Wireless Sensor Networks (WSN) in Oil and Gas Industry: Applications, Requirements and existing Solutions

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***Abstract*— Effective measurement and monitoring of certain parameters (temperature, pressure, flow etc.) is crucial for the safety and optimization of processes in the Oil and Gas Industry. Wired sensors have been extensively utilized for this purpose but are costly, not best suited for harsh environments and are difficult to deploy and maintain. Wireless Sensor Network Solutions is revolutionizing the Offshore Oil and Gas industry providing evolving solutions that introduces significant benefits in cost, ease of deployment, flexibility and convenience. The adoption of Wireless Sensor Networks is expected to be tremendous in industrial automation owing to a report that projected the deployment of 24 million wireless-enabled sensors and actuators worldwide by 2016.With limited literature on this specific subject matter, this paper presents a critical survey into oil industry monitoring specifications, requirements and Wireless Sensor Network applications as it directly impacts the Oil and Gas Industry. An overview of Wireless Sensor Networks is presented, applications from literature are highlighted and finally challenges and existing solutions are discussed.**

***Index Terms*— Oil and Gas, WSN Standards, Pipeline monitoring.**

I. INTRODUCTION

The energy industry increasingly dependent on information technology. Although the oil and gas companies may have not invested the same percentage of money that is invested by other industrial sectors in information technology, such as the financial services sector, but that there is a growing awareness of the role of this technology in shaping the future of the industry. Since the world economic growth depends largely on the oil and gas industry and the demand for energy resources increases, there is a need to adapt to intelligent technologies for the improvement of all areas of industrial practice in connection with the oil and gas processing stages including refining, exploration, extraction, transport and marketing of petroleum products [1] and thus increases the productivity while reducing costs.

In the light of the above mentioned phases, the hash and intensive remote environments of oil and gas plants, required an adaptive monitoring system that is ideal for temporary installations, flexible, adaptable and in a position to reduce complexity and cut operational costs. In the last few years, oil and gas industries have used wired communications as a solution for applications monitoring. The installation, operation and maintenance of such a solution are usually costly and not appropriated for short-term installations and might be not be easy to adapt in a harsh environments [2] [3].

The major benefits of the sensor nodes lie not only in their small size and self-organising capabilities but also in their ability to provide reliable, fast, flexible, secure and cheap wireless communication. These features in wireless sensor nodes has introduced a convenient alternative to the wired nodes [3] [4].

The technical capability of wireless sensor networks (WSN) is still under ongoing exploration in science, as its true potential has not been fully exploited. This survey aims to provide WSN designers, oil and gas companies and researcher a critical review at the provision of WSN in the oil and gas industry taking into account the specific requirements of the applications and challenges. Furthermore, a particular attention is given to the existing architectures of efficient mechanisms that fulfil the requirements and overcome the challenges that arise when deploying a WSN in Oil and Gas industry.

The paper is organized as follows. In Section 2, the potential applications in oil and are identified. Then, in Section 3, existing standards for low-power wireless sensor networks are discussed. In section 4 the technical requirements of WSN deployments in oil industry are reviewed. In Section 5, we review techniques and solutions proposed in the literature. Finally, Section 6 concludes the survey.

II. WSN POTENTIAL APPLICATIONS IN OIL INDUSTRY

The For Oil & Gas Industry WSNs offer a large amount of applications that are useful for the production of Performance Optimization [1] (monitor pipelines, gas detection, corrosion, H2S, equipment health [2] status, and real-time reservoir and process control, safety, maintenance.

This section will present a classification of WSN possible applications in oil and gas industry Fig.1 illustrates a classification for potential WSN applications in oil and gas industry.

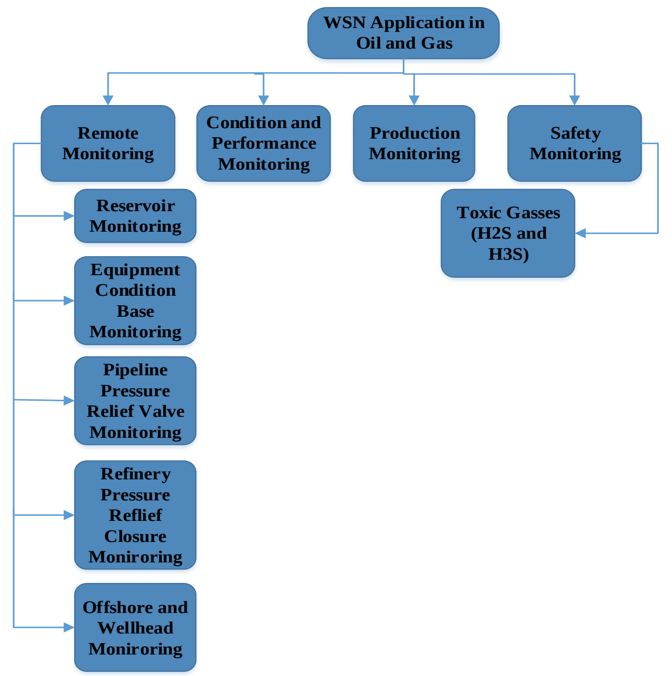

Figure 1: A Classification of WSN applications in Oil and Gas Industry

A. *Remote Monitoring*

One of the main purposes of Remote Monitoring is to monitor Pipelines for gas leakage and damages [5]. Remote Monitoring is very beneficial for oil and gas industry in improving safety, enhancing operations, detecting problems and reducing overall operational costs [1]. Hence sensor nodes are placed in numerous remote locations and hazardous environments such as in oil and gas pipelines can suffer from a variety of catastrophic events such as explosions due to high flammability [6]. This will result in serious environmental hazard and financial damage due loss of production Therefore it is crucial for the real time monitoring system to meet certain requirements to be able to predict possible failures before they occur.

There is a number of oil and gas remote monitoring applications that include [7]:

- Reservoir level monitoring
- Equipment condition based monitoring
- Pipeline pressure relief valve monitoring
- Refinery pressure relief closure monitoring
- Monitoring offshore (marine locations) and wellhead automation.

In Pipelines monitoring the unique long distance linear topology characteristics of the network infrastructure in which a large pool of sensor nodes are distributed linearly along the pipeline and limited to a single path to transmit the data, increases the challenges associated with network reliability, connectivity and an efficient energy management for sensors and actuators. Fig.2 illustrates the deployments of WSN in distributing and monitoring oil fields. The main requirements identified of WSNs applications for remote monitoring are delay, robustness, data reliability and security [8].

B. *Condition and Performance Monitoring*

In oil and gas industry as in many other industries condition and monitoring of equipment and machinery plays an essential part in the overall operation. The aim of condition and monitoring is to provide fault diagnostics of different equipment and conduct machine health monitoring and temperature monitoring. Wireless sensors can be used to detect vibration, temperature heat, dissolved gas, electromagnetic properties, power consumption [1], to gather information about the health status of machineries and provide fault diagnostics, that help identify the root cause of a problem, detect and even predict potential upcoming faults, thus the operation downtime, repair costs, damage and potential danger are minimized.

C. *Safety Monitoring*

The exploration and refinery procedures of oil is usually accompanied by several toxic gases that include ammonia (NH3), hydrogen sulphide (H2S), and sulphur dioxide [1] [7]. The leakage of such materials could have a serious impact on human beings and the environment. Therefore, the monitoring of the H2S considered important WSNs for prospecting for oil and gas companies [10].

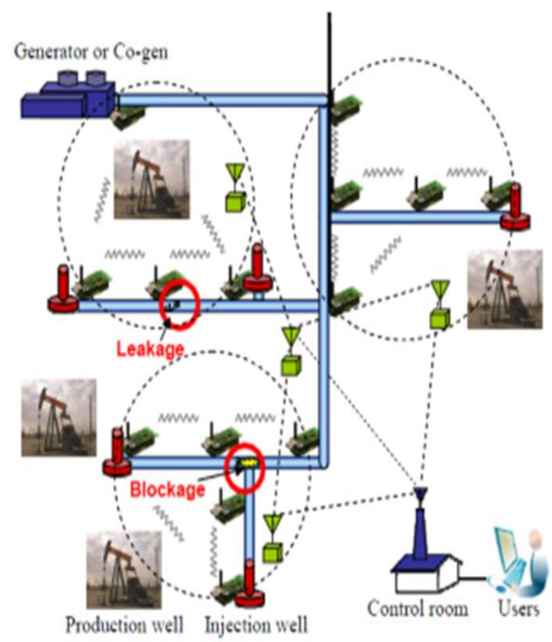

Figure 2. Oil Distribution and Monitoring using WSN [9].

III. WSN STANDARDS

As WSNs and their applications become more widespread in the oil and gas industry, companies are challenged with the decision of choosing between several emerging technologies and standards, such as IEEE802.15.4, Zigbee, ISA100.11a or WirelessHART. These standards are developed with the goal to provide high-level communication protocols for WSNs and build the foundation of a complete network infrastructure taking into consideration the limited resource of the wireless sensor nodes in terms of power, reliability, security, etc.

In this section, we provide an overview of the existing standards. A detailed Comparison of WirelessHART, ISA100.11a and ZigBee for industrial applications is studied in [11].

Fig.3 illustrates a classification of existing WSN standards.

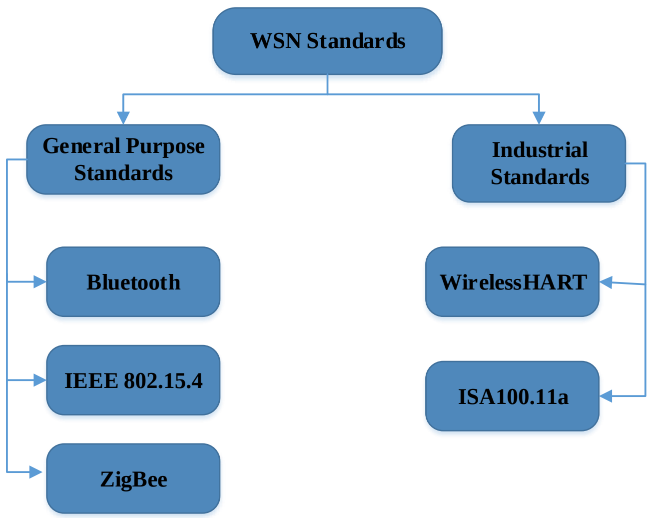

Figure 3. Classification WSN Standards

A. Bluetooth

Bluetooth [12] is designed as an open wireless communication protocol to provide cost efficient services for devices that operate within short distance range with no longer than 10 meters with 2400 and 2483.5 MHz frequency range. Bluetooth support the communication between 1 master and more than 7 nodes per piconet [13]. In terms of energy consumption Bluetooth has limited battery life time. However, Bluetooth can be very beneficial for a wide range of application that are deployed in a short distance range such as Personal Area Network (PAN).

B. IEEE 802.15.4

IEEE 802.15.4 [14] specifies the physical layer and Medium Access Control (MAC) for low data rate Wireless Personal Area Networks (WPANs) LR. This standard uses a duty cycling mechanism with which all participants nodes go into a sleep state in a regular interval so that energy can be saved. The standards uses two modes: (1) non-beacon modes in which a Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) (2) a beacon mode in which the PAN coordinator sends beacon frames to detect the PAN and starts node synchronisation. It also sends a super-frame structure that contains 16 time slots the so called guaranteed time slots (GTS) that can be assigned to nodes in each PAN, where only a maximum of seven GTS slots can be assigned to nodes contention free period (CFP),. Other nodes can either transit into a contention access period (CAP) or inactive period of time during which the end-devices and coordinator transit into sleep state.

There are two types of devises supported by the IEEE 802.15.4 standard [15]:

- Full Function Devices (FFD): Is responsible for maintaining the network initialization and function as a router or coordinator.
- Reduced Function Devices (RFD): Are simple in their implementation and can only be deployed in a star topology to stablish communication with physical world.

C. WIA-PA

The Chinese Industrial Wireless Alliance [16] has designed the Wireless Networks for Industrial Automation - Process automation (WIA-PA) that is based on IEEE 802.15.4 without modifications [17] with aim to provide a reliable, energy efficient, and multi-hop mesh network that adapt to frequent changes in the network. The standard uses a combination of CSMA, TDMA, and FDMA with a maximum of I6 channels under the 2.4 GHz band and frequency hopping [18]. It uses three types of frequency hopping mechanisms namely the Adaptive Frequency Switch, Adaptive Frequency Hopping, and Timeslot hopping. It can co-exist with other standards that are compliant with IEEE 802.15.4.

D. ZigBee

ZigBee [16] [19] is an open standard designed with the aim to provide an intelligent solution that meets wireless devices requirements in terms of cost, energy consumption, reliability, etc. ZigBee utilize the upper layer of the IEEE 802.15.4. ZigBee network supports mesh, star and tree topologies and are categorized into three device types, each has a specific role [20]. As shown in Fig 4.

- ZigBee Coordinator (ZBC): It is task is to provide interconnection with other networks, set up, control and maintain the network. Moreover, it holds information about the entire network and provide the security keys. The coordinator handles tasks such as address assignment and address management in the mesh network.
- ZigBee Router (ZBR): It is a Full Function Device (FFD) operating in all topologies and may sometimes act as ZBC. The memory required by ZBR is less as compared to ZBC node. It helps routing the data between the nodes and extends network coverage.
- ZigBee End Device (ZBE): It is a Reduced Function Device (RFD) that is always associated with an FFD and can be present in the network as a node. It is capable of talking to the network, but it is not allowed to associate or route data messages.

The main function of the Coordinator in all ZigBee networks is to set up the network, therefore it must be aware of all the constituent nodes and should be able to store information and manage communication and security keys of the network. Routers are the intermediaries, which facilitate information flow between devices. The endpoint devices are required to perform a limited function of interacting with their parent nodes.

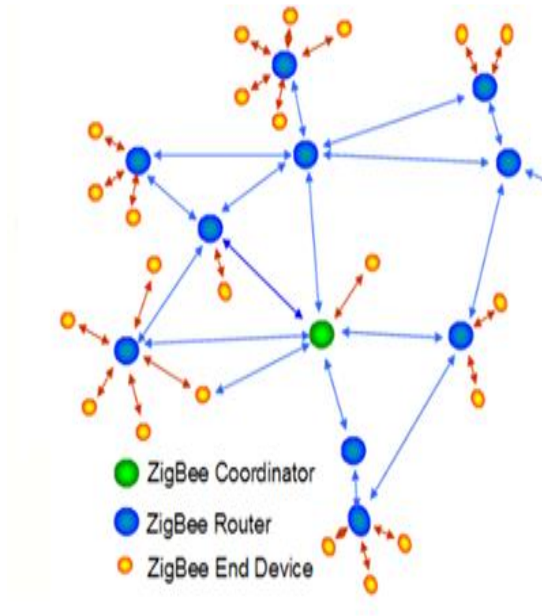

Figure 4: ZigBee Network Architecture Adapted from [20].

E. WirelessHART

The Highway Addressable Remote Transducer (HART) [16] is an industrial standard developed on the basis of IEEE 802.15.4 specification using up to 15 different channels and a frequency of 2.4 GHz [21]. WirelessHART was developed to support power efficiency, reliability and integrated security. It uses Time Division Multiple Access (TDMA) with Frequency Hopping Spread Spectrum (FHSS) to access different channels at different time slots, while blocking channels which experience interference with the signal by creating a Blacklisting. These mechanisms will result in less interference with the existing wireless systems and reduce noise impact [18] [22].

The security in wirelessHART, is mandatory and handled in both the MAC and the network layers offering hop-by-hop and end-to-end security employing AES-128 block cipher symmetric key as a method of data encryption and authentication [23].

A typical WirelessHART network that the network manager can support are mesh, star and combination of both topologies and it consists of four components that are essential to provide a fully functional network as illustrated in Fig 5. and described as follows:

- Field Devices: Theses are sensor nodes with a built-in WirelssHART that normally connected to the plant equipment with the purpose of sensing, actuating and collecting data. They are all capable to perform routing. A wireless adapter is used to bridge the field devices with other deceives in the field [20].
- Gateways: Is responsible for connecting host applications and Field Devices. A gateway can uses Access Points to connect to the WirelessHART mesh network [24].
- Network Manager: Is responsible for the configuration and maintenance of the mesh network by managing the routing tables, monitoring and reporting the health of the network. It also provides communication between field devices. The allocation of the slot time access for device to device communication that is defined by TDMA mechanism is also a responsibility of the network manager, where each slot is 10ms [23].
- Security Manager: It is responsible for securing the communication by providing each new device with an encryption security key, while holding a record of all authorized devices [22].

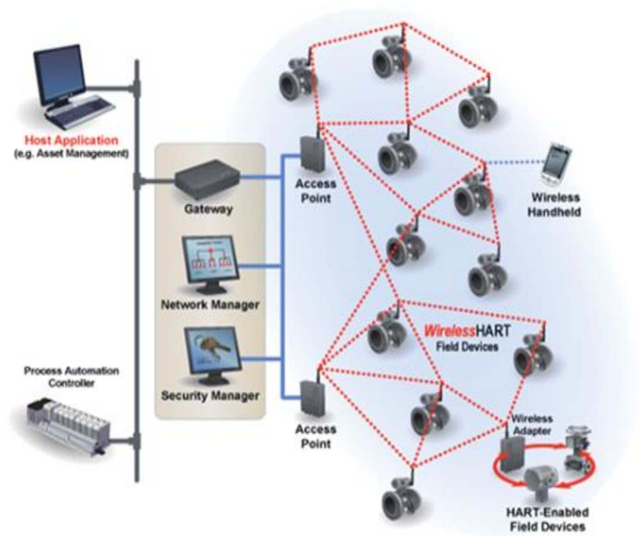

Figure 5: WirelessHART Network Architecture adapted from [20].

F. ISA100.11a

This standard designed on the basis of the IEEE 802.15.4 with the aim to provide reliability to the wireless communications infrastructure for monitoring and control different types of applications [25] [26]. ISA100.11a like WirelessHART supports channel hopping and channel blacklisting to reduce interference and allows a device to coexist with other RF devices in the same band. It also benefits from TDMA mechanism that enables a device-to-device communication without delay in accessing an RF medium using the allocated time slot of 10 ms [22] [23]. At the network layer the standard facilitates the use of 6LoWPAN that is needed to handle IPV6 traffic and thus gives users the opportunity to connect to the internet. The ISA100.11a standard supports symmetric AES 128bit encryption.

An ISA100.11a network supports star, mesh and a combination of both and facilitates co-existence with wirelessHART [23] and it consists of different components that are essential to provide a fully functional network as illustrated in Fig 6. and described as follows:

- Input/Output (A). Presents a field sensor device that is responsible for forwarding and collecting data about the environment such as temperature pressure to or from other devices.
- Router (B). This device carries out the routing and message exchange between the neighbouring devices in the field. It is also acts as an Input / Output device.
- System Manager (C). It is responsible for creating network communication, relationships once a network session initiated and update those relationships in case of any topological change that may occur in the network.
- Security Manager (D). Provides and generate cryptographic Martials to insure a secure network session between devices based on both symmetric and asymmetric shared session keys [22].
- Backbone Router or Access Point (E). A device with the backbone routing role acts as an OSI Layer 3 interface between the wireless network and an IP backbone. An ISA100 Wireless backbone router is commonly called an "access point", and in practice the terms are interchangeable.
- Gateway (F). A device with the gateway role describes the function that translates ISA100 Wireless messages to other formats such as Modbus or OPC.

These logical roles can be, and often are, combined in actual devices. For example, the gateway (F), system manager (C), and security manager (D) roles may be combined into one device, commonly y marketed as a "gateway". Such a "gateway" may also include a radio link for direct wireless communication with the mesh by incorporating a backbone router (E) role, all in a single infrastructure device. As another example, the I/O role (A) and router role (B) are commonly supported and active in wireless field devices.

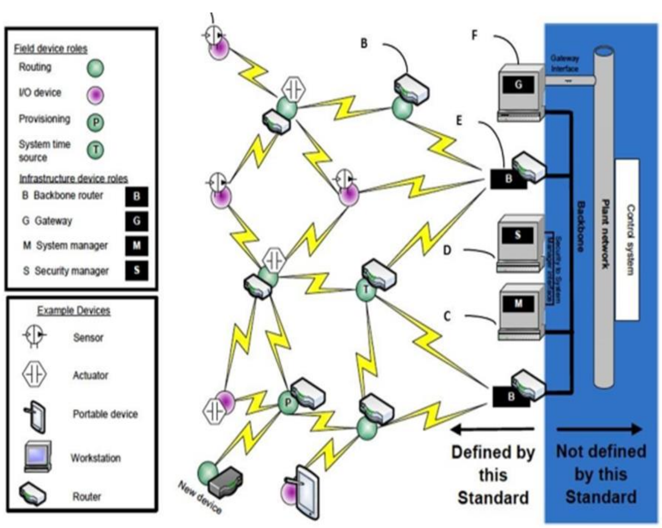

Figure 6: ISA.100 Network Architecture adapted from [27].

The authors in [30] have conducted study comparing WirelessHART and ZigBee in terms of some quality of services metrics such as robustness, coexistence and security. The outcome of the study showed that WirelessHART is a better choice for industrial applications compared to ZigBee in some quality of services terms. The authors in [17] (Liang, et al., 2011) have performed a comparative study on the WSN standards (wirelessHART, ISA100.11a and WIA-PA).

Figure 7 illustrates the protocol stacks of ISA100.11 a, WirelessHART, IEEE802.15.4, and ZigBee

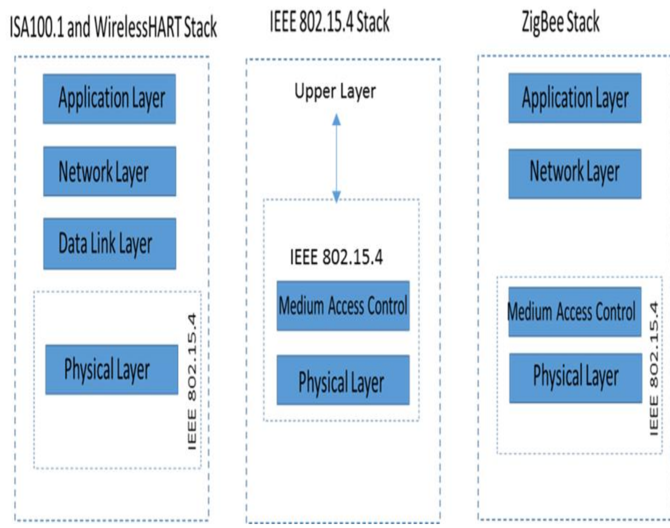

Figure 7. Protocol stacks of ISA100.11 a, WirelessHART, IEEE802.15.4, and ZigBee [28].

G. *Discussion*

Based on the above review on WSN standards we can conclude that wirelessHART and ISA100.11a both are suitable for industrial and larg scale deployment, while ZigBee technology is suitable for general applications due to the limitation on radio range of 100 meter. WIA-PA is relatively new and it is still not widespread deployed.

WirelessHART and ISA100.1 both standards defines the radio on the basis of the IEEE 802.15.4 standard for low-rate wireless personal area networks (L-R WPAN). WirelessHART also uses unmodified IEEE802.15.4-2006 MAC, while ISA100.11a uses a modified, flexible IEEE802.15.4-2006 MAC. Both use the same mechanisms for establishing the wireless network and exchange data between network devices. Both standards deploy energy saving mechanisms that offer batteries longer life-time. Both standards survive the interference caused by the presence of other network system by combining channel-hopping and direct-sequence, spread spectrum (DSSS).

The TDMA-based mesh topology used by WirelessHART and ISA100.1 provide a centralized infrastructure, that is required for large scale deployment. This makes both standards preferred ZigBee with its tree topology

WirelessHART and ISA100.11a differ from each other in their aims and objectives they designed to achieve. WirelessHART aim is to tackle quality of service issues associated with user applications, such as reliability, security. ISA100.11a is flexible and customizable.

Table 1 summarizes the various quality of services requirements of the previously discussed standards.

Table 1: A COMPARISON BETWEEN WSN STANDARDS [25] [2] [29]

Features	ZigBee	WirelessHART	ISA100.1
Underlying Standard	IEEE 802.15.4	IEEE 802.15.4	IEEE 802.15.4
Security	High Symmetric	High Symmetric	High Symmetric/ Asymmetric
Scalability	Yes	Yes	Yes
Power Consumption	High	Low	Low
Latency	Low	High	High
Co-Existence	NO	Yes	Yes
Application	Commercial	Industrial	Industrial
Bandwidth	20-250 Kbps		
Transmission Range	2.4GHz and 868/915MHz	2.4GHz	2.4GHz Free Band
Network Size	65,000	Up to 250 nodes on a network	above 250 nodes per network
Topology	Mesh	Mesh and Star	Mesh and Star
Radio Channel	CSMA-CD	TDMA	TDMA / CSMA-CD
Network Routing Strategy	AODV/ Tree Routing	Graph/Source/Superframe Routing	Addressing; Routing

IV. REQUIREMENTS OF WSN IN THE OIL AND GAS INDUSTRY

There are certain requirements that are essential for a successful deployment of WSNs in the oil, gas and resources industries. In this section, the major requirements are discussed. In Fig.8. We propose a taxonomy of the requirements of WSN in the oil and gas industry.

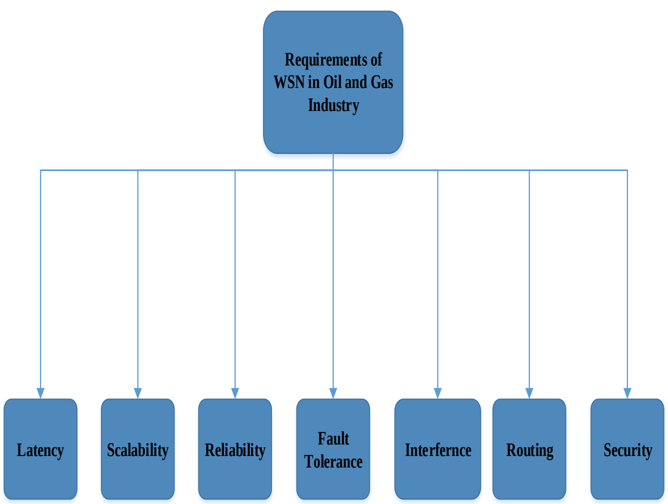

FIGURE 8. TAXONOMY OF REQUIREMENTS OF WSN

A. Latency

Latency is a measure of delay in time [31] that is requires a data packet to succefully reach the receiving node and acknowledged, it is measured in ms. The probability of a succefull transmission depends largely on the quality of transmission media, which influenced by the signal-to-noise ratio in the RF domain. The number of hops from source to destination can also affect the latency [29].

B. Scalability

Scalability is the ability of the network to cope with the growth in number of the sensor nodes which vary from a few to several thousands. Different requirements of applications in oil and gas industry require protocols and standards that are scalable and able to adapt new functionalities such as adding and removing numerous sensor nodes without impacting the quality of service (QoS) performance metrics [18] [29].

C. Fault Tolerance

Fault tolerant is described as the capability of the network to operate in a reliable fashion and adapt any topological changes that might occur as a result of node failures and link failures. Many factors [22] can affect the performance of a sensor node and cause frequent failures, such as energy depletion, hash physical location and other environmental effect [32].

D. Reliability

Reliability is the measure of the amount of data that is delivered from source and accurately received by the destination with minimum possible packet loss [29]. Reliability can be defined by the application. For instance: reliability for data transfer is the integrity of data and all information are accurately received by the receiver; reliability for audio or video , reliability concerns more of tolerable distortion at the application layer. Usually the reliability in each layer of the communication stack [18] has various requirements and definition of error rates, error burst, delay, error concealment techniques, etc.

WSN nodes with low power suffers from a relative low link reliability in comparison to conventional wireless networks. This will impact the deployment of WSNs in an industrial environment, due to the high packet loss and high delay [33]. These limitations can be talked by improving the retransmission mechanism at both link and transport layer alternatively replication-based routing protocols can be used [34]. Error checking and correction should be considered in the reliability schemes and the wireless technology should make less interference on other devices in the network, so that sensor data can be transferred correctly and reliably.

E. Co-existence and Interference

WSNs transmit on low-power signals are extremely sensitive to noise, which makes the radio signal subject to interference multi-path distortion with other wireless networks and communication systems operating under the same radio-frequency (RF) medium. WSN standards should be able to function efficiently and co-exist in the occurrence of interference [18] [35] [36]. The authors [37] have surveyed the impact of interference on WSN working under the 2.4GHz frequency and the existing approaches to tackle it.

F. Routing

An essential design criteria is the capability to deliver packets from source to destination consuming the least amount of energy possible. There are various constraints that must be taken into account when designing a routing protocol for WSNs, such as node deployments, energy, scalability and other quality of services necessary metrics for reliable data delivery. It is therefore important to overcome these challenges before efficient communication and reliable monitoring system for oil and gas industrial applications can be achieved in WSNs [38].

G. Security

One of the major benefits of WSNs is the ability to place sensor nodes in an environment without any supervision. This can provide security drawbacks to the network and backend system if the sensor nodes are located in harsh environments or in an unsecured manner while being readily accessible to people. Another limitation that makes WSN more vulnerable to eavesdropping and security breaches than its wired counterpart is the wireless transmission of data. Therefore there is a need for security system that protect access and privacy [22].

The authors in [22] have surveyed the security requirements of WSNs in the Oil and Gas Industries and provided a taxonomy of possible security attacks.

H. Power Consumption

The Oil & Gas Industry urges longer battery lifetimes that lasts over years for wireless sensors as a long term solution for the enormous effort required to maintain the network when replacing depleted batteries. In WSNs rechargeable batteries the main source of power for sensor devices, a regular replacement of the batteries is complex due to the number of several thousand sensors per plant, therefore nodes need to adapt an energy-aware mechanism in order to rationalize the consumption of energy and thus ensure a longer lifetime of the network. Power consumption also plays an important for the routing of packets between the sensor nodes and must be considered by the routing protocol design criteria strike a balance between energy savings and functionality [25].

The authors in [25] have conducted a top-down survey on the energy efficiency in wireless sensor network and presented a classification of energy conservation schemes. Their study focuses on existing techniques used to design efficient and sustainable sensor networks.

V. Existing Solutions

In this section, an overview of the existing solutions that tackle the challenges and enhance the deployments of WSNs in oil and gas industry are discussed.

A. Pipeline Monitoring

The authors in [7] applied WSNs in refineries, petrochemical plants, underwater development facilities, and oil and gas platforms to monitor the production process, to either avoid or identify health and safety concerns. Such a network was used to remotely monitor pipelines, natural gas leaks, corrosion, H2S, tank status in real-time. The result has shown the data collected in this system allows new opportunities in plant function and provides innovative ways that help oil, gas and resource industries to improve the safety and decrease operation costs.

The authors in [6] surveyed and proposed a solution (REMONG) to monitor pipelines that is based on WSNs with a reliability focus on leakage sensing and wireless data communication. The system is developed to reliably monitor the condition of pipelines that are stretched over large geographical locations using ZigBee protocol. It also has a dashboard software that delivers collected sensor data in real time.

Authors in [39] have developed a fiber optic reservoir monitoring system based on fiber Bragg gratings to monitor in pressure, temperature and multiphase in an oil and gas pipeline. The results showed that their proposed system allows spatial multiplexing of data, however the system is costly to deploy.

In [40] the authors proposed a magnetic-induction based pipeline monitoring system (MISE-PIPE) that is intended to provide real time leak detection in both underground and above ground pipeline. MISE-PIPE consists of two layers, a hub layer with pressure sensors and acoustic sensors and in-soil layer with soil property sensors. A performance evaluation test showed precise results in detecting and localizing leakages.

In the work mentioned in [41] a framework that aimed to provide cost-effectiveness, security and reliability in monitoring pipeline structures is proposed. However the work does not provide neither technical design details nor performance tests, it is limited to the architectural description of the system.

The authors in [41], implemented a scalable wireless sensor network for structural health monitoring. An open source TinyOS software compained with MicaZ mote, a 2.4 GHz radio-frequency RF Chipcon and CC2420 transceiver were used to validate the scalability of the system.

A crude oil leak detection and location monitoring system has been proposed by the authors in [42]. The system has 4 station one station is a main and the other act as a backup in each of these station there are pressure, flow and temperature transducers, signal regulator, data acquisition card, industrial PC, MODEM, GPS, and telephone communication lines. A wired PLC-5 programmable controller and wireless 1785-KE card were used to provide connectivity to the internet. The system is deployed and tested in 8000-kilometer crude oil and product oil pipelines in China, it has proven its stability and reliability by detecting a leak that is larger than 2% of the total flow in 180 seconds, and accurate position that is less than 2% of the length of the pipeline.

In [43], the authors discussed the reliability of using wave as a solution to detect leakages in pipelines.

The authors in [44] introduced a heterogeneous network for underwater monitoring of oil and gas production to detect oil and gas leakages and to improve the flow and well production. A combination of ultrasonic and optical networks is used in additions to wires, to provide redundancy. This system used tiny IR extension wireless motes (Moteiv Tmote Sky Type) with TinyOS drivers and ultrasonic transceivers. Results showed that, connecting Tmote nodes with Micro- Electro-Mechanical Sensors (MEMS) to other Tmotes in the network using frequency (RF) communication or ultrasound or light connection improve the device flexibility.

A system that provides an early detection and warning ahead in time of failures and unexpected events such as sand production in oil and gas industry Early Event Warning (EEW) has been proposed by the authors in [45]. The aims of the system are to meet the requirement of a real time monitoring in terms of the time delay between discovering a failure, examining the cause and preventing damage. The system uses the Web Ontology Language and SOAP as communication methods and MQ Telemetry Transport (MQTT) for message exchange. It also provides two notification messages, DataEventMessage that holds information about the channels and EEWEventMessage that stores information about the monitored application. They have conducted a latency performance test by sending 150,000 messages to the EEW then observe how long the time between receiving the messages at EEW and dequeening them for analyses. The results show that 80% of messages received in less than 1ms, where 90% have an average of 10ms latency.

The authors in [46] have proposed an online monitoring and inventory management system (TOTE INVENTORY MANAGEMENT) based on Radio Frequency Identification (RFID) and WS that helps monitor production activities in oil and gas plants. The system consist of the various hardware that meets the requirement of offshore deployment, such as an RFID system with a tag and reader, an integrated weight measurement system, a WirelessHART enabled sensor node to build a mesh network, WirelessHART gateway and a web server application. The results show that the system will improve the operation, however the proposed system might face several challenges such as power consumption and interference with other in plant existing system.

The authors in [47] have tackled the problem of the safety in gas fields by introducing a multi-sensor gas monitoring platform that detects possible gas leakage in reliable manners and provides an accurate positioning of the source. The proposed system consists of an industrial STM32F103 microprocessor, main board equip with a couple of gas sensors, GPS\FRID position module, power management, SD card and JTAG test interface. A μC/OS-II operating system is used as a platform for different application. The system has been tested for its performance in Guangyuan natural gas purification plant in China for 72 hours to monitor data. During the test there were 24 multi-sensor gas detectors used from which 18 sensors monitor gas leakage and the rest for monitoring the position of the worker in the field for security. It is concluded that the system has shown accurate and reliable data for both activities.

The authors in [48] have addressed the moisture problem related to LPG, LNG pipeline in oil and gas production plant by introducing a monitoring system that is equipped with RFIDs sensor to detect the level of the received signal energy in a certain amount of time and thus the existence of moisture in the pipeline is determined. A practical test has been carried out in the Texas A&M University's Wireless Research Lab in Qatar using a metal pipe, Pico-RFID module as a transmitter, Agilent's PSA E4440A. According to the obtained results the authors have confirmed that RFID system and the Cognitive Radio's spectrum sensing technique were capable to efficiently detect moisture based on the received signal energy estimation.

B. Latency

The authors in [49] designed and deployed a wireless sensor network in a petroleum facility at College of North Atlantic, Cove Campus, and Newfoundland. . The study focused on investigating the data rates and latency as important requirements of building a heterogeneous sensor network in an industrial area. An analysis of environmental noise in an industrial plant has also been conducted. The network consisted of four nodes and one actuator, Tmote sky devices, MIMO access AGN1200 in addition to a TS-3300 board. The results showed that sensor networks for an industrial environment have stable supplies of latency, throughput and channel access. They have also conclude that the usage of pure CSMA-CD or TDMA might not be the optimal solution for some of the sensor or actuator points in the petroleum plant.

C. *Fault Tolerance*

The authors in [50] proposed a wireless sensor networks application to monitor shipboard PdM aboard an operating oil tanker. They have conducted an experiments using a mesh topology with three Intel Mote clusters and three Mica2 Mote clusters were used to investigate the fault tolerance problem. To confirm the effectiveness of proposed application the used reliability, energy consumption and electromagnetic interference. They have proved the efficiency of their solution in terms of the amount if data collected through the nodes.

A fault tolerance solution, called FTSHM (fault-tolerance in SHM is proposed in [51] the authors aim is to predict the node or link failure and repair them before they occur. This is done first by identifying a repairing point in a cluster, then employing a backup sensor placement (BSP) mechanism. The backup sensor placement (BSP) places backup sensor in the cluster that acts as a redundant path for the network traffic in case of node failure.

The authors in [52] have proposed a network infrastructure that combines the features of both wired and wireless sensor networks. The wired network devices act as primary connection and the wireless network sensors providing a backup in the presence of network failures. Thus a reliable, fault tolerant pipeline monitoring system is guaranteed. They tackled the fault tolerance and power constraint by designing a network system in which the connection between nodes is performed through wireless transceiver and wired links, while the wireless transceiver are turned off for future backup activities the communication occur using the wired links. The power is provided through wired Devices. The node failure is discovered by exchanging echo messages between nodes if no reply has been received the nodes is considered as dead. However the authors have not provided a comparative investigation of their proposed that can show reading related energy consumption and reliability.

D. *Reliability*

In [31] the authors deployed a WSN at the Gullfaks offshore oil and gas facility in the North Sea to forecast production stops caused by pressure drops in well pipes. For this an ATEX version of the DUST wireless communications protocol with a wireless temperature sensor network was selected to forecast the loss of flow from a well. The result of this study demonstrated that the WSN allowed fast, relatively inexpensive and reliable detection of lost flows, therefore enabling quick action to re-establish flow. The WSN has provided almost 100% reliability with an acceptable latency (<2 Sec). These results show that WSNs are completely capable of strong and reliable connection in the severe environment of offshore platforms.

E. *Co-existence and Interference*

The authors in [53] [54] carried out a research about the technical possibility of implementing WSN in oil and gas industry environments. For they used WSN standards (WirelessHart, ISAl00.11, ZigBee) as solutions for applications monitoring. The results showed that all three studied standards function efficiently in the presence of other network systems and are able to survive the interference and noise issues.

F. *Routing*

The authors in [5] have addressed the issues of deploying WSN in monitoring different types of pipelines in oil and gas industry, they proposed a routing protocol with a hierarchical addressing scheme that designed for linearly deployed sensor networks. The routing protocol is aimed to enhance the network in terms of reliability, power consumptions and fault tolerance. In the proposed system three types of sensor nodes are introduced that build a hierarchical parent/child relationship. The communication between the sensor nodes follows a multi-hop routing algorithm that is built on the basis of MAC protocol.

An enhanced version of the original AODV routing protocol has been proposed by the authors in [38]. In the M-AODV the HELLO and ERR messages exchanged by the neighbor's device in the original AODV to announce their presence and update the routing table are eliminated and thus flooding the network with unnecessary broadcasts is avoided. The results obtained from the comparative study between M-AODV against AODV and HERA protocol showed the A-AODV outperformed both protocols in terms of delay, but has similar performance to HERA in terms of stability and collision. It is also found that M-AODV has a higher transmission that reaches 99% in 3 minutes time interval 4 times faster as the original protocol.

G. *Energy Consumption*

The authors [2] have investigated the technical requirements of deploying WSNs in oil and gas industry in terms of security, reliability, power consumption, interference and maintenance. To verify the capability of the existing WSN standards to meet the technical requirements of oil and gas industry in terms of power consumption, reliability and co-existence, a mesh and SensiNet network were set up. The results showed that both studied standards fulfill most of the requirements, however an enhanced power management is required to further decrease the power consumption and increase battery lifetime to a minimum of five years.

A study of Sensor life time maximization with respect to sensor placement along a pipeline under different power model, ideal power model and Tmote power model has been investigated by the authors in [55]. For their study, they distributed a set of Tmote Sky sensors with low power MCU MSP430, TI CC1101 transceiver chip. The sensor equipped with an amplifier and external antenna to increase the transmission range to 2.5 kilometers. The sensors were distributed uniformly with equal distance. It is found that an increasing in the number of nodes under the equal distance scheme will result in decreasing the life time. In addition an equal power placement solution has been proposed that provides a balanced power consumption between sensors by distributing them in an uneven manner along the pipeline. The result shows that the equal power schema outperforms the equal distance scheme in terms of lifetime by 2.4 times.

H. Security

The authors in [56] have tackled the security issues faced when deploying WSNs in to control and monitor the safety of crude oil pipelines in industrial automation, specifically the Niger Delta region of Nigeria. They proposed a security solution that could protect oil and gas facilities and wireless sensors deployed from Vandalism by enabling a reliable and fast detection and reporting of possible security breaches. They used Cyber Physical Systems (CPS),

Table 2 provides a summary of the existing solutions that tackle the challenges and enhance the deployments of WSNs in oil and gas industry.

Table 11: Summary of Existing Solutions

Study	Technical Requirements	Technology used	Types of Motes	Network Type
[2]	Energy consumption and Reliability,	WirelessHart	N/A	Mesh and a SensiNet network
[5]	Reliability, power consumptions and fault tolerance	Multi-hop routing algorithm	N/A	Linear Infrastructure
[6]	Gas leaks in pipeline localization	ZigBee protocol	Temperature sensor	Linear Infrastructure
[7]	Gas leaks, corrosion, H2S	CDMA/GPRS	Temperature, pressure, motor current and voltage	Redundant Multi-hop Topology
[31]	Reliability	ATEX version of DUST Wireless Networks	N/A	N/A
[38]	Stability and Reliability	M-AODV (modified AODV)	N/A	Mesh Topology
[39]	Gas pipeline pressure, temperature	Optical Fiber	Pressure and temperature	Distributed
[40]	Gas Pipeline Leakage	Pressure, acoustic and soil property sensors	N/A	Magnetic induction-based wireless sensor networks
[41]	Pipeline Monitoring Scalability	N/A	MicaZ mote,RF Chipcon and CC2420 transceiver	N/A
[42]	Stability and reliability in Gas leakage detection	MODEM, GPS and wireless 1785-KE card	Pressure, flow and temperature	N/A
[43]	Leakage detection reliability	Wave	N/A	N/A
[44]	Redundancy in underwater gas Leakage monitoring	Ultrasonic and optical networks	Moteiv Tmote Sky Type) with TinyOS	Heterogeneous
[45]	Time delay in Gas Leakage detection	SOAP and MQTT	N/A	N/A
[46]	Monitoring and management inventory system	WirelessHART and RFID	N/A	Mesh topology
[47]	Safety in Oil and Gas Field	GPS\FRID,STM32F103 and μC/OS-II	Gas sensors	N/A
[48]	Moisture in LPG, LNG pipeline	Pico-RFID and Agilent's PSA E4440A	N/A	N/A.
[49]	Latency and Data rates	N/A	Tmote sky devices, MIMO access AGN1200 and TS-3300 board	Heterogeneous

[50]	Fault-tolerance,	N/A	Intel Mote and Mica2 Mote	. Mesh topology
[51]	Reliability, energy consumption and interference	backup sensor placement (BSP)	N/A	N/A
[52]	Fault-Tolerance	N/A	N/A	Wired/Wireless Sensor Network
[53]	Interference	WirelessHart, ISAl00.11, ZigBee	N/A	N/A
[54]	Interference	WirelessHart, ISAl00.11, ZigBee	N/A	N/A
[55]	Energy consumption	N/A	Tmote Sky sensors with low power MCU MSP430, TI CC1101	Uniformly Distributed Nodes
[56]	Security	Cyber Physical Systems (CPS), Wireless Fidelity (Wi-Fi) and low-cost digital Close Circuit Television (CCTV) cameras	N/A	N/A

VI. Conclusion

The For Oil & Gas Industry WSNs offer a large amount of applications that are useful for the production of Performance Optimization (monitor pipelines, gas detection, corrosion, H2S, equipment health status, and real-time reservoir and process control, safety, maintenance.

The technical capability of wireless sensor networks (WSN) is still under ongoing exploration in science, as its true potential has not been fully exploited. This paper aimed to provide WSN designers, oil and gas companies and researcher a critical review at the provision of WSN in the oil and gas industry taking into account the specific requirements of the applications and challenges. Furthermore, a particular attention is given to the existing architectures of efficient mechanisms that fulfil the requirements and overcome the challenges that arise when deploying a WSN in Oil and Gas industry.

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