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Wireless Condition Monitoring of Machinery and Equipment in Maritime Industry: An Overview

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ABSTRACT

Seagoing vessels are highly complex systems. Major requirements of marine vessels are continuous running time and high production output. As such, these systems require high availability and reliability, and are dependent on preventive maintenance procedures. Development of diverse range of sensors, combined with overall reduction in price, enabled implementation of condition based maintenance in such systems. Large increases in fuel cost, environmental restrictions and further crew reduction are current trend in maritime industry. Considering marine sector emphasis on the reduction of fuel consumption, environmental restrictions, and reduction of crew size, implementation of condition based maintenance is favourable, especially with regard to lost man-hours. However, high initial cost of installation on moving vessels, necessary crew training and additional sensor maintenance inhibits implementation of condition based maintenance. Replacing wired monitoring system with wireless ship-board sensor network would mitigate the above mentioned problems. However, current research of wireless sensor networks is based on terrestrial installation. This paper analyses the application of wireless sensor network technology on board seagoing vessels. Practical engineering solutions, including sensor types, configurations and wireless network topologies have been identified and reviewed.

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1 Introduction

Seagoing vessel is a complex system with a variety of independently manufactured subsystems where a high level of the system availability and reliability is required. To comply with international regulations and environmental requirements, it is mandatory to perform vessel maintenance. Proof of the performed maintenance is to be recorded in Planned Maintenance System (PMS) [1]–[3]. Due to trends in the reduction of the crew on board, there is a decrease of available man-hours required to perform planned maintenance procedures. This in turn reduces the overall system reliability, and increases risk and possibility of incidents or accidents [4]. Condition Based Maintenance (CBM) depends on Condition Monitoring (CM) for management and monitoring of equipment condition and is an improvement over traditional planned maintenance [5]–[8]. The goal of CM is detection and identification of system deterioration prior to failure, in order to preserve system availability and safety [9], [10].

Various methods of CBM approach on board seagoing vessels has been devised, but there is still slow implementation within the global fleet [11]. With new developments in wireless technologies, this attitude towards CBM is changing [12]. The main reasons that inhibit the use of CBM consist of: high initial cost of deployment, long off time during installation, and additional maintenance of the installed equipment [13]. There is low confidence in CBM implementation even though benefits of CM enhanced maintenance are well documented in various fields of research [14]–[19].

Rapid development of an *ad hoc* networking and wireless communication technology has allowed for interconnection of large number of wireless sensors. Research for low power, wireless solutions has enabled implementation of Wireless Sensor Networks in various sectors. Wireless Sensor Networks have already been utilised in industrial sector [20]–[22], transportation sector [23]–[26], agronomic sector [27], [28] and oceanographic environmental sector [29], [30], successfully. Feasibility of the implementation of WSN technology on board seagoing vessels has been re-

searched in [13], [31]–[33] with promising results from the aspect of availability and reliability in harsh conditions.

Instrumentation for the measurement and control of shipboard machinery has traditionally been implemented via analogue point-to-point interfaces, Highway Addressable Remote Transducer system (HART), Fieldbus, Modbus or Profibus system [34], [35]. In such traditional architecture, every sensor must be connected to the central control unit via separate wiring or, alternatively, in a cable loop with intrinsic safety barriers as required. In characteristic tankers, such cabling can be over 100 km long [36]. In addition to high financial cost of sensor cabling, ship is a harsh environment where cabling is exposed to high temperature, salt, humidity and toxic chemicals. Wireless approach to sensor networking would allow a large sensor cabling reduction which would reduce the system complexity, weight and overall cost of the ship [37]. The second benefit is easy and simple reconfiguration of the existing wireless system in case modifications to the system are necessary.

This survey paper aims to describe the state-of-the-art WSN technology for condition monitoring of machinery and equipment on board a seagoing vessel.

2 Wireless Sensor Network

Wireless Sensor Network (WSN) consists of multiple independent, autonomous devices and sensors. In WSNs, the data organisation scheme is implemented and organised at central location or base station. Such distributed sensor networks are able to perform continuous monitoring of systems and machinery [38]–[40]. Machinery and infrastructure monitoring can be done by wireless devices on a single point of interest or cooperatively by distributed sensors within a network over multiple points [41]. Compared to un-networked systems, WSN condition monitoring technology enables continuous, autonomous, real-time data acquisition, which in turn improves data management and accessibility. Once installed wireless sensor nodes can form a self-organising network that can be automatically reconfigured. Different data types, acquired from different sensors, can be combined or separately processed. Individually acquired data are processed centrally in a networked system which allows an intelligent data analysis and fault prediction. Acquisition of

large amount of data over time enables creation of global trends. This type of process overview can be used to analyse and determine long term system degradation [42].

WSNs can be used to [6], [43], [44]:

- Maintain satisfactory operating conditions of processes under observation
- Verify and protect system and process stability
- Detect maintenance requirements
- Minimise downtime or repair time
- Prevent failures
- Perform maintenance scheduling according to prediction of failure instead of planned maintenance system

Both WSNs and traditional sensor networks enable real-time data acquisition but approach to WSN design is different than that of a traditional sensing network.

WSNs are inherently more unreliable in comparison to different types of distributed systems. There are severe constraints on sensor resources which affect programming, on-sensor code size, and pre-processing and computing capabilities. The greatest critical constraint is energy consumption which puts great emphasis on sensor energy efficiency. WSNs can be easily scaled upwards of thousands of sensor nodes so network support for large heterogenous networks becomes necessary. In case of large networks, manual sensor maintenance or configuration is unpractical or unfeasible, so self-configuration and self-management are of utmost importance [30], [45], [46]. For those reasons, a specific approach to WSN design must be implemented to prevent transmission errors, latency and missing or corrupt data. On board a ship, the quality of communication signal propagation is a major issue. Steel hull and ship bulkheads can attenuate signal penetration power and overall signal quality. Other issue is multipath effects from reflective and refractive surfaces as well as electromagnetic interference from surrounding machinery.

2.1 Wireless Sensor Network Model

Every WSN topology consists of some configuration of base stations and sensor nodes. There are several types of WSN topologies such as Star, Mesh (P2P) or Tree. The choice of WSN topology is constrained and mostly depends on the monitored system, network availability, required level of process reliability, and sensor node power

Table 1 Comparison of Traditional Network Design Approach with WSN Approach [42]

Traditional network approach	WSN approach
General-purpose approach	Usually for single purpose with specific design
<i>Major concern:</i> network performance and latency	<i>Major concern:</i> Network/Sensor energy consumption
Strictly planned design and implementation	Network structure and resource use defined ad-hoc
Generally used in mild environments	Used in harsh condition environments
Easy access maintenance and repair	Difficult physical access to sensor nodes
Device failure can be easily repaired	Sensor failure is addressed in the network design
Use of centralized network management	Local decision making

consumption. Mesh network is best suited for the optimisation of communication range, network flexibility, reliability or availability. For the maximisation of sensor node battery life, star topology is better suited.

Mesh WSN topology has been successfully tested on a ferry, with signal reliability greater than 97% [32]. Hybrid mesh-star architecture has been researched into [34], with good results from the aspects of redundancy and WSN reconfiguration in case of a sensor node fault. Multi-tiered hybrid wired/wireless sensor network for structural hull monitoring has been researched into [47]. The system has been tested in supervised and unsupervised mode for 30 days. Intercommunication between sensor nodes and wireless subnetworks has been found to be reliable with data losses within acceptable margin. WSN tree topologies for ship condition monitoring have been researched as part of a Commercial of the Shelf (COTS) product [48].

Base station is a gateway for data transmission between sensor nodes and a remote server. Sensor nodes communicate using short range communication protocols (WIFI, Bluetooth) and transmit measured data to the base station. Communication between base station and central control server is generally done over longer distances than internodal communication. Therefore, base stations require more power to operate and cannot operate long-term on battery power. Communication is achieved by long distance high powered wireless communication or via wired infrastructure such as Profibus or Modbus [34]. Lower power consumption constraint allows the use of more powerful computational and processing capabilities. Depending on the network topology choice and environment of installation, there are issues with short range of sensor nodes. Short range can severely limit reliability and availability of

sensor node communication with the base station. In that case, high throughput relay nodes can be used to relay information between sensors and base station.

2.2 Communication Protocols

Data transmission in wireless sensor networks depends on developed and implemented communication standards. Design and implementation of WSN depends on the choice of the communication protocol. Different communication standards for use in WSNs have been researched into [37], [40], [49], [50].

Wireless Fidelity (WIFI) is based on IEEE 802.11 b/g/n specification. It is one of the most popular general-purpose standards. It operates on 2.4 or 5 GHz frequency band with a maximum signal rate of 54 Mb/s. It has a nominal range of 100 meters and allows for up to 2007 cell nodes [50]. It is easily configured and allows good on board WLAN integration with high bandwidth. The major benefit to this standard is a long term device availability which is crucial for on board ship implementation. The major problem of WIFI technology is relatively high energy consumption compared to other standards which put greater constraints on implementation in sensor nodes. It can also be used as communication for interfacing mobile condition monitoring devices [51].

Bluetooth is based on a wireless radio system for interconnecting peripheral computer devices into a wireless personal area network (IEEE 802.15.1). It allows networking with mobile devices and personal mobile equipment like laptops or tablets. Bluetooth operates on 2.4 GHz frequency band with a nominal range of 10 meters. Piconet Bluetooth standard allows 8 cell nodes, but new Bluetooth 5 stand-

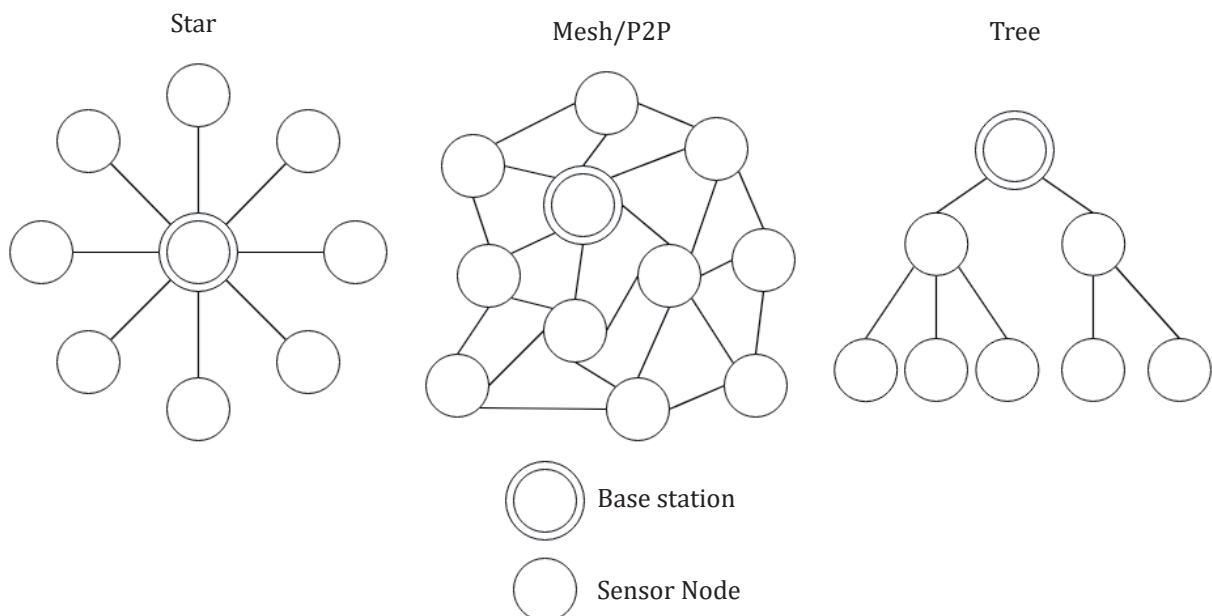


Figure 1 Block Diagram of WSN Topologies
Source: Adapted from [44]

ard with Low Energy amendment enables wireless mesh networking for up to 32767 nodes with the data rate ranging between 125 kb/s up to 2 Mb/s depending on the networking topology. It has a larger theoretical range up to 240 meters with low-power consumption of 30-40 mW during transmission [52]. Bluetooth wireless networking has been researched with regard to cold storage container temperature monitoring with backend cloud server support [53].

WirelessHART is a standard based on the HART communication protocol defined by the HART Communication Foundation and has been standardised as IEC 62591. It allows the use of star, mesh and combination of both topologies. WirelessHART operates on 2.4 GHz frequency band with IEEE 802.15.4 compatible Direct Sequence Spread Spectrum (DSSS). It and utilises TDMA communication scheduling with robust channel hopping scheme with a nominal signal rate of 250 kb/s. Frequency hopping scheme on a single packet basis improves on power consumption and system reliability. Nominal range of WirelessHART protocol is 30 meters up to 100 meters with an increase in power consumption [54].

ANSI/ISA 100.11a (IEC 62734) has been developed through the International Society of Automation (ISA) and is a standard similar to WirelessHART. It defines system management and security for wireless networks with low data rate and low power consumption. ISA 100.11a protocol supports mesh, star-mesh and star topologies. Standard operating frequency band is 2,4 GHz with DSSS/TDMA channel access and nominal signal rate of 250 kb/s [55].

ZigBee (IEEE 802.15.4) is a standard that defines specifications for low rate wireless personal area networks. ZigBee network consists of routers and end-devices. It provides mesh networking with self-organisational, multi-hop capabilities and low power consumption. ZigBee operates on 2.4 GHz frequency band although there are longer

ranged 868 MHz and 915 MHz bands for the use in Europe and North America, respectively. The nominal signal rate of ZigBee protocol is 250 kb/s or 500 kb/s depending on the device. It allows the use of mesh network topology with the possibility of interconnecting over 65000 end devices although, in practice, subnetworks can contain a maximum of 255 sensor nodes. Its nominal range for low power applications is 10 meters, but can be increased to 100 meters [50]. Sensor nodes that utilise ZigBee standard can be produced small because processing and communication subsystems of sensor node can be mounted on one chip. This includes both the microprocessor and the RF module. The user can adapt the communication cycle or active time versus sleep time as desired which is useful taking into consideration the sensor node battery life between 6 months and a year. There are issues with ZigBee application on board ships. In [56], the authors have researched into ZigBee WSNs for shipboard use and have found that there are problems with signal penetration of the ship hull. Signal attenuation due to low power transmission and interference with the existing WLAN and Bluetooth technologies has been found to be a prevailing issue. However, in [33], [57], the authors have successfully implemented self-healing multi-hop sensor ZigBee WSN on board a ferry and have concluded that, despite the steel architecture, ZigBee standard WSNs are possible aboard ships if the topology is chosen correctly. The full-scale ship application of WSNs has been researched into [58], [59], where the feasibility of ZigBee network on board a ship is confirmed by measurements done in the engine room and cabins of a training ship.

2.3 Sensor Nodes

Sensor node or a mote is a building block of a WSN. It consists of a sensing, processing, communication and power subsystems [42], [60].

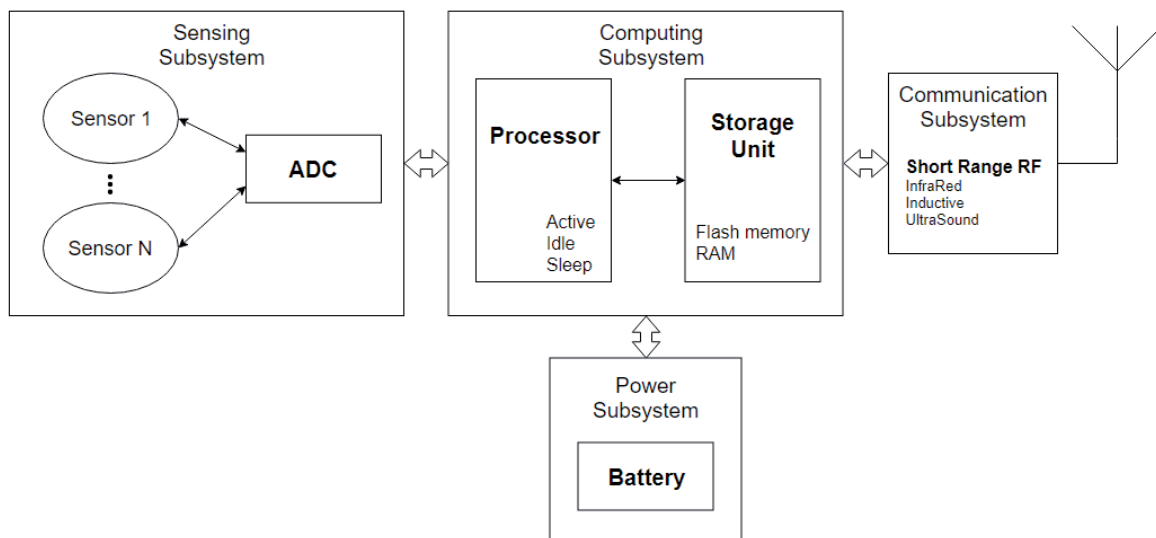


Figure 2 Block Diagram of a Characteristic Sensor Node
Source: Adapted from [42]

Table 2 Sensing Transducers Used on Shipboard WSNs

Accelerometers	Accelerometers are used for vibration measurements of rotating machinery on board a ship. They measure x-, y- and z- direction acceleration direction of propulsion machinery. Accelerometers are also used to measure rigid body dynamics of a ship, usually in combination with strain gauges to monitor ship motion and structural response.	[47], [62], [63]
Strain Gauges	Strain gauges can be used together with accelerometers to determine ship's hull strain response with regard to dynamic response. They are also used for shaft torsion or torque measurements of on board rotating machinery, primarily main engine. They can be resistive, or vibration wire based.	[47], [64]
Level gauge	Level gauging is prominently used on board to monitor fuel and lubrication oil level in holding tanks where it is necessary to know current liquid level. Where exact liquid level is not important, only low/high level state, floating gauges are used (bilge tanks). I	[34]
Temperature sensor	Temperature sensors most common measuring devices on board a ship. Most common uses are temperature measurements of: transformers, generators, engine and boiler exhaust gases, fuel and lubrication oil, cooling water system.	[65], [66]
Pressure	Pressure transducers are used on board to measure pressure of: Fuel and lubrication oil, hydraulic line, air and water system. Wireless pressure sensors are used in piezo-resistive configuration where change in membrane pressure affects output voltage.	[67], [68]

Table 3 WSN Sensor Devices Used for Condition Monitoring of Shipboard Machinery

Monitored Object	Measurement	Sensor	References
Hull	Dynamic response	Strain-gauge	[47], [62], [72]–[74]
	Vibration	Accelerometer	
Air Quality	Air contamination	Gas sensor	[75]
Fire System	Fire Detection	Thermocouple	[56], [59], [76]
		CO ₂	
		Humidity	
		Light	
		Accelerometer	
Main engine	Crankpin bearing temperature	Surface Acoustic Wave	[66]
	Gearbox Vibration	Accelerometer	[63]
Generator/Motor	Rotor Temperature	Digital Thermometer	[65], [77], [78]
	Excitation Voltage/Current	Hall Field Sensor	
	Rotor/Stator air gap	Capacitive sensor	
Holding Tank	Tank Gauging	Pressure transducer	[34]
Engine Room	Air Temperature	Digital Thermometer	[79]
	Shipboard machinery vibration	Accelerometers	[80]
Liquefied Petroleum Gas System	Gas leakage	LPG Gas sensor	[81]

Wireless technology allows the Micro-Electro-Mechanical Systems device (MEMS) integration with the wireless sensor node processing and communication subsystems. The advantage of MEMS is low operating power requirement and reduction in size and implementation cost. MEMS devices can perform temperature, pressure, displacement, piezo-electrical, capacitive and strain-gauge sensing, which allows the measurement of rotation, acceleration, vibration, proximity, velocity and position [61].

In a conventional wired sensor network, sensor is a sensing device or a transducer together with signal conditioning support electronics. In wireless networks, sensor is only a **sensing subsystem** of a sensor node.

Processing subsystem of a sensor-node consists of a microprocessor and a storage unit. Microprocessor con-

trols sensor node components and executes programmed commands. The main part of the storage unit is flash memory. Programming code that is executed by the microprocessor is stored in the flash memory. The second part of the storage unit is Random Access Memory (RAM). It contains measured or sensed data as well as variable data necessary for microprocessor computations. It is possible to extend storage data with external storage for off-line data retrieval such as SD card [60].

Communication subsystem allows inter-node communication and sensor-base station communication. Both of these communications are usually short-range ones. Most common communication technique is short range radio frequency. Other communication techniques such as Infrared or RFID can also be used, but are severely limited by power consumption or line of sight limitations.

Power subsystem of a sensor node is most often a battery. Battery drain of the sensor node depends on several factors. Those are power consumption of: individual sensors, wireless communication subsystem, microcontroller while in active power mode and power consumed in the sleep mode. WSNs require long sensor node life-time. In order to maximise battery life of a wireless sensor node, ultra-low power consumption with efficient power management is required. In addition to strict power management, there is a possibility of a local energy generation with emphasis on motion and vibration energy scavenging [69].

Implementations of vibration energy scavenging in the ship environment have been researched into [70], [71]. Self-powered sensor nodes have been installed on a BP ship Loch Rannoch and operated for four months. It has been shown that sensors have reliably harvested energy from low level pump vibrations in harsh ship environment with a good quality of measurement. Energy harvesting has been researched into [63], where authors have suc-

cessfully installed a vibration measuring sensor node with Seebeck energy scavenger in marine gearbox.

3 Wireless Condition Monitoring

Data acquired from sensors are characteristically obtained in the form of time series where the process is typically continuously measured. Continuous condition monitoring can immediately detect system faults and problems. Issues of continuous monitoring are high price of installation and overall large system of power consumption. This approach is not suitable for WSNs because of energy constraints on sensor nodes. In case of noisy sensor readings, data pre-processing is required to obtain reliable results. Sensor nodes can already have pre-processing capabilities implemented in the processing subsystem, but power intensive data processing is generally done in base or central stations. Time scheduled, or periodical monitoring uses less energy and allows data filtering and pre-

Table 4 Overview of Prevalent Commercial Products for Ship Machinery Condition Monitoring

Machinery Monitoring Systems	Description	Ref.
SKF – MULTILOG	SKF Multilog is an eight-channel, field-mounted monitoring device. Communication is based on 802.11b/g/n wireless protocol. It is used to collect acceleration, velocity, displacement, temperature and bearing condition data with automatic upload to SKF @ptitude Analyst software.	[82]
Nomia S.A. – LAROS	LAROS system sensors measure RPM, torque, power, fuel and lube oil consumption, pressures and temperatures. It is based on ZigBee protocol based on IEEE 802.15.4 standard.	[48][83]
OneProd – EAGLE	WSN condition monitoring system based on IEEE 802.15.4 communication standard on 2.4 GHz ISM band. It allows for sampling frequency between 256 kHz and 51.2 kHz with nominal range of 100 meters.	[84], [85]
VESKI – CoDiS RM	Wireless Rotor Monitoring system for monitoring generators with brushless exciter. CoDiS RM is used to monitor temperature of rotor pole windings, excitation current and voltage, magnetic field and rotor/stator air gap. It utilizes WIFI RS232.	[65], [78]
Kongsberg – SENTRY	SENTRY System is designed for temperature monitoring of: reciprocating compressors, large diesel and gas engines, turbo couplings and generators. Wireless sensors are radar based passive devices without need for external power. Low energy, high frequency radar pulse is transmitted from base station to sensor via stationary antenna.	[66], [86], [87]
Noris Group – NORIFID	Wireless data acquisition system where data and power are inductively transmitted (13.56 MHz RFID). Reader consists of a transformer, microcontroller, and signal converter. Reader is supplied by external power source. Sensor is constructed from a transformer, microcontroller and Pt100 measuring element	[88]

Table 5 Overview of Prevalent Commercial Products for Condition Monitoring of Ship Cargo

Intermodal Monitoring Systems	Description	Ref.
ORBCOMM – VesselConnect	VesselConnect enables local and remote monitoring and control of refrigerated containers on board a ship. It allows monitoring of temperature, humidity, location and slot position and reefer container status. VesselConnect application can also be synchronized with remote land-based server. It utilises ReeferConnect Unit (RCU) with 3G UMTS capability on 850/1900/2100 MHz frequency bands and ZigBee mesh network functionality.	[89], [90]
Maersk – RCM	Remote Container Management (RCM) is a WSN for reefer container monitoring in a star topology. Reefer containers are fitted with a remote container device (RCD). Each RCD unit is equipped with a 3G SIM card, a GPS unit, a ZigBee radio transceiver and an antenna. RCM base station receiving antennas are installed on the bow and stern of the ship. They receive the data from containers and transmit them to a VSAT dome where data are sent via satellites to Maersk's data centre.	[91], [92]

processing. Data sampling frequency or time scheduling scheme determines sensor node microprocessor active and sleep times, as well as time slots for wireless data transfer. The choice of the monitoring strategy depends on measurement frequency criticality of a monitored system.

3.1 Shipboard Wireless Condition Monitoring Systems

Ship is a complex system with different subsystems included. This complexity, together with a harsh environment, separates ship's wireless condition monitoring systems into two main groups: fixed systems for the monitoring of machinery and intermodal systems that enable wireless monitoring of movable cargo and equipment.

Different ship subsystems are commonly purchased from different manufacturers with distinct technology for system measurement and control. These systems are designed and produced to provide condition monitoring solution for a single or multiple ship subsystems as presented in Table 4.

Intermodal WSN condition monitoring systems enable wireless monitoring of movable cargo or equipment. Commercial systems for cargo monitoring rely on the implementation of GSM communication technology on board ships. In this way, it is possible to create a floating WIFI sensor network that enables on board monitoring of containers with installed sensor nodes. General status, alarms and monitored values of reefer container can be directly monitored by the crew on board a ship and operations personnel ashore at the same time. The acquired data can be transmitted from ship to shore by broadband satellite network. Wireless on board monitoring reduces work-hours and increases crew safety, by reducing the need for a visual check of refrigerated containers [89]. Commercial WSN cargo condition monitoring systems encompass on board and ashore cargo and equipment monitoring. Prevalent solutions are presented in Table 5.

4 Conclusion

In this paper, a review of WSNs in condition monitoring of ship machinery and cargo has been presented with emphasis on current engineering solutions. Although conventional CM systems have already been proven to enhance fault detection and increase system availability and reliability, there is still low confidence in shipboard CBM implementation. Advantages of WSN CM systems that allow mitigation of conventional CM issues are presented. Major issues in shipboard implementation of WSN CBM systems are feasibility with regard to transmission quality, operation in harsh marine environment and cost effectiveness. Communication standards have been presented and it has been established that communication quality primarily depends on the chosen communication standard and the ad-hoc network topology selected. ZigBee protocol is most commonly researched into due to its low power consumption in low data rate applications. Mesh and mesh/star topology variants are most prevalent and give the best

results from the aspect of signal quality and network robustness. Practical engineering implementations of WSN sensing transducers have been presented for different types of ship systems. Power consumption issues of WSN sensor nodes with regard to feasibility of long term power scavenging have been reviewed. In this paper, WSN CM is divided into fixed systems for the monitoring of ship machinery and intermodal systems for movable cargo and equipment monitoring. Several commercial implementations of WSN CBM for the ship use have been researched into, where different manufacturers focus on different ships subsystems.

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