many common tools such as Secure CoPy (SCP), NTP and PERL. For the trial, the Stargates were outfitted with a high power 802.11b card, extra secondary storage and a mote. Each unit was housed in an industrial enclosure with antenna for the mote and the wireless Ethernet card and outlets for power, RS-232 and wired Ethernet.

4.3 Accelerometers/Transducers

EI / 1100C Series transducers that are used for handheld acquisition of vibration data were used for the trial. They have the following specification;

Sensitivity	100 mV/g ± 10% Nominal at 80 Hz
Frequency Response	2 Hz to 8 kHz ± 10% (3 dB at 0.8 Hz)
Mounted Base Resonance	18 kHz (nominal)
Isolation	Base isolated
Transverse Sensitivity	Less than 5%
Electrical Noise	0.1 mg max
Current Range	0.5 mA to 8 mA
Bias Voltage	8 volts DC nominal
Case Material	Stainless steel
Cable	overbraided PTFE temp min-25º C, max 140º C @ 4mA.
	(EI / 1100HCQ)
Weight Weight	110 gms (nominal)
Sealing	IP67
Options	Connector Version (see SS0166/A)

5 The Trial

5.1 Loch Rannoch Engine Room

There were several locations aboard the ship considered. The bow equipment spaces that house the bow thrusters and hydraulic gear for the bow loading system were one area. This location was very desirable since it posed a challenging environment for sensor networks due to the extreme vibrations during operation. However, backhaul network connectivity for this space is difficult as there are no wired Ethernet ports in this area. Establishing wireless connectivity would require mounting an antenna on the weather decks that would be subject to RF considerations from the ships navigational systems and intrinsic safety (IS) requirements for cargo. Intrinsic safety limitations are also required for the cargo pump room located in a separate compartment forward of the engineering spaces. For these reasons, we chose to focus survey on the aft engineering spaces as a likely location for the trial. There is a wide variety of critical equipment here and the environment equivalently challenging in terms of mechanical shock and thermal extremes (35C and up). Power and wired network connectivity are readily available and these compartments are outside the IS boundary.

The Loch Rannoch aft engineering spaces are arranged into three major vertical sections across 4 horizontal decks. The sections are isolated from each other by bulkheads that extend through all decks. At the 1st deck, there are permanent openings and/or non-watertight (NWT) doors between the sections. Below the 1st deck, where the ship's hull is beneath the waterline, the bulkheads are separated by watertight hatches. These hatches are open during in-port periods and during working hours while in transit. After working hours or when the ship is holding station at the FPSO, the hatches are closed for periods occasionally exceeding 24 hours.

The port and starboard sections house the larger propulsion plant machinery. They include the main diesel engines, the auxiliary engines (diesel generators), the cargo transfer pumps and the aft stern thrusters. Each of these sections is constructed as a large gallery open from the 1st deck down with peripheral walkways and a gantry crane in the centre. The first deck mezzanine has visible line of site to all the major equipment in the decks below, except those in the lower aft portion (i.e. the stern thrusters).

The centre sections house smaller, auxiliary equipment. This includes oil transfer pumps, oil purifiers, various water pumps, evaporators and air compressors. For fire isolation, the oil transfer and purifier equipment is separated from the rest of the 2nd deck centre section by a steel bulkhead with a NWT fire door for access.

A survey of the Loch Rannoch was performed to determine the location of the transducers, motes and stargates and to determine whether the RF background emissions on board the ship would make low-powered wireless communication in the engine room impossible.

5.2 Survey

5.2.1 RF Analysis

The ship uses a wide range of RF based equipment for navigation and communications. A list of key communications systems and there frequencies is listed in the table 1. Most important among these is the DGPS Absolute Relative Positioning Sensor (DARPS) which is used intensively during FPSO positioning. Interestingly, intra-ship voice radio also provides coverage in the engineering space. There are RF repeaters located at high points in the engineering spaces and reportedly provide wireless coverage of the entire area.

System	Frequency Range
ARTIMAS (RADAR)	9.2 GHz
DGPS Absolute Relative Positioning Sensor (DARPS)	412 – 465 MHz
Marine VHF	156 – 158 MHz
Differential GPS (DGPS)	202 MHz, 210 MHz, 392.5 – 401 MHz
Telemetry	450 – 480 MHz
HELO VHF	122.8 – 129.1 MHz
Intra-Ship Voice	457 – 468 MHz

Key in-use frequencies board the Loch Rannoch
Table 1

Phase 1 - Mote RF Connectivity

The first phase of the survey involved basic wireless sensor connectivity tests for each of the radio frequencies under consideration – 433 MHz, 916 MHz and 2.4 GHz (Bluetooth). For the 433 MHz and 916 MHz MICA2's, we used the Surge multi-hop application. This application exercises the ad-hoc multi-hop capabilities of TinyOS (the open source operating system that the Crossbow motes run) by simulating application traffic and collecting topology and link reliability statistics. Sequential numbers packets from each node are used to determine aggregate reliability, or yield, from the node to the base-station. For the Bluetooth devices, we used a special connectivity application that reported details on scatter-net topology and ACKS/NAKS encountered by each node the various links in the topology.

The locations of the wireless nodes were chosen so as to be as close as possible to the actual locations that would be used in the deployment. Criteria here included proximity to the sensor points, availability of mounting locations, potential for RF interference, and crew interference. Base station locations were chosen based on a central position relative to the sensing nodes, proximity to power outlets, and estimated 802.11b coverage. Of note, the ship has several 110 Volts60 Hz outlets that are seldom used by the crew and we located the test base stations adjacent to these points.

The survey was broken down into three separate sub-trials involving a single base station location and 6-7 wireless sensor nodes. The number of nodes chosen ensured coverage of all the equipment of interest while providing a representative RF analysis of the space of interest.

The first trial involved placing the sensor nodes and base station on a single horizontal level in the engine room starboard compartment, 2nd deck. The objective of this trial was to establish a simple sensor-net topology when all the wireless nodes are on the same vertical level. Instrumentation points included those around both diesel generators and the engine room/workshop AC compressor. The trial points enabled complete coverage of all vibration monitoring points around the generators. The base station was located near the watertight hatch on the port side of the compartment.

The second trial was a multi compartment trial situated in the engine room center compartment, 2nd deck. This space is divided fore and aft by a NWT bulkhead with a single NWT steel door and is separated from other spaces by watertight steel hatches. The objective of this trial was to evaluate RF connectivity through the fire bulkhead and 802.11 connectivity (discussed later). The sensor nodes were distributed near monitoring points in the oil purifier room and the freshwater pump space. A single base station was located near the fire door on the forward (freshwater pump) side of the bulkhead.

The final trial was a multi-level trial in the starboard engine room. The goal here was to analyze RF coverage vertically between decks where large equipment openings exist. The base station was situated as in Trial 1st on the 2nd deck. Wireless nodes were placed on equipment at levels below the base station.

In all the trials we proved that all frequencies were viable as potential candidates for the trial. We attribute these wireless characteristics to the steel materials used in the engine room. Originally expected to hamper RF, it appears that just the opposite is true. It is likely that the bulkheads and machinery tended to reflect rather than attenuate RF energy thus promoting connectivity pathways that might not be observed in other environments of soft-material construction. Surprisingly, we also observed good connectivity across bulkheads for the 916MHz and Bluetooth technologies. During the second trial, reliable connectivity was established with nodes in the oil purifier space that were separated from the base location by a non-watertight steel bulkhead. A separate test using the Bluetooth also demonstrated some watertight bulkhead penetration when nodes were place immediately opposite the watertight hatch. We believe that the connectivity in both these cases was due to RF energy penetrating through the edges of the doorway/hatch. Such connectivity was not observed for the 433 MHz MICA2, perhaps due to its longer wavelength.

Phase 2 – 802.11b Connectivity

The second phase the survey examined 802.11b wireless coverage across the engineering spaces. 802.11b was the intended to be the link between the stargates used for the sensornet deployment. The tests involved establishing connectivity in ad-hoc mode between two Stargates, verifying connectivity using ‘ping’ and transferring an 8MB file between the stargates using secure copy (scp). One of the stargates was fixed at a position in the starboard compartment, 1st deck, near the available port for the ships wired Ethernet. Other stargates were placed near the base stations locations in the starboard and centre compartments, 2nd Deck. All stargates were outfitted with High Power 802.11b cards (PRISM2 Model XI-325H) and configured to use maximum power on Channel 6.

The tests confirmed excellent 802.11b connectivity between all the stargates. For the stargate in the centre compartment, connectivity was lost if the watertight hatch was closed. However, it quickly regained connectivity once the hatch was re-opened.

Phase 3 – Ambient RF

In the last phase of the survey, we monitored the ambient RF environment of the surveyed spaces to determine the presence of an RF energy that might hinder sensornet communication. Passive spectrum analysis snapshots centered at 433 MHz, 916 MHz and 2.4 GHz were taken on the 2nd deck of the engineering spaces. Measurements were taken using an Anritsu MS2711B Spectrum analyzer attached to a 2.4 GHz miniature antenna. Although technical difficulties prevented use of other antennas, we believe the 2.4 GHz was sufficient for passive monitoring across all the frequency ranges of interest. In fact, this antenna is more representative of the antenna actually used on the wireless motes. The ambient surveys did not detect any significant noise peaks at frequencies which might interfere with sensornet operation. A small amount of RF energy was noted at 2.4 GHz in one of the surveys. While its source is unknown, it did not appear to affect any of the functional tests in the rest of the survey.

5.2.2 Results and Conclusion

The results for all three trials demonstrated excellent wireless mote connectivity in the engineering spaces. The network discovery mechanisms were able to form a network within a few seconds and maintain connectivity throughout each test. For the MICA2, the topology formed was consistently single hop and test packet end-to-end yields were greater than 99%. With the exception of the 433MHz devices, this performance was regardless of the mote locations. For the Bluetooth based motes, each trial was able to form a stable scatter-net (a Bluetooth ad-network) with only occasional reorganization of the topology. These reorganizations have been witnessed in several other environments and are not attributed to the RF environment.

5.3 Trial Configuration

In this section, we discuss the specifics of the sensornet installation aboard the Loch Rannoch. The hardware inventory for the trial included 98 accelerometers, 26 sensor nodes, 4 Stargates and 1 IBM T40 Laptop PC. Three of the stargates were used as root nodes and one as the bridge node. The trial PC was installed in the Ship’s office and was connected to the bridge node via the ship’s wired Ethernet. The PC and the bridge node were assigned static IP addresses from the ship’s 24 bit subnet. The use of static IP addresses was in lieu of a dynamic name service that would permit the bridge node to locate the PC and vice versa.

The sensornet itself was installed in two compartments in the engineering spaces: starboard 2nd deck and floor, and centre 2nd Deck. The starboard compartment had easy access to the ship’s wired Ethernet via the unused port in the parts stowage space on the 1st Deck. The bridge node was installed just outside this compartment on the 1st Deck gallery. The centre compartment was included in the trial because it could be isolated via a watertight hatch/bulkhead. This allowed us to evaluate operation of the sensornet in an occasionally connected environment. The root nodes were placed in the same locations as in the RF survey, adjacent to available power outlets.

In some cases, the number of sensor nodes was ‘doubled-up’ to prevent installing sensor node on equipment that would not be running during the trial.

Loch Rannoch Sensor Net – Logical Network Layout

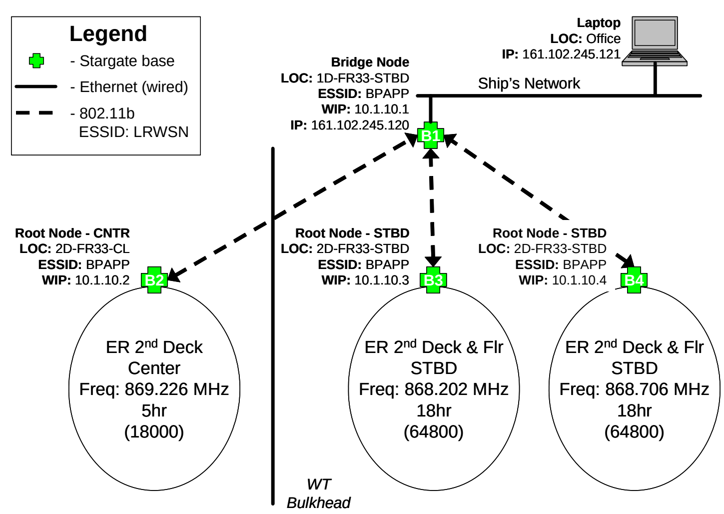


Fig 8

Figure 8 shows the logical configuration of the sensornet including frequencies, cluster sleep periods and IP information. A separate IP subnet was used for the root nodes to provide additional isolation from the shipboard network. The trial PC was provided with a persistent route table entry to access this subnet over the ships network.

The different sampling periods for the starboard and centre clusters were chosen on two distinct objectives. The first was to ensure the sensornet survived the entire length of the trial without excessive loss of battery life or sensor data quality. The other, somewhat competing objective was to drive the sensornet as hard as possible to observe potential failures and behaviour near the end of battery life. To estimate the sensornet lifetimes, we performed energy consumption measurements of the sensornet hardware in the lab during sampling & transmission, idle, and sleep modes. Table 2 summarizes these parameters and other assumptions used to calculate the sampling periods.

Parameter	Value
Sample/Transmit Current	34.96 mA
Idle Current	24.41 mA
Sleep Current	~0 mA
Time for a single node to sample/transmit 6 channels of data	12 minutes
Battery Total Capacity	3600 mAh
Useful Battery Capacity (based on ADC limitations	1800 mAh

Table 2

Energy calculation parameters & assumptions.

For the trial sensornet software/hardware combination, the sample period is determined by the cluster sleep interval and the number of nodes in the cluster. The software determines the duration in which all the nodes sleep. The nodes in the cluster determine the amount of time it takes to transfer all the results back to the root node. Thus, an entire sample period is the sum of the sleep duration and the data transfer time.
We chose the starboard cluster to exhibit the longest possible sensornet lifetime, and the centre cluster to be driven to early failure. The starboard cluster was set to a sleep duration of 18 hours, the maximum permitted by the current software. At this rate, the sensornet was expected to produce good data for over 82 days with a sample period of ~20.5 hours. The centre cluster was set to a sleep duration of 5 hours which was calculated to yield at least 21 days of good results with a sample period of ~7 hours.

Included on the PC software installation were dynamic webpages, diagnostic collection scripts, and backup script. The web pages provided 'at-a-glance' indication of sensornet health (Figure 9). Each sensor node was listed in a row of a table indicating the time the last result would receive. Depending on the time elapsed since the last result was received, the node would be highlighted in red (more that 2 periods overdue), yellow (one period overdue) or green (not overdue). In addition to the tabular format, there were links to separate pages which overlaid sensor locations on a diagram of the engine room. Each node was highlighted with the same colour scheme as in the table. The diagnostic collection scripts would collection continuous network packet trace data from the sensornets in the Starboard compartment. This trace data would help assist in diagnosing potential problems with the sensornet itself. Trace data could not be collected from the centre compartment because connectivity there would not be continuously available and there was insufficient storage space on the Stargate to store the trace data. Finally, the backup script provided a simple means of copying the trace data, converter logs and Enshare database to a CD which could be delivered ashore for analysis.

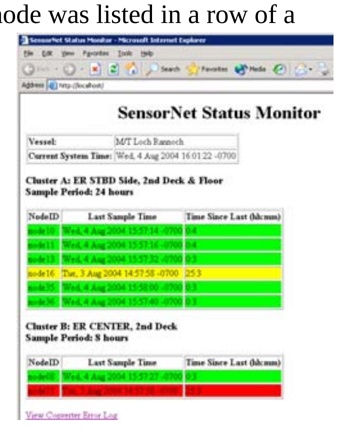


Fig 9

5.3.1 Equipment monitored

A variety of rotating equipment was chosen to be monitored in the starboard engine room, from Auxilliary engines, A/C units, Turbochargers, Oil purifiers, water pumps, ballast pumps, oil pumps etc. In total, 30 motes (nodes) were deployed and 98 accelerometers.

5.4 Trial Duration

The trial ran from August to December 2004

5.5 Installation

Installation of the sensornet was accomplished over a period of 1.5 working days. Six individuals working for a total of 18 elapsed hours were involved in the installation. The vast majority of this time was occupied by the physical installation of the hardware itself. The original method of using plastic tie-wraps was not sufficient for mounting to the larger, sometime odd shaped support structures onboard the ship. Replacing the plastic with larger, nylon tie-wraps proved to be more effective and this was used to mount the majority of the devices. Steel banding was the original installation design method but proved to be very cumbersome and the install team wasted a great deal of time trying to use it, this may have been due to the unfamiliarity of the method to the installation team.

A slight incompatibility was noted between the bridge node and the ship's wired network that initially prevented connectivity to the trial PC. This was apparently caused by incompatibilities between the stargate Ethernet hardware and the ships networking infrastructure. The situation was resolved by placing a mini-hub between the ships network and the stargate. While it is not known what the exact cause was, such behaviour is frequently due to problems with the auto negotiate feature of many Ethernet implementations. Due to the constrained time period of the install, we were not able to verify this as the cause.

Once the physical installation was complete, starting the sensornets went relatively smoothly. The first sensornet to be activated was the centre cluster network. Initially, the stargate had problems booting, but this was traced to a loose connector that was easily fixed. The starboard cluster came up without incident.

5.6 Running of the Trial (Operation)

In this section, we analyze the operation of the sensornet during this period. There are two separate aspects to the data analysis from the shipboard trial. The first concerns the performance of sensor network itself as it relates to data delivery and robustness. The other is an examination of the quality of the machinery vibration data collected and how it compares to results obtained by traditional means.

5.6.1 Sensornet Analysis

Sensor network performance was evaluated on two criteria: 1) the ability to collect and deliver data to the backend PC, and 2) the ability to recover from loss or errors. The analysis was accomplished from the sample data received at the laptop, the packet trace data and the locally archived data at each root node.

Figures 10 and 11 plot the histogram of vibration samples

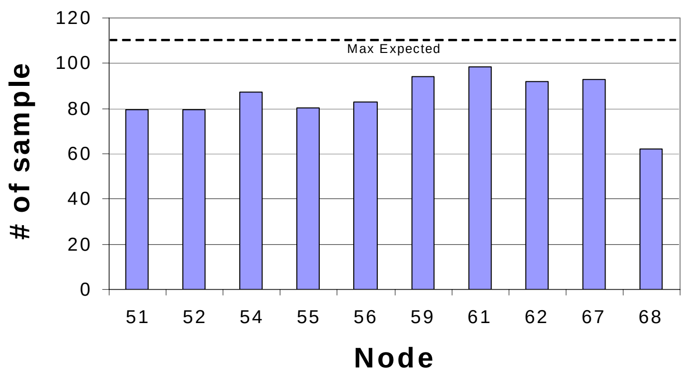


Fig 10

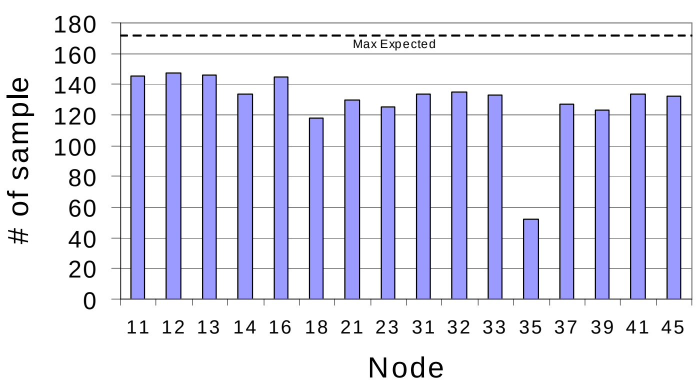


Fig 11

received from each node/channel in the starboard and center clusters. The starboard cluster exhibited a lifetime of 136 days and centre cluster 42 days. Both of these are well beyond their expected lifetimes. Furthermore, the sensornets exhibited an 80% reporting success rate during the cluster lifetime. The nodes overall maintained a regular reporting schedule and were able to recover from errors in a previous sampling round. Notable exceptions are nodes 35 and 68. Node 68 had lower overall reporting yield because it was the first to exhaust it's battery supply. Even though other nodes lasted longer, it was well beyond the computed lifetime of 3 weeks nodes in the centre cluster. Node 35 appeared to be a rogue node during the course of the trial, with the lowest result yield of all other nodes in its cluster. Analysis of the trace data suggests this node may have had a hardware problem which caused it to behave erratically. This is evident from the fact that it often failed to respond to the discovery protocol at the beginning of each cycle and its behaviour on 8/31. Post deployment inspection of the node showed no obvious abnormalities with the hardware: the sensor node PCB's were dry and clean with all wiring secure.

The vast majority of observed sensornet failures were characterized by a cascading loss of all connectivity during a sample collection cycle. At the start of the cycle, all nodes would wake up and respond to the initial routing and service-discovery beacons and the data transfers would commence normally. At an arbitrary point mid-transfer with a particular node/channel, the root node would not receive any further packets from the target. Once the timeout with the current node expired, the root would attempt connectivity with remaining nodes in the cluster without success. After a full sequence of timeouts, the root would send the sleep beacon and delay for the next sample cycle. At the next sample cycle, the network would often fully recover without problems. While the trace logs showed both starboard clusters were subject to this failure, individual instances of failures appeared uncorrelated. That is, a problem in one cluster did not affect the opposite cluster. The exact cause of this cascading loss of connectivity is not clear. One possibility is that transient RF interference is causing localized loss of connectivity. Alternatively, it may be a transient software bug triggered by a certain set of conditions, but clears when the nodes reset at the end of the cycle. Additional debugging information at the node level would be necessary to further diagnose this problem.

The remaining failures of the sensornet were traced to specific hardware failure or a loss of ships accommodation power. The hardware failure seemed to be largely due to a transient failure on the serial link between the root node 4 stargate and it's attached mote. At the end of the sample cycle, the automatic reboot would clear the serial link errors and allow the sensornet to recover. The loss of ships power affected the sensornets by erasing the sleep state at the root nodes. Worst case, an individual cluster would have to wait for an entire sample cycle before regaining sleep/wake synchronization.

5.6.2 Data Quality

In addition to sensornet health, we also performed an analysis of the quality of the data from the sensornet. The objective was to evaluate the accuracy of the sensornet results and whether sensornet itself introduced errors. Although providing highly accurate vibration data was *not* an ultimate objective, an understanding of any errors or limitations of the data would be important for future installations. The determination of data quality was accomplished by controlled experiments and an evaluation of the shipboard collected data.

To quantitatively determine errors in the sensornet vibration data, we conducted experiments using a controllable vibration source and a calibrated measurement instrument. The vibration source was an Unholtz-Dickie model TA250D-206 with a Dactron DSP shaker control. The calibrated reference instrument was an Rockwell EnPac 1200 (SN#:000607). This is the same model device currently used to collect industrial vibration measurements which permitted a direct comparison of sensornet vs. conventionally collected data. In the experiments, two accelerometers were mounted to the vibration source and separately connected to the EnPac 1200 and a sensor node. Separate measurements were made with the vibration source set to 500Hz @ 2g's and 1000Hz @ 2g's. To factor out possible sensor anomalies, additional measurements were taken with the accelerometers interchanged between the two devices. We also note that, while the vibration source is cannot reproduce a perfect sine wave, any distortion here would be observed in the measurements collected by both devices and would not affect the comparison.

The results of the experiment do not suggest that the wireless nature of the sensornet introduces additional distortion in the measurement data. The errors observed in the experimental data were traced to the bugs in the digitizing board used in the sensor node.

5.6.3 Review of Wireless Data Calculated Data Trends and Spectrum

In reviewing the data the objectives are to calculate the time waveform into meaningful data for trending and analysis purposes in determining the health of the machine, severity of vibration and rate of change in understanding whether or not a change in operational performance is occurring.
A general observation that must be noted is that given the trial nature of the sensornet the data gathered was not used to diagnose any of the rotating machines.

The Main Turbo Charger (Fig 12) has been selected, to review and comment on the data acquisition. These machines have been selected to highlight satisfactory data within the constraints reviewed in the conclusion and poor data due to quality or insufficient operational knowledge.

Main Engine Turbocharger , Location Horizontal

Fig 12

Generally the data has proved quite difficult to obtain quality output calculations due to the raw data collected, although in several instances such as the Main Engine Turbo Charger, meaningful and relative output frequencies can be seen. Using the calculated points enabled spectrum Integration, band energy trends to be formulated to give outputs for valuable trending purposes from the data acquired on a schedule.

Trend data is primary in acknowledging rates of change and can be seen to be successful in providing trends in this trial using the Rockwell Enshare software from the acquired data. Spectrum FFT calculations however can not be deemed like for like therefore direct comparison is difficult as highlighted in the comments section of this review brief.

The Main engine turbo charger has been highlighted for review due to a positive review of the data being relative to existing output frequencies

The trend below (Fig 13) shows the overall amplitude taken from time waveform data. This value is calculated using the tools in Enshare and generates an overall magnitude in the measurement unit required. In this instance g's acceleration is used,
As can be seen there is null data at the bottom of the scale which is thought to be when then the Main engine is not running therefore not generating vibration signals. The rise in Amplitude, shown by the spikes in the trend is thought to be

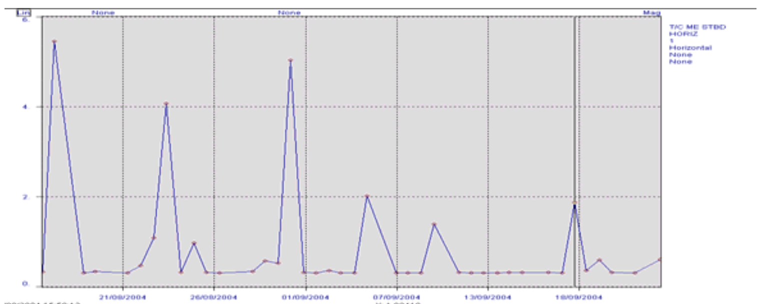


Fig 13

when the Main Engine and turbo charger are operational, and creating energy thus vibration energy. Operational data is required such as ME speed and Turbo charger as the engine loading will have proportional link to how fast the turbo charger is running and what loading and vibration signal will be generated.

The FFT spectrum overleaf (Fig 14) has been calculated using the tools in Enshare. Interestingly in this data set, known vibration frequencies have been captured that are valid in the existing routine CM system. The frequency identified is Blade Pass which is usually seen in turbo charger systems and doesn't usually represent a problem. Comparing the routine spectrum acceleration plot from the existing system, the blade passing frequency (Diagram C) is clearly evident, although it must be noted this data set is not from the same time stamp, but several months previous.

Concluding several known vibration frequencies have been identified from both acquisition techniques.

The FFT Spectrum Waterfall plot (Fig 15) shows the data FFT spectrums plotted in the time domain, latest data at the furthest plot. Vibration energy increases can be seen in the plots at the Turbo charger generates a strong blade pass frequency signal. This is most probable when the data acquired was with the Main Engine and Turbo charger operational.

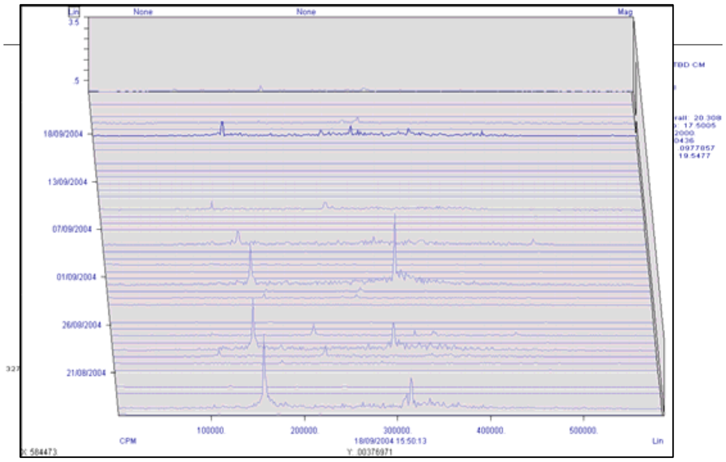


Fig 15

Comments on Set-up, Measurements and Data

Data Calculations

Trends - Successful calculations of the time waveform enabled trends to be created of the data.

FFT - Successful Spectrum FFT can be calculated and generated using the tools although it is recommended to consider point (2)

The created calculated data can be used in similar fashion to the existing CM data base for analysis and diagnostic review. Which includes the use of alarms, frequency component set-up and data archive.

Data Quality

Resolution of the data spectrum needs to be increased, the bin width is not adequate thus creates leakage due to too high FMAX.

Window function needs to be aligned to the optimum collection; common setting for routine collections is the Hanning Window.

The use of filters to eliminate high amplitude low frequency data, to increase data sampling times and ensure quality data acquisition is deemed appropriate.

Averaging - number of averages on data acquisition on top of overlapping of each data sample would benefit to acquire accurate and repeatable data samples.

Signal Detection - requires to be applied RMS, PK, PK to PK etc.

Saturation - This is evident in a large number of data sets where they are of low frequency component speed for the FMAX, a ski-slope affect takes place where the running speed frequency components within the FFT are saturated by high amplitude low frequency noise at the critical part of the spectrum.

The spectrum below (Fig 16) shows the ski-slope effect, where all the fundamental frequencies of diagnosis such as unbalance, misalignment and looseness are lost.

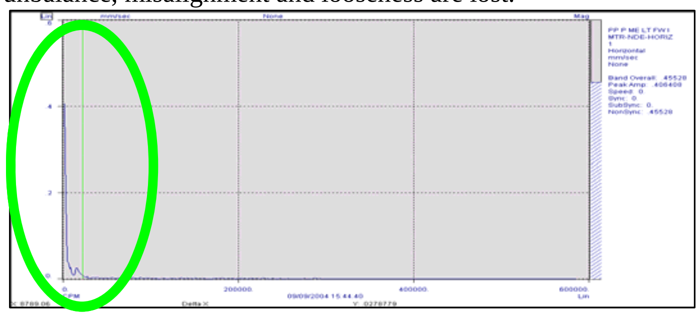


Fig 16

Fmax - The Fmax on the data sets when calculated results in a FMAX of 600kcpm, realistically high Fmax exists resulting from high speed machinery such as Turbo chargers. Rule of thumb is to sample data at a FMAX of 20-50 orders. This rule is optimised on historical failure mode knowledge, filtering and output frequency knowledge.

Amplitude “Creep” and rise of band Energy
On many occasions noise levels increased within the spectrum which reflected in the trends increasing linearly. The lack of operational data and resolution causes difficulties in diagnosing the frequency or frequencies responsible for increases, when analysed the band energy in these spectrums however does increase adding to the overall amplitude.
It would be beneficial to investigate this for future considerations.

Considerations must be made to:

Background Vibration Data

Lack of Operational data to conclusively validate a machine is running.

Ships Speed
Ships Mean Draft Condition
Weather Conditions with ME Engine Speed (background Hull Vibration)
Status of Accelerometer Mounting if on occasions, as reported has come adrift.

Enveloping Techniques
No ESP, Enveloping techniques were applied on the trial.

5.7 Mechanical Aspects

Overall the equipment survived the 5 month trial with remarkably few issues. The problems that we did see were minor and easily curable with better packaging and installation. Importantly none of the main electronic components failed due to mechanical stress. The summary of problems found during decommissioning is as follows;

#	Failure
2	Mounting Broken
8	Detached/Severed Sensor cable
12	Battery Corrosion

Table 3

It is clear that in any future solution the three areas highlighted in table 3 would need to be addressed.

6 Conclusions

Even though this project is a work in progress, important results have been obtained from this collaborative effort. The following summarizes the conclusions from this study.

It is important to establish hardened devices that operate reliably, and require minimum set-up and installation effort. The remote operation of sensor nodes in particularly harsh ship engine rooms requires an additional level of integrated design, testing, and validation before deployment.

Data analysis requires more than sampled data from the sensor node. It is important to interpret sampled data in context with ship operation, other machinery operation, sea state, and with historical data.

Collaborative development and in-field technology evaluation can accelerate technology development – the complexity of highly distributed, remote technology development has been more than compensated for by the high-calibre staff and staff dedication from BP CTO, BP Shipping, Shipboard captain and crew, and Rockwell Automation GMS working on this project.

This following summarises the results against the Success Criteria listed in 3.1; for detailed results, see section 13.

6.1 Works well in areas with high ambient and or transient RF

This was proven conclusively. Please refer to the RF analysis conducted during the 10 May 2004 trial that shows the Sensor Net. The results for the three RF trials demonstrated excellent wireless mote connectivity in the engineering spaces. The network discovery mechanisms were able to form a network within a few seconds and maintain connectivity throughout each test. The topology formed was consistently single hop and test packet end-to-end yields were greater than 99%. This performance was regardless of the mote locations. For the Bluetooth based motes, each trial was able to form a stable scatter-net (a Bluetooth ad-network) with only occasional reorganization of the topology. These reorganizations were witnessed in several other environments and are not attributed to the RF environment.

6.2 Works well in harsh physical conditions, i.e. Heat, vibration, salt water

The Sensor Net performed well in the engine room environment. Corrosion of the battery terminals was evident at decommissioning, some 7 months after installation. The fixing of the accelerometers using the “quarter-turn and glue” method did not work satisfactorily and a significant number became detached. None of the faults was due to the fundamental design of the Sensor Net.

6.3 Ability to operate in an “occasionally connected” mode

The nodes overall maintained a regular reporting schedule and were able to recover from errors in a previous sampling round.

6.4 Able to reliably capture data from multiple high-frequency analogue sensors and move the data to a central location using a multi-layer architecture

In addition to Sensor Net health, an analysis of the quality of the data from the Sensor Net we also performed. The objective was to evaluate the accuracy of the Sensor Net results and whether Sensor Net itself introduced errors. Although providing highly accurate vibration data was *not* an ultimate objective, an understanding of any errors or limitations of the data would be important for future installations. The determination of data quality was accomplished by controlled experiments and an evaluation of the shipboard collected data.

6.5 Ability of the system to accommodate the possible failure of a sensor or mote and continue to capture data with remaining operational components

The starboard cluster exhibited a lifetime of 136 days and centre cluster 42 days. Both of these are well beyond their expected lifetimes. Furthermore, the sensornets exhibited an 80% reporting success rate during the cluster lifetime.

7 Business Benefits

It is clear that if Sensornet technology can be packaged in a robust and certified manner to an acceptable pricepoint it can be a major contributor to Enterprises moving towards the goal of the “Realtime Enterprise”.

This project has shown that a rapid deployment is feasible (17 hours) and that having to wait for or pay for sensor cabling may be a thing of the past.

8 Acknowledgements

The achievements of this project should not be underestimated, it brought together 4 companies who rarely met face to face to design and deploy a system on a ship that berths around every 9 days. The logistics of creating a deployment that was installed commissioned and left for 5 months without being attended to.

The extraordinary collaboration between BP Shipping, Intel, Crossbow, Rockwell Automation and the Chief Technology Office of BP should be noted.