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Applications of Industrial IoT and WSNs in O & M programmes for Offshore Wind Farms

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Abstract Expanding reliance on offshore wind as a renewable energy source requires thorough consideration of the role of remote monitoring in improving operations & maintenance and reliability of wind turbine access, reducing costs and increasing health and safety for repair workers. Costs related to O&M and challenges with reliable turbine access are likely to increase as wind turbines move further from the shore and into more extreme ocean environments, such as those under exploration for floating wind turbines.

Real-time collection, transfer and analysis of data relating to the sea state, and monitoring the integrity of the wind turbine structure and its individual systems and components has significant potential to reduce the Levelised cost of electricity (LCOE). Advances in computational capabilities and the increasing connection of sensor networks through the Internet of Things (IoT) have allowed for an expansion in the use Wireless Sensor Networks (WSNs), capable of monitoring the condition of individual components of a wind turbine, such as temperature and vibrations or the system as a whole. This research provides a review of past experience installing WSNs to monitor several aspects influencing offshore wind energy, such as the turbine structure, components and local environment and discusses WSN technology and computing requirements. Although the experience in installing and utilising WSNs is extensive, there is a lack of coordination and standardisation for WSN systems in offshore locations. This paper seeks to clearly define the steps to follow when setting up a WSN connected by IoT, based on an example gas turbine from oil & gas and and introduces suggested guidelines for implementing these systems.

Keywords Internet of Things · Operations & Maintenance · Wireless sensor networks & Offshore wind energy · renewable energy

1 Introduction

Wind energy is recognised as one of the most promising renewable energy resources, and rapid deployment can be attributed to the falling costs of both onshore and offshore wind power, which combined, could be the least-cost option for new power generating capacity (Taylor et al. 2016). REN21 (2018) noted that, as of 2018, the cumulative capacity from both onshore and offshore wind farms is 539 GW, an 11% increase from the total capacity in 2017. As of 2020, the total capacity has increased to 622 GW, of which 28.3 GW is from offshore wind (Whiteman et al. 2020), though this is projected to increase rapidly; for example, the total installed offshore capacity saw a sevenfold increase from 2007 to 2018, and this is expected to continue rising.

However, high operations and maintenance (O&M) costs pose a hindrance to more universal deployment. The lack of on- and off-shore infrastructure, high costs of site selection, construction, installation, and O&M are some reasons that offshore wind has not expanded more uniformly and has a comparably high levelised cost of electricity (LCOE), relative to onshore wind. As of 2020, 78% of installed offshore wind capacity is located off just 11 European countries with 21% located in China (Whiteman et al. 2020).

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Taylor et al. (2016) has estimated that the LCOE of offshore wind energy could be decreased by as much as 35% with continued improvements in technology and turbine access methods. The increasing distance from the shore and more extreme ocean conditions found in deeper water exacerbates challenges in accessing the wind turbines, an ongoing issue for both fixed and floating wind turbines. Meeting global carbon emissions targets will rely partly on offshore wind energy, and it is therefore more vital than ever to develop reliable and secure non-intrusive systems for environmental and condition monitoring. For a more complete summary of factors considered influential to offshore wind farm operation and maintenance planning, see i.e. Seyr and Muskulus (2019).

1.1 Remote monitoring in offshore environments

Advances in remote sensing and computational capabilities have increased the prospect of remote monitoring wind turbine components and real-time data collection of environmental and sea state conditions. Increased availability of inexpensive, low-powered computational components such as processors, radios and sensors all integrated on a single chip has allowed for expansion in wireless sensor networks (WSNs). WSNs function by sensing fluctuations in their environment and collecting and processing data relevant to the monitoring parameter. The simultaneous evolution the Internet of Things (IoT) has then allowed for real-time transmission and communication between the sensors, representing the data in an "internet-like" structure (Yinbiao et al. 2014).

Wired sensor networks are widely employed but require cables and conduit to reach devices in remote locations; WSNs could provide a more affordable and versatile system (Lestari and Arafat 2019). Properly utilising WSNs can minimise the number of *in situ* personnel required, thereby increasing health and safety for repair workers; allow for real-time data input to decision-making; maintain system integrity; reduce the O&M costs and greenhouse gas emissions due to transport within the offshore industry (Akhondi et al. 2010; Carlsen et al. 2008; Petersen et al. 2008; Shukla and Karki 2016). The expansive benefits of effectively applying WSN technology in offshore wind O&M are further include potentially increasing the turbine lifespan, improving health and safety, reducing turbine downtime and increasing the power output. Sensors can be applied to each element of the turbine structure, as well as the support vessels, and other instrumentation to remotely monitor the sea state. Data collected from sensor measurements or wave buoys monitor changes in parameter such as temperature, flow, pressure, vibrational frequency, sea state (Chen et al. 2018).

Despite the growing deployment of WSNs, there exists a lack of comprehensive guidelines available to offshore wind farm O&M managers and stakeholders for organising WSN installation decision support systems. Decisions encompassing WSN application require multiple inputs based on measurement parameters, selecting appropriate sensor components, determining suitable topology, WSN system architecture and data requirements. The decision framework is similar whether required measurements relate to condition monitoring (CM), structural health (SH) monitoring, or environmental monitoring, although differences exist in the most applicable technology. This paper will seek to address the current state of WSNs where remote monitoring could be crucial, particularly in these three listed areas of focus.

This paper is structured as such: Section 2 provides a review of previous research in WSN applications in the offshore wind energy sector, including an overview of practical deployment of WSNs in the offshore wind industry and identification of the common challenges and proposed solutions; Section 4 illustrates a sample structure of the decision-making process when building a WSN system for offshore wind turbine monitoring; and Section 6 summarises the suggested guidelines when designed the decision support system for application of WSNs for monitoring offshore wind turbine structure, condition and ambient environment.

2 Background - practical applications of WSNs in offshore environments

The offshore industry has extensive experience installing and using WSNs to monitor three areas of focus mentioned in Section 1.1, condition, structural health and environmental parameters. Condition monitoring tracks the health of the turbine components, such as gears and bearings (Carroll et al. 2015), structural health monitoring looks at the structure as a whole (Lestari and Arafat 2019) and environmental monitoring can consider a wide range of areas from sea state, free surface and environmental conditions, scour, and biofouling from microorganisms, all which can impact the health of the wind turbine and ease of access (Xu et al. 2014).

Sensor measurements of vibrational, acoustic, pressure, or temporal parameters allows for improvements in both preventative and predictive maintenance with the potential to improve post-fault diagnostics (Petersen et al. 2008). Diagnostics are typically performed on the structure and system separately, where equipment and structure diagnostics tries to determine the root cause of a component failure and system diagnostics is performed on a wider system of components.

Detection of component condition or structural faults in the wind turbine relies on monitoring of certain physical properties in a healthy system in operation, such as vibration frequency. Data based on a system in correct working order can be used to "teach" a sensor network using machine learning algorithms to detect when issues within the system arise.

WSN solutions that provide remote monitoring capabilities for the offshore industry must adhere to new technology, regulatory and productivity demands, and be capable of safely collecting, transmitting and processing data at an

Table 1 Types of condition monitoring systems and relevant mechanical components, according to \cite{Carroll2015}.

	Vibrational Analysis	Acoustic Emission	Oil Analysis	Strain	Shock Pulse Method	Displacement	Optical Fibre	Electrical Effects	Temp.
Gearbox	x	x	x		x				x
alternator	x				x			x	x
Bearings and Shaft	x				x	x			x
Blades		x		x			x		
Tower		x		x		x	x		
Foundation		x		x		x	x		

appropriate bandwidth (Carlsen et al. 2008; Lestari and Arafat 2019). This section will provide a review of inputs into the decision making system for setting up a WSN connected with IoT, based on past literature and reporting of practical usage. In addition to specific technology and areas to monitor, the following review provides a discussion of overlapping themes such as battery power and secure data storage and transmission.

2.1 Structural and Condition Monitoring

Some common methods of detecting faults in the condition of the system components or structure rely on vibrational analysis in time, frequency, or modal domains (Carden and Fanning 2004). Vibrational monitoring has been used in fields with difficult-to-access components, such as the aerospace and offshore oil industries since the 1970s and 1980s where computational models were compared with measured modal properties from undamaged and damaged machine components to detect damaged parts (Farrar and Doebing 1999). Carroll et al. (2015) outlines common methods of analysis and the relevant asset within the turbine where the methods are relevant, displayed in Table 1.

Extensive research has been conducted to explore which of the numerous structural components in a wind turbine are most prone to failure, i.e. (Fu and Yue 2012; Hahn et al. 2006; McMillan and Ault 2007). Figure 1 depicts the malfunction rate as a percentage of the total number of malfunctions, and the corresponding downtime as a percentage of the total downtime (Soua et al. 2013). From this figure, it is apparent that although the turbine gearbox, alternator and main shaft/bearing and gearbox account for only 10% of the malfunctions, they result in 53% of the total downtime. Figure 1 collates data from previous research to summarise the likelihood of failure of turbine components. Interestingly, structural components most prone to failure do not necessarily result in prolonged turbine downtime, which is illustrated in the right side of Figure 1.

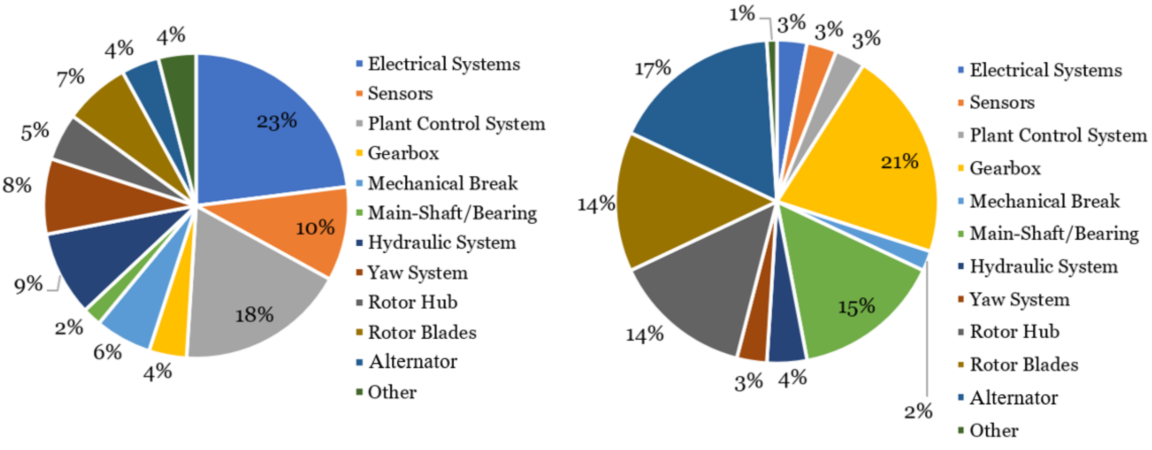

Fig. 1 Break down of equipment malfunctions and subsequent turbine downtime. Left: Unforeseen malfunction rate as a percentage of the total number of malfunctions; data adapted from (Hahn et al. 2006). Right: Downtime per system as a percentage of total downtime; data adapted from (McMillan and Ault 2007). Image adapted from (Soua et al. 2013), where absolute downtimes vary in the range of 7.5-15 days between different wind farms.

Damage to the turbine structure is most often caused by moisture absorption, fatigue, wind gusts, thermal stress, corrosion, fire and lightning strikes (Martinez-Luengo et al. 2016). Environmental impacts, such as Wave and current forces and biofouling, corrosion and scour affect the lifetime of the turbine support structure (Martinez-Luengo et al. 2017; Klijnstra et al. 2017). Multiple distributed monitoring systems, such as the system suggested by Wu et al. (2019), can measure several aspects of the structural health simultaneously using conventional 1/4 bridge single dimension strain gauges.

Wang et al. (2012) note several commercially available WSN systems for monitoring the condition of the structure and system components, such as the University of California, Berkeley TinyOS/Mica, Smart Dust, and PicoRadio platforms and the ZigBee Alliance, developed by Invensys, Mitsubishi Electric, TI, Motorola, Philips, and more than 20 other semiconductor and IT companies. The authors also explored some of the key issues related to setting up a structural health monitoring system within a WSN, including compatibility between sensors, their sampling frequencies and operational modes, transmission bandwidth, selection of a transmission frequency and balancing energy consumption requirements across a range of monitoring needs.

Swartz et al. (2008) discusses dynamic data collection and modal analysis for a WSN system utilised for on-shore wind. The structural health data is collected dynamically, which is input into mathematical models applied to predict outputs of an asset in good working condition. Real-time monitoring allows for a comparison to the modal frequency, where changes can indicate damage detection. Additional discussion around scientific computing is included as Section 3.4.

2.2 WSNs for Environmental Monitoring

WSNs play an important role in improved real-time collection of environmental data influencing the performance of an offshore wind turbine, such as temperatures, airflow, air pressure (Dunbabin and Marques 2012). Wave buoy measurements of free surface displacement can be integrated into the WSN to consider wave pressure on the turbine structure, and pressure gauges measuring the hydrodynamic force within the wind turbine access zone could improve the reliability of inputs into the vessel motion monitoring systems and increase the success of access (Xu et al. 2019; Lazarescu 2013; Edesess 2018). Meteorologists assist in predicting turbine power output by monitoring set of physical variables such as temperatures, airflow, and air pressure, to study the weather and to forecast its behavior. WSNs, autonomous vehicles and radar technology collecting information about the sea state and seabed can also positively influence the success of O&M decision support systems, and assist in structural health monitoring. Data collected about the environmental conditions through sensor networks and other remote monitoring methods be connected with the structural data to better plan access windows (Dalgic et al. 2015).

Fahrni et al. (2018) discusses the feasibility of utilising autonomous vehicles to monitor the subsea structure, classified into the following two areas of importance: export/array cable surveys and repairs; and measuring scour around the base of the turbine. Appropriate use of sensors and standard work class and observational Remotely Operated underwater Vehicles (ROVs) could reduce the need for human operators to install, maintain, inspect and repair subsea infrastructures, especially in unplanned or routine condition monitoring or regulatory inspections (Fahrni et al. 2018; Jacobi 2015).

Advancements in wave radar technology has allowed for some good initial comparisons between spectral wave models obtained from a Doppler radar and a wave buoy (Ponce de León et al. 2017). Sea clutter images, which are a sequence of images of the sea surface obtained through a wave radar system, can also be integrated into the WSN to assist with maintenance planning and repair crew access. Sea clutter images can be inverted to monitor the sea state in real time (Nieto Borge et al. 2000, 2004). Researchers found that two-dimensional spectrum obtained from a two-dimensional Fourier transform of digitised radar images is similar to the spectrum obtained from a wave buoy (Young et al. 1985).

At present, the most economical crew access method for offshore wind turbines is via transfer vessels and predicting safe access relies wave buoy measurements of significant wave height (Dalgic et al. 2015; Halvorsen-Weare et al. 2013). However, H_s has not been shown to be an accurate predictor of successful access Rostrøm (2018). Although the frequency of failed access attempts is difficult to determine accurately, it has been found that even for near-shore wind farms, such as those off the coast of Ireland, access for planned maintenance was only possible 50-75% of the year (Breton and Moe 2009).

Integration of environmental systems, such as a combination of wave buoy, marine radar and pressure gauge measurements with a WSN system monitoring the structural and asset health could assist in increasing the probability of successful access, lowering the overall costs of offshore wind energy production and in reducing the risk to repair workers (Echvarria 2008; Fahrni et al. 2018).

Increased connectivity across each of these devices using industrial IoT would allow a means to collate environmental and structural data together and increase the robustness of decision support models. Xu et al. (2014) provides a summary of existing marine environment monitoring projects, as of 2014.

3 Technology requirements and challenges to address

Section 2 outlined some of many uses for WSNs in an offshore environment, such as in increasing the life cycle of the turbine, improving predicted power output, better maintenance planning and more reliable access. In this section, a discussion is provided about technology requirements and challenges to address when designing and installing a WSN. Akhondi et al. (2010) summarises Some of difficulties related to connectivity and data transmission:

- Restricted size, shape, construction and certification of sensors;
- Limited processing power, memory storage and battery life;
- Difficult wireless environments: noise and obstructions are common, as well as areas where there are restrictions on the use of radio devices;
- Must integrate with existing IT solutions;
- Must operate in a harsh and dynamically-changing environment;
- No clearly defined guidelines for operating and using WSNs in the offshore environment.

In addition to these challenges related to data collection, transmission and power requirements, rapid expansion of WSNs in the offshore environment is the fast-changing rules and processes for deployment and maintenance strategies. At present, systems for wireless monitoring are being developed separately, and are often incompatible with each other. There exists a need to standardise the devices used, methods of data management, analysis and reporting Xu et al. (2014). It is also important for the WSN to be sufficiently robust in the marine environment to reduce the need for personnel on-site; Petersen et al. (2008) noted that the issues often arise in the adoption of new technology when the human factors, such as seasickness and safety in installation, are ignored.

With technology improvements and expansion of IoT capabilities, efficient wireless communication is a crucial component managing power and data storage needs. Table 2 details some wireless communication protocols available for structural monitoring. These low cost, low power and low bandwidth WSN systems are mainly suitable for non-urgent strain deformation measurements, which require a slowly varying signal. Higher frequency data, such as that from vibrational measurements or image acquisition require a higher transmission bandwidth (Wang et al. 2012).

Table 2 The carrier frequency and transmission bandwidth of ZigBee Alliance and the IEEE 802.15.4 standard. Table adapted from Wang et al. (2012).

Carrier Frequency	Band Nature	Maximum Bandwidth	Frequency Point
2.4 GHz	ISM Worldwide	250 kbps	16
868 MHz	Europe	20 kbps	1
915 MHz	ISM Americas	40 kbps	10
780 MHz	802.15.4c (Chinese)	250 kbps	8

Hempstead et al. (2008) summarises a range of sampling rates for varying monitoring areas from very low-frequency sample rates like atmospheric pressure measurements, which have a sample rate around 0.017-1 Hz, up to high-frequency components such as acoustic or vibrational measure, which can require sampling rates of 40k Hz to 1M Hz.

The sections below will consider power requirements and suggested solutions, a summary of typical topologies, issues related to cyber security and a brief overview of high performance computing and machine learning algorithms for managing the WSN and collected data.

3.1 Power requirements

The architecture of most WSNs in the marine environment incorporates a power supply module and energy storage devices such as rechargeable batteries, and a power management system with renewable energy harvesting devices, such as solar panels, wind harvesting, a tidal power generator, or a seawater power generator (Xu et al. 2014; Anastasi et al. 2009). These methods of energy harvesting can display non-continuous behaviour however, thereby requiring their own energy storage method (Paradiso and Starner 2005).

Battery-powered sensor nodes can have an adverse effect on their sensory range if the batteries do not hold significant charge. When the sensor nodes are in a sheltered environment or within machinery, the sensory range reduces rapidly to no more than a few meters (Yinbiao et al. 2014). Optimal ranges of between 800 – 1,000 meters can be reached when nodes are in free space with a clear line of sight to one another, and range extenders for radio frequency (RF) transceivers are commonly used to increase the range (Albaladejo et al. 2010). As power is a key factor in the operation of a sensor node, transceivers and other utilities can be put into an idle state to conserve power and reduce energy consumption.

Figure 2 illustrates that the transceiver consumes comparable energy when transmitting or receiving as when it is in an idle state. A significant amount of energy can be saved if the transceiver is put in a sleep state rather than idle, effectively turning it off when the node does not need to send or receive information. While in the 'sleep state' certain parts of the transceiver are switched off, and nodes cannot immediately relay information which can result in a significant allocation of battery power for start-up and recovery time required to leave the sleep state (Ferreira and Alves da Silva 2007; Mhatre and Rosenberg 2004)

Anastasi et al. (2009) provides a comprehensive review of power needs of different subsystems within the WSN and notes that the energy consumption of the communication subsystem is considerably higher than the computation substation. Swartz et al. (2008) recommends reducing the need for communication by processing the data on site within the WSN and being selective when choosing the wireless communication channel. Parallel and distributed algorithms

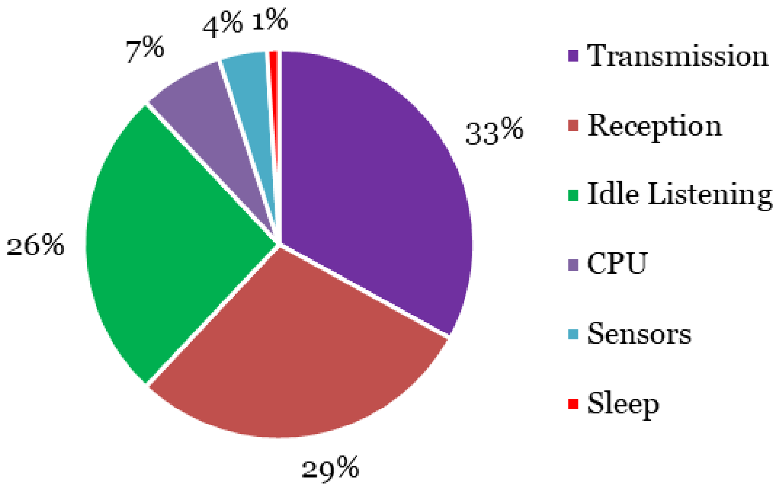

Fig. 2 Power consumption of a generic sensor node to receive and transmit information. Image adapted from (Fischione 2014)

allow for data to be processed directly within the sensor network and reduce battery requirements (Tanner et al. 2002). A summary of example algorithms to process data *in situ* are further discussed in Section 3.4.

3.2 Topology

Selecting a good topology can extend the overall life cycle of the network Xu et al. (2014). Wang et al. (2012) provides a comprehensive summary of the three common topology types: star, cluster tree and mesh and discusses the advantages and disadvantages of each.

The best topology type and method of communication depends again on the needs of the system. Nodes in single-hop communication can transmit information directly to the centralised gateway whereas multi-hop communication seeks to reduce the distance between nodes. Theoretically, multi-hop routing has been shown to be more energy efficient (Fedor and Collier 2007), but some research has shown that single-hop routing can be more efficient (Pesovic et al. 2010).

If the transmission ranges of the sensor nodes are sufficiently large or the sensor cloud radius is less than that of the sensor nodes transmission radius. The nodes form a star topology, each with single-hop communication. Nodes in single-hop communication can transmit information directly to the centralised gateway if the transmission ranges of the sensor nodes are sufficiently large or the sensor cloud radius is less than that of the sensor nodes transmission radius. Figure 3 displays the common topology types, where cluster/tree and mesh use multi-hop communication.

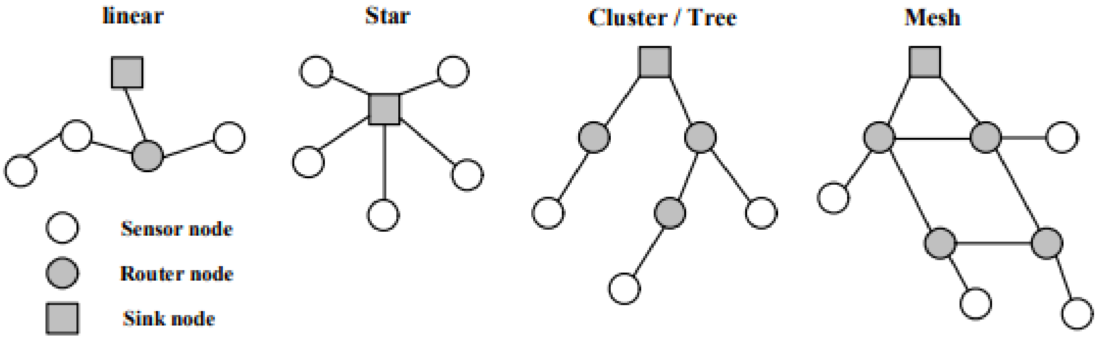

Fig. 3 Typical wireless sensor technology topology types. Image adapted from Xu et al. (2019).

When sensors make use of single-hop communication, there is no relaying of packets of information (Pesovic et al. 2010; Fedor and Collier 2007). Each node should transmit their data in sequence, given that communication is directly between the sensor node and the gateway, *i.e.* one at a time. In this instance, the lifetime of the network is determined by the node with the shortest life span, typically the node furthest away from the gateway in a single-hop network. The lifetime of this node is reduced because it must expend the most energy to transmit information (Chhaya et al. 2017;

Gupta and Kumar 1999). If it is assumed that all sensor nodes are alike within the sensor network, it is possible to dimension the battery based on the sensor node with the greatest energy needs. In addition, fewer connections reduces the possibility of losing data in transmission and provides fewer entry points to the network from foreign invasion.

The environment also influences the battery power and is characterised by the ‘propagation loss exponent’, or the k value, also known as the Peukert constant (Doerffel and Abu Sharkh 2006). In free space $k = 2$, and within buildings, factories, machinery spaces and dense vegetation, the value of k increases to approximately 3 – 5; values of which can be estimated from tables representing different environmental layouts or parametric values.

There are advantages to a multi-hop topology, depicted in Figure 4 such as shorter distance between nodes and greater contingency planning in case of beacon or gateway failure. In multi-hop transmission, each beacon transmits its data in sequence directly to the gateway.

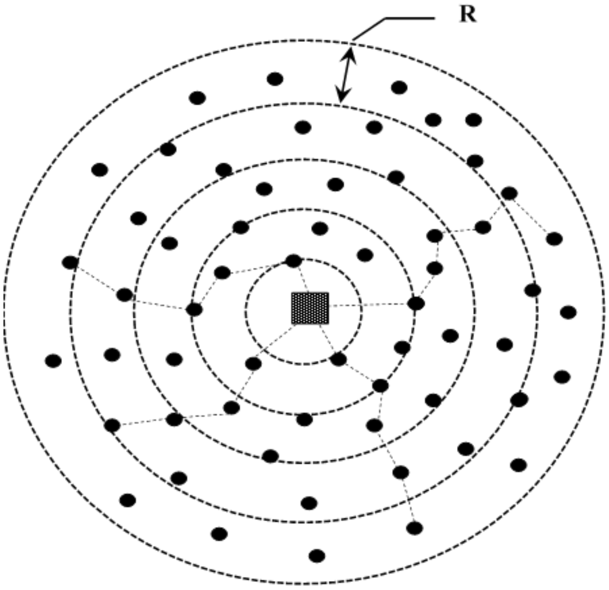

Fig. 4 Multi-hop wireless network with indicated sensor communication radii, R.

The quality of coverage is typically defined by the coverage ratio (Mamun et al. 2010). A target region or monitored network. An example of node deployment of maximum coverage for multi-hop transmission is shown in Figure 6.

Data loss is possible in the case that the node becomes faulty. Some beacons, such as those designed by Bluvision have a small amount of RAM to temporarily store data in the event that the beacon fails to operate. Once the temporary storage capacity has been allocated, the oldest recorded data is deleted to allow for the recording of more up-to-date data. Bluvision technology is also capable of transmitting to an alternative gateway as a temporary storage point in case of failure.

Commercially available beacons such as Bluvision beacons also equipped with a method of notifying an operator in case there is no alternative gateway, and a human can go to replace the gateway along with any mobile device fitted with the Bluvision technology. This allows for almost any Bluetooth enabled device (Smartphone, tablet, laptop, etc.) to act as a temporary gateway while the main gateway is repaired or replaced. In this event, a sufficiently fast response can recover all data, as the beacons will transmit past stored data to the mobile gateway along with any updated data.

3.3 Cyber security

As WSNs become larger and increasingly intricate autonomous systems, the level of security required for an operator, individual and transmitted data significantly increases. The overall level of security in the network is defined by the weakest link or point. Whilst the research contained within this report is focused on the physical design and layout of a WSN and does not consider the software in great detail, it is important to give an overview of cyber security and cyber-attacks, which are essential to consider when designing a WSN (Chhaya et al. 2017; Rahmand et al. 2010).

Security concerns are typically related to the following issues:

- confidentiality, which concerns the secrecy of data communication;
- availability, which implies that consistency in service should remain upheld in the event of attack;
- authentication, which is necessary for the prevention of fake data from malicious nodes;
- integrity, which signifies that the data, information or messages are received unaffected at the destination;

- authorization, in which only authorised sensor nodes can communicate to each other, and unauthorised access of data must be prevented;
- freshness; fresh data is important to ensure that the attackers do not replay old data to hinder the security of the WSN.

WSNs must implement strict encryption, transmitter availability and consistent data validation with constraints on power, memory, computation and bandwidth. Generally, WSNs are susceptible to a multitude of cyber-attacks and security issues. In sensitive applications, it is imperative that the security of WSNs is assured from generic attacks (Alajmi 2014; Rahmand et al. 2010).

Production of effective WSNs must ensure that addressable security issues are dealt with, and other security issues identified should be managed and accepted. Bellekens et al. (2015) proposes incorporating a cyber-physical-security model into the development of the WSN, rather than consider this issue as an after thought. With this in mind, many WSN devices and nodes should be used for redundancy purposes as they cannot be relied on for critical tasks (Rahmand et al. 2010).

3.4 Machine Learning and Scientific Computing: Algorithms for decision systems

Scientific computing and machine learning algorithms play an important role in every stage of remote monitoring through WSNs, such as; operational evaluation; data acquisition, normalization and cleansing; feature extraction and information condensation; and statistical model development. If the data processing step can be completed within the WSN itself, the amount of data to be broadcast is relatively small relative to the high-bandwidth raw data. Scientific computing through parallel and distributed algorithms, where data is promised directly in the WSN, has been explored more recently as a promising solution to managing battery power (Swartz et al. 2008).

Most wind turbines are presently manufactured with an integrated system for condition monitoring, such as a Supervisory Control Alarm and Data Acquisition (SCADA) system (McMillan and Ault 2007). Computational methods are crucial in determining the overall benefits of a WSN system; (Andrawus et al. 2006) attempted to quantify the economic benefits by considering a reliability-centred maintenance and asset-life cycle analysis coupled with a Monte Carlo simulation to introduce uncertainty into key variables.

Lian et al. (2019) summarised algorithms developed for feature information extraction and identification, safety evaluation and reliability analysis, and the intelligent operation and maintenance. Martinez-Luengo et al. (2016) summarises several structural monitoring methods using a statistical model development framework comprising both supervised and unsupervised learning algorithms.

Xu et al. (2014) provides a thorough review of algorithms utilised for processing data on-site within the WSN and for filtering data to be processed. Agarwal and Kishor (2014) discusses application of a threshold selection and fuzzy inference system for real-time fault detection.

4 Case study

Sections 1, 2 and 3 review past literature investigating past experience and research in installing WSNs in the offshore wind environment, including: exploring the importance of identifying key parameters; selecting the appropriate technology and topology; consideration of storage and required bandwidth; and security requirements. Despite the extent of the literature, no clear guide exists for the decision making process more generally.

Although the physical parameters, suitable technology and bandwidth requirements differ depending on the monitoring domain, some steps can be generalised to apply more broadly. In this section, a decision theory application is presented for determining the most suitable WSN topology for a sample asset integrity monitoring system employed in the offshore industry. An example decision tree for developing a WSN to monitor an electrical system component in an offshore wind turbine is presented here, based on research by Loughney (2018), which focuses on the constructing a WSN to monitor the electrical generation system on board a fixed steel platform in the North Sea.

The sample given here will consider the applied methodology in assembling the decision system to construct a WSN to conduct vibrational, thermal and acoustic analysis of offshore wind system components. Although the research conducted by Loughney (2018) relates to a gas turbine electrical system, the methodology is relevant to a WSN constructed to monitor comparable systems in offshore wind. Similar vibrational, thermal and acoustic measurements can assist in determining the health of an offshore wind turbine gearbox and alternator, which result result in the most significant amount of failures and cause the greatest amount of turbine downtime (Soua et al. 2013; McMillan and Ault 2007).

The decision making process presented here is primarily concerned with the design and topology of a WSN with varying connection types and methods of relaying data within the gearbox and alternator monitoring system. This provides a baseline sample from which the network can then be further expanded by incorporating more nodes and selecting software to complete the WSN.

The primary step is to identify the key physical parameters that influence the health of a system. The machine monitoring strategy for the system should take the potential failure mode of the machine design into account. The machinery design and the recommendations of the manufacturer are equally important with respect to location and type of process and vibration sensors. Nine key parameters have been identified based on recommended measurement parameters from i.e.Carden and Fanning (2004); McMillan and Ault (2007); Carroll et al. (2015) experience with gas turbines from Loughney (2018) and that can are relevant from experience with gas turbines should be monitored, these are as follows:

1. Absolute vibration - the seismic vibration of the system relative to the Earth
2. Shaft vibration – These sensors monitor the levels of vibration incurred by the main generator shaft that runs through the gas turbine and the alternator.
3. Shaft displacement – Sensors here are used to measure the movement of the shaft in the vicinity of the probe, such as unbalance and misalignment
4. Temperature – The sensors here simply measure he temperature of various areas of the generator such as: temperature of the combustion chamber, the exhaust gases and the bearing lubricant oil
5. Speed – This sensor measures the speed of the main shaft at the bearings in-between the gas turbine and the alternator.
6. Hydraulic system pressure - delivers hydraulic power to the drive motor for adjusting the pitch angle (Qiao and Lu 2015)
7. Blade health - sensors here to detect and monitor blade cracks & tolerance, and provide early damage warnings.
8. Emissions – Sensors to detect exhaust emissions or leaks from the oil lubricant.
9. Alternator discharge – Sensors here can measure the level of partial electrical discharge from the alternator.

In the example posted by Loughney (2018) four WSN configurations are proposed for an offshore platform of dimensions 27 m (length) x 14 m (width) by 10 m (height). These WSN configurations considered most appropriate for this application were: i) WSN 1 – Single-hop, ii) WSN 2 – Single-hop with cluster nodes, iii) WSN 3 – Multi-hop with a small sensor radius and iv) WSN 4 – Multi-hop with a large sensor radius.

Following identification of suitable topologies, a qualitative evaluation hierarchy was then established to further solve the decision-making problem. In this case, which WSN would be most suitable for application within an electrical power generation module. The Evidential Reasoning approach, which is a generic evidence-based multi-criteria decision analysis method capable of handling both numerical data and qualitative information with uncertainty, was applied to each of the WSNs based upon an outlined attribute hierarchy, this hierarchy consist of 3 general criteria and 8 basic criteria as shown in Figure 5.

The subsequent analysis determined that a multi-hop configuration, similar to the Cluster/Tree orientation in Figure 3, with a small sensor radius (WSN 3) would be the optimum solution to monitoring the integrity of an offshore gas turbine-driven electrical generator. First of all, the nodes would be contained within the machinery itself, severely reducing the transmission range, so the ability to relay information from one node to another would be ideal. Secondly, due to the restrictions in transmission, the data would be collected by a sink (cluster head) located on the mezzanine deck of the power generation module. Finally this would be transmitted to the base station and control room for the installation, where data would be collated and analysed, and decisions would be made regarding the asset integrity. This is the most transferable to an offshore wind device due to the enclosed nature of the machinery. In this environment, it is optimal to have a series of sensor and router nodes transmitting to a sink in an accessible location for data recovery. This data recovery could also be wireless by sending a vessel within range of the external sink or by sending a drone.

While the cited example focuses on a Safety Critical System on an offshore oil and gas installation, the similar environmental conditions and physical measurement parameters, such as vibrational analysis, allows for the system to be re-imagined for monitoring offshore wind components, such as the electrical system, alternator and gearbox, or blade and alternator set. Thus many of the parameters and the decision theory application can be transposed for application of a wind turbine.

5 Suggestions and guidelines

This paper has reviewed remote monitoring systems for a number of applications in structural, condition and environmental monitoring of offshore wind turbines in order to increase power output, improve maintenance planning and access, increase component life cycle, and reduce the overall LCOE. Although areas such as the challenges, technology, power and computational requirements have been extensively researched, there existed a lack of a generic and structured set of steps or guidelines that can be utilised to aid in the top-level organisation and implementation of a remote condition monitoring system.

Based upon the information and literature reviewed in this paper, the steps have been streamlined into four steps to follow to aid the development of WSNs for offshore wind devices. Given the amount of complexity within each step, the guidelines here are presented as top areas of importance for key stakeholders in charge of the overall remote monitoring system. Future research will provide a more detailed decision making systems for each area of import.

The steps to follow are outlined as follows:

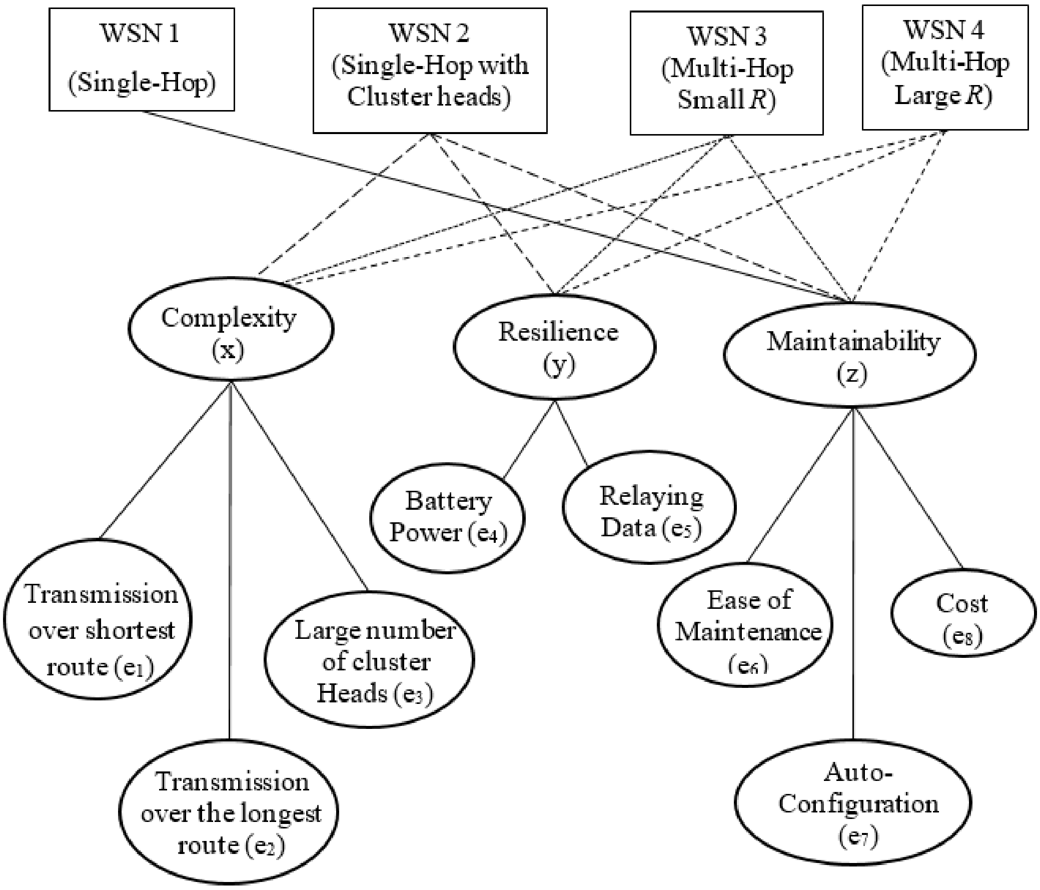

Fig. 5 Example of an Evaluation Hierarchy for our WSN topology designs.

Step 1: Identify and outline the application

This step entails identifying and outlining the scope of the remote monitoring WSN system, depending on whether structural, component condition, environmental monitoring or a combination, such as for selecting a safe access window, are of interest. A WSN could monitor the condition of the gearbox, alternator or turbine as whole systems or they could be monitoring specific sections or components within the systems. The operator, asset manager or whomever is responsible for constructing a remote monitoring system must first ensure that the scope for the WSN and important features are well understood to select suitable hardware and software are utilised.

During this step, the physical parameters influencing the system of interest must be identified, which will inform the necessary sensor transmission range and required hardware. The domain and environment in which the WSN will operate is also identified during this stage to ensure suitable robustness and to optimise data collection and transmission.

Similarly, in order to optimise the identification of the scope and domain, the Key Performance Indicators (KPIs) should be reviewed for the system or components, as well as the KPI hierarchy. Safety requirements feature heavily in marine industries for example, thus indicators such as “incident”, “accident” and “near miss” can be used. The WSN in this case is performing the role of a front-line worker in terms of taking periodic measurement for reporting to next level management for decision-making. The most critical components, in terms of malfunctions and downtime, must also be identified, although previous experience such at that and an presented previously in Figure 1.

Step 2: Identifying key fault indicators

This step is essentially asking the question of ”what to measure?”. The obvious answer is to measure the physical parameter that best informs about the integrity of the system . Proper consideration in this step is too often ignored, noted by the Health and Executive (2007) in its review of the management of installation integrity. The report found that the availability of information was not the issue for most companies; instead the dilemma was data overload and accuracy of the information collected.

Modern maintenance management systems produce vast quantities of data, much of which are at levels of detail that, in the form of raw data are not appropriate as high level indicators. Where possible, senior management should therefore employ sensor systems capable of processing data and make use of scientific computing and machine learning algorithms, such as those discussed in Section 3.4 to reduce costs, energy requirements and to process safety risks effectively (the Health and Executive 2007; Whewell 2012; the Health and Executive 2014).

Step 3: Identify the technology requirements

A WSN monitoring system based in an offshore wind turbine environment will utilise various kinds of sensors to monitor and measure different physical and chemical parameters such as temperature, pressure, wind direction, wind speed and vibration. The development and deployment of an adaptive, scalable and self-healing WSN system needs to address a number of critical challenges including: autonomy; scalability; adaptability; self-healing; and complexity (Xu et al. 2014). The design and deployment of a lasting WSN for wind turbine condition, structural health or environmental monitoring should take into account additional challenges (Hempstead et al. 2008; Xu et al. 2014; Hsieh et al. 2014):

1. High water resistance: sensor nodes should have sufficent water resistence to withstand the corrosive nature of sea water;
2. Robustness: An offshore monitoring system must be sufficiently robustness, to cope with the aggressive and complex ocean environment, where the wave and currents can cause movement of nodes.
3. Higher energy consumption: sensor systems that must community over the increased distances from the shore or base in an environment that may be prone to movement, i.e. a floating wind turbine (Hywind Scotland), will face increasing energy consumption. Data processing on site coupled with improved methods of energy storage and wireless communication can reduce energy consumption. To further reduce power consumption, transceivers and other utilities can be put into an idle state.
4. Difficulty of deployment & maintenance: In many cases the offshore WSNs are most useful in areas that are hard to reach for humans, and thus this poses a problem during installation, particularly if it is a retro fit. This also affects maintenance of the WSN and therefore the battery life is vital at this stage of the WSN development (see Section 3.1). Incorporating a WSN in the planning stage of offshore wind farm development would reduce the need for extra personnel trips.

Step 4: Develop the WSN topology and coverage

This step is concerned with the development of the WSN cloud and subsequently the number of sensors and topology required for sufficient coverage and optimal data collection and transmission. The level of coverage required for a WSN is defined here characterises the required the number of nodes.

The node coverage ratio should also be considered here: if the coverage ratio is not 100%, blind points or sensing voids occur, which may be intolerable depending on the application identified in Step 1. Although some applications may require 100% coverage of the target region all the time, it may be acceptable for a small number of blind points for a short time (Mamun et al. 2010). The schematic in Figure 6 illustrates of the node number required to obtain the required coverage ratio for the offshore 2D gas turbine and alternator example from Loughney (2018).

6 Conclusions

This paper has summarised types of technologies that can be used to develop a WSN and IoT solution for monitoring the condition of an offshore wind turbine structure or components and environmental monitoring, and the challenges to be considered in the design phase of these wireless sensor networks. For each element of a wind turbine and *in situ* environmental aspects, there are different techniques and technologies that can be employed to monitor and merge data from a diverse range of factors. In this research, several key topics of concern were explored, including power, memory, transmission, security and type of technology.

Further to the challenges faced in selecting which asset to monitor, understanding the most appropriate parameter and ensuring the security of the sensor network, the main obstacles facing the designers of remote monitoring systems continue to be hardware-related. Important hardware-related issues to be addressed include: selection of the number and type of sensors; choosing the most effective signal processing methods associate with the selected sensors; and design of an effective fusion model (i.e. the combination of sensors and signal processing methods, which give an improved performance) (Márquez et al. 2012).

The application of remote environmental and condition monitoring systems can increase the power output and lifetime of turbine components, decrease costs and contribute to the optimisation of planned maintenance scheduling. Better maintenance planning would aid in minimising wind turbine failures, decreasing downtime, reduce the potential danger to repair workers and increase the reliability of the O&M decision support system. Finally, by streamlining

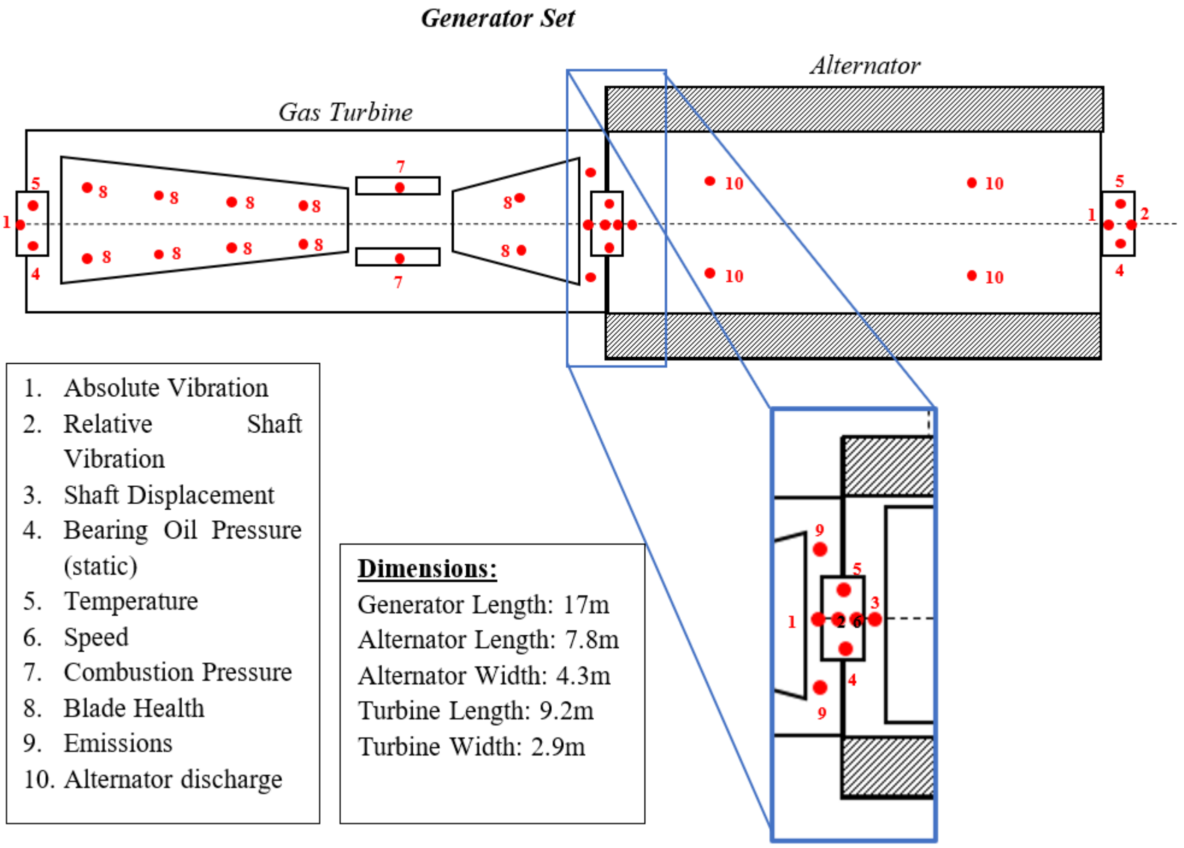

Fig. 6 Example of WSN node location for condition monitoring of an offshore power generator for optimal coverage and data transmission

remote monitoring systems, there is significant scope to reduce the CO_2 emissions due to unnecessary trips to the wind farm, also reducing the LCOE.

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