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An investigation into routing protocols for real-time sensing of subsurface oil wells.

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An Investigation into Routing Protocols for Real-Time Sensing of Subsurface Oil Wells

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Abstract. Pervasive computing has transformed society, and there is a desire to extend this mass data connectivity to the ocean, implementing an Underwater Internet of Things (UIoT), especially by energy companies seeking real-time sensor data from assets such as oil wells and pipelines. As evidenced by the Deepwater Horizon, Piper Alpha, and other disasters, failure of these assets can result in disaster. To avoid these risks, energy companies are interested in using Underwater Wireless Sensor Networks (UWSN) to achieve real-time asset monitoring, allowing for proactive maintenance. Generally, acoustic transmission technology is utilised to communicate with emerging ad-hoc UWSN, an established technology characterised by large coverage areas and reliable connectivity at the expense of high energy consumption and low operational bandwidth. Given that it is impossible to increase the speed of sound without altering the underwater channel itself physically, maximising end to end delivery time in each scenario is largely dependent on the hardware design involved and the selected protocol on the network and data link layers as well as the physical topology of the network. This simulation driven investigation aims to establish how routing technique and topology choice effects end-to-end delivery times in populated, active deep water oil drilling areas. The simulation was carried out in NS-3/Aquasim-NG and ascertained that a layered topology of fixed position nodes with Depth Based Routing (DBR) would be optimal for time critical scenarios achieving the best time between sink and source and therefore the best option for a quick response to a hazard when compared to Hop-to-Hop Vector Based Forward (HH-VBF).

Keywords: Underwater Sensor Networks (UWSN), Routing techniques, IOT, UIOT.

1. Introduction

Pervasive computation and densely connected networks are steadily encroaching into the industrial sphere. Emerging technological paradigms such as 6G Networking and Digital Twins merging with industry is a new trend in the research domain [1]. As such, this can be extended to industries with assets in the sea such as the energy or mining sectors with academia referring to new paradigms like Underwater Wireless Sensor Networks (UWSN) and the Internet of Underwater Things (IoUT) as Qiu discusses in [2]. These concepts have the potential to revolutionise activity in the subsurface domain as it is being steadily proliferated with industries that stand to gain from exploiting formerly inaccessible resources with emerging oceanic mining on the forefront of this. Venditti of Visual Capitalist has written about ocean mining in [3]. This has a direct impact on the oil and gas industry, which has a vested interest in the potential of underwater wireless communication. This is since long-distance deep-sea communication is still carried out via tether, typically fibre optic, resulting in a cable that can be kilometers long and subject to forces at sea as well as interference from sea life such as biting sharks. There are also possible benefits such as weight shedding (the cable of an ROV is an expensive and heavy piece of equipment in of itself) and cost cutting especially as operating depth increases raising pressure and length demands along with it. Acoustic communication is still the standard for wirelessly communicating underwater due to the nature of long propagation range and relative reliability of wireless communication, propagating omnidirectionally and through solid objects, as discussed in [4] by Stojanovic and Preisig. However, because of the limited operational bandwidth, this communication methodology is incapable of transmitting multimedia such as video.

However, despite this, acoustic technology could still be of use as a signaling method within the UIoT enabling a level of autonomy. The energy industry, as well as any other industry, stands to benefit greatly from the autonomy gained through pervasive computing and the nature of proactive asset monitoring as Motlagh discusses in [6]. Proactive monitoring of assets allows for issues to be detected in the current sense rather than allowing them to develop into a risk in the future. As can be seen from a brief history of oil rig disasters, this is still a risky profession with explosions occurring every few years on a global basis resulting often in multiple deaths as well as both economic and ecological damage beyond that. Often, these tragic events are a result of an accumulation of errors, however, there are common themes that emerge, warnings were ignored, maintenance was neglected, the report [5] was a Public Inquiry into Piper Alpha by Lord Cullen, discussing the events and failing that caused the tragedy. [7] by Aasalem *et al* discusses various academic investigations into utilising Wireless Sensor Networks (WSN) in upstream oil and gas production. This information could be transmitted through either an ad-hoc network for inspection purposes or as part of a permanent network for long term monitoring and alerting. Other purposes could be to facilitate an "Automatic Disconnection of Supply" control system where, in the case of a transient subsurface event, a sensor can propagate a command signal that automatically stops oil and gas production quickly at the emergency valves or the wellhead in the blowout prevention system. There were several issues of failure in BP's own Deepwater Horizon Report [8] that could have been identified with proactive monitoring of the safety assets facilitated by IoUT (the flat battery on the blowout preventer) or avoided completely with effective automation (data science driven risk interpretations and diagnostics on components such as the blowout preventer). Table 1 shows sensor technologies utilised for the inspection subsurface pipelines.

This investigation aims to carry out research into the current field of UWSN technologies to investigate practical network paradigms that will allow emergency systems to be proactively maintained via diagnostics so that issues can be identified and solved before there can be accumulation of risk factors resulting in a catastrophic event such as Deepwater Horizon. If that fails, then this same network can be used to transmit low data command signals that can operate emergency systems. Having identified the relevant technology, a simulation in NS-3/Aquasim-NG [9, 10] respectively will be carried out that shows that the novel UWSN network can carry out this function. This investigation will cover the following subjects organised in the following sections in this report. Section 2 covers the relevant work into the real-time monitoring of Subsea assets. Section 3 describes the theoretical network parameters and section 4 describes the carried-out simulation as based on these parameters. The results and discussion of this investigation will be brought forth in section 5 with the conclusion and future work discussed in section 6.

Table 1. Typical sensors used for inspecting pipelines [11]

Issue	Technologies
Erosion	Acoustic Emission
	Electromagnetic Acoustic Transducer
	Computed Tomography
	Remote Field Eddy Current
	Ultrasonic sensor technologies
Corrosion	Electromagnetic Acoustic Transducer
	Remote Field Eddy Current
	Computed Tomography
	Guided Ultrasonics
	Magnetic Flux Leakage
Fatigue	Electromagnetic Acoustic Transducer
	Sonar Imaging
	Fibre Optic Deformation sensors
	Remote Field Eddy Current
	Computed Tomography
Deformation	Fibre Optic Deformation
	Sonar Imaging
	Motion Detection technologies

2. Real-time Monitoring of Subsea Assets

There are not many case studies within the academic body for real time monitoring the subsea oil and gas assets, most technological work tends to focus on generic situation with non-descript functions being carried out. A case was identified where FJL Ribeiro *et al* discussed the Campos Basin in Brazil [12]. This lack of publications suggests that there is a gap that needs to address regarding how these technologies could be implemented in industrial scenarios. Given this, the literature review identified several case studies to investigate for root causes that can be addressed with UWSN technology. Although, there have been many oil production disasters, two of the most infamous were the Piper Alpha (1988) and Deepwater Horizon (2010) incidents which both resulted in mass casualties and landed the operators with billions in fines. Reports detailing the findings of the incidents are given by [5] and [8] respectively. In both reports there were incidents propagating that could be used in modern systems to control the process automatically, reducing the impact of the disasters. From there, feasible geographic locations were picked based on the number of oil rigs present in that area for the experiment to be based on. These were the North Sea (184), the Gulf of Mexico

(175), the Persian Gulf (159) and Far East Asia (155) according to the data [13] from Statista. Physical layer technology was then identified that could facilitate transmission of low-data rate sensor data through the aquatic channel, the series of 42/65 modem from EvoLogics was selected to define the parameters used in the simulation. This series comes as a diverse range of modern devices that allow for an Underwater Acoustic Sensor Network (UASN) to be realised. They can be sourced from the EvoLogics website [14]. The next task was to research the routing algorithms readily available to be utilised in the simulation. The protocols chosen were Depth Based Routing (DBR) [15] and Hop to Hop Vector Based Forwarding (HH-VBF) [16]. These protocols are famous and readily available, a lot of modern routing technologies are based on these founding protocols. These protocols have also seen regular development since these initial papers [17].

3. Case Study

The key issue of this simulation is to produce a simulation that shows a network that can quickly deliver diagnostic data from sensor or send control data to valves from the seabed when a risk is detected. Depending on the depth of the water and type of media being transmitted this can have ramifications on network design as in an acoustic network as distance and bandwidth parameters are in direct conflict in relation to one another, a caveat must take place to achieve significant capacity for sensor data whilst achieving the range to reach the surface. These ideas are discussed in [4]. Depths were picked as to reflect the deepest wellhead in each field (to communicate wirelessly from inside the well itself would require a different physical layer technology), as such, it can be seen in table 2 that there is a large variation in depths.

Table 2. Depths of some select Deepwater energy projects

Location of Well	Depth of Wellhead
Rockall Trough (North Sea)	1886m
Perdido (Gulf of Mexico)	2450m
Salman (Persian Gulf)	43m
DeepSea 1 (Far East Asia)	1500m

Given that 42/65 series modems can cover 1000 m transmission distance with a maximum 31.2 kbits/sec data rate the deeper wellheads will require relay nodes between the sea surface and the seabed to extend the range. This bit rate will be ample enough to allow for seismic sensors to propagate data as these devices are generally low sample rate due seismic waves being predominantly low frequency in nature. This results in different topologies being implemented for each wellhead. Fig 1 shows an example of a novel Deepwater acoustic sensor network [12]. This fig shows how sensors and devices in the seabed can communicate data via acoustics to surface vessels, forming a component of the IoUT. These vessels can then communicate the aggregated data via typical Wide Area Network (WAN) technology such as radio frequency (RF) communications. This allows for the data to be integrated with the greater Internet of Things.

Data and alerts could be feasibly transmitted out to experts and emergency services onshore within a few seconds of data being propagated at the wellhead. This would allow for quicker responses than what has typically been seen in disaster scenarios. Given this the four networks were to be designed in such a way that the device at the wellhead, whether it is a blowout preventer or a seismic sensor, can communicate with the surface, there must also be several paths that can be taken to reduce the impact of a single relay node failing. Therefore, the networks took the following 3D grid-based shape based on this information.

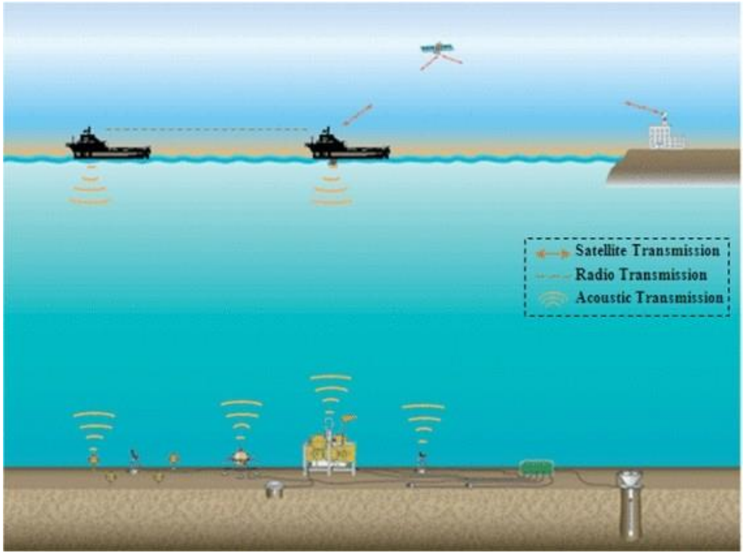

Fig 1. A visual of a basic UASN [12]

Fig 2 shows a visual of how the nodes would be arranged to transfer the data from seafloor to sea-surface dependent on the depth of the wellhead in relation to the surface. As can be seen, the network varies in complexity depending on the depth of the wellhead at the location. The oil field at Salman can function on a relatively simple network as the Persian Gulf is relatively shallow compared to many deep-sea operations reaching only tens of meters at its deepest point. The other three networks are relatively complex with varying numbers of nodes and layers being utilised. These layers are spaced out so that they are within the 1000 m range of the source and sink node's acoustic modem, allowing for reliable data transfer to take place from source to sink. The purpose in having the layered approach with multiple nodes per layer rather than just a single node is to allow for the redundancy in the routing to take place. These layered nodes are anchored in a square formation whose sides are 100 m length, with a single node in the middle. The reason for this, is to offer distance between the asset and the critical communication nodes, so that if debris falls and knocks out nodes automated emergency systems can still activate, limiting damage. In this situation, if all nodes

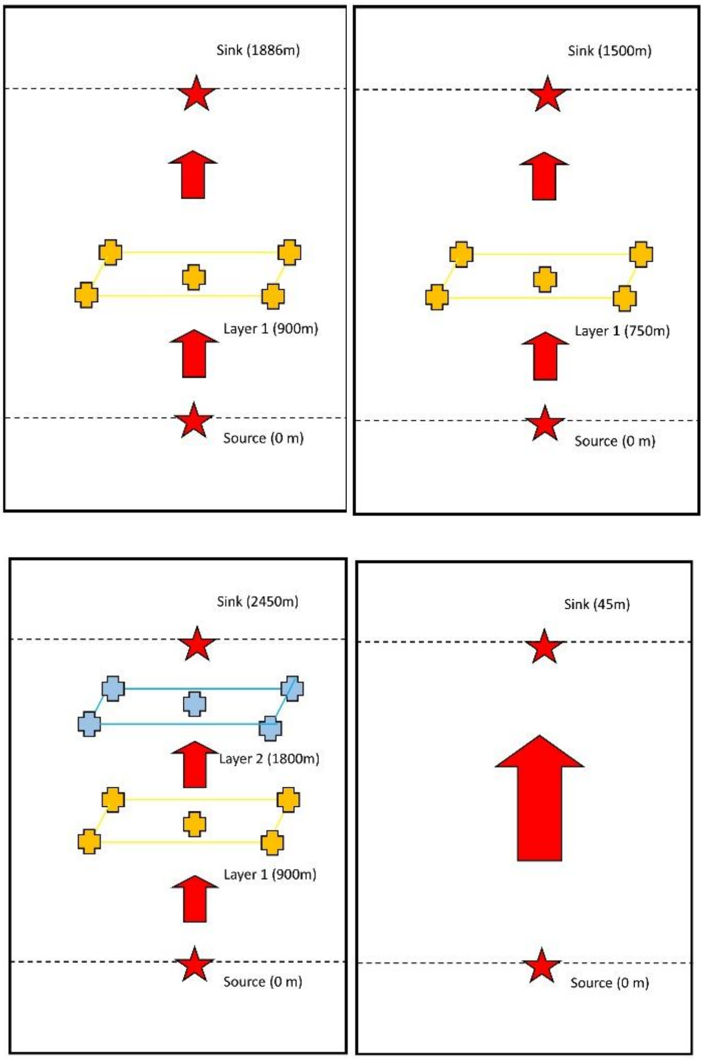

Fig 2. Network topology according to the different location and depths. From left to right, Rockall Trough, Deep Sea 1, Perdido and Salman

were clustered in proximity and debris collapsed down on that location there is a significant chance that the flow of communication could be disrupted, preventing emergency system from activating. The routing technique was selected as DBR for numerous reasons regarding the case study, as discussed, it is computationally simple and processes the data quickly, greedily forwarding the packeted data onwards with minimal calculations taking place. It is also useful as it is decentralised from a central hub using only pressure information to make routing decisions, this renders the network like a mesh topology, a robust formation where there is no single point of failure in routing. Therefore, in an emergency, if the network is maintained in terms of battery and diagnostics are carried out frequently, whether automatically or manually, this network will be robust enough to transmit sensor or command data when necessary and, of prime concern, in an emergency scenario. HH-VBF was selected for similar reasons, it is a simple computationally, decentralized algorithm with a high delivery ratio in sparse UWSN, it is also a standard protocol in the UWSN literature when it comes to drawing comparisons overall. Once again rendering the network into a mesh topology with no single point of failure. This protocol forwards data based on a calculated vector between the source and the sink, then establishes routes on a hop-to-hop basis based on this vector. The network should be, therefore, relatively robust.

In this scenario, it would be desirable to break the chain reaction of accumulating problems as quick as possible considering the gravity of these disasters. Although the events themselves take minutes or hours from onset to eventual complete collapse, the time in between an individual incident leading to a fatal problem itself can be quick, as seen in the reports [5] and [8]. Unfortunately, acoustic signaling is relatively slow in comparison to RF and optical propagation (acoustics propagate at 1500 m/s in water whereas optics and RF propagate at $3*10^8$ m/s). This means that there will always be a finite delay in time between actuality and perception particularly at longer distances. What can be affected however, is the processing time, this is influenced by the number of nodes on a given route and routing process itself. Therefore, a well-designed network can limit this time to be as small as possible. The underwater acoustic networks, as seen in fig 2, have been designed to keep this in mind. Concerns about power can be erased or alleviated depending on how the network is implemented and how the applications are operated. If the application is managed as such that it is constantly being accessed, then battery will be consumed excessively due to the nature of acoustics requiring such power to transmit. However, if the network design is to be utilised sporadically with a wake-up scheme that means it activates only when needed then the network can be preserved for a considerable amount of time. Thus, if this is to be the case, for this simulation at least, lifetime is not considered.

4. Simulation Results

A simulation was carried out utilising Network Simulator 3 (NS-3) and the UASN extension library Aquasim-NG. NS-3 is an open-source C++ library for simulating all manners of experimental networks and it is commonly utilised in research throughout the academic community. This software was utilised to implement the scenarios above and test for connectivity then end to end delay. Tracing packets will confirm that the system can establish end-to-end transmission and the length of time needed to reach the surface. The parameters for the simulation were as follows in table 3.

Table 3. The parameters used in the simulation

Parameter	Value
Source Node	1
Sink Node	1
Relay Nodes	Variable
Depth	Variable
Communication Range	1000 m
Data Rate	31.2 kb/s
Packet Size	400 bits
Speed of Sound	1500 m/s
HH-VBF Pipe Width	100m

Results can be analysed by confirming from the generated the trace file that a packet generated by the source has reached the designated sink through the series of relay nodes, then using formula 1 the end-to-end transmission time can be determined.

$$End\ to\ End\ Time = Trx - Ttx \quad \ldots.\ [1]$$

T_{rx} symbolising the time instant in seconds where the sink receives the first copy of a source generated packet and T_{tx} being the time instant where the packet is first propagated in the network from the source.

Formula 2 describes how propagation delay can by calculated. This metric being the network induced time delay. This is given as: -

$$Propagation\ Delay = End\ to\ End\ Time - \frac{Distance\ between\ Source\ and\ Sink}{Speed\ of\ Sound} \quad \ldots.[2]$$

The results are as follows as displayed in table 4 and fig3.

Table 4. Results of each network simulation

Location	**End to End Connectivity**	**DBR End to End Time (Secs)**	**HH-VBF End to End Time (Secs)**	**DBR Propagation Delay (Secs)**	**HH-VBF Propagation Delay (Secs)**
Rockall Trough	Yes	1.368	2.844	0.114	1.590
Perdido	Yes	1.817	3.756	0.184	2.123
Salman	Yes	0.091	0.825	0.062	0.796
DeepSea	Yes	1.111	2.047	0.111	1.074

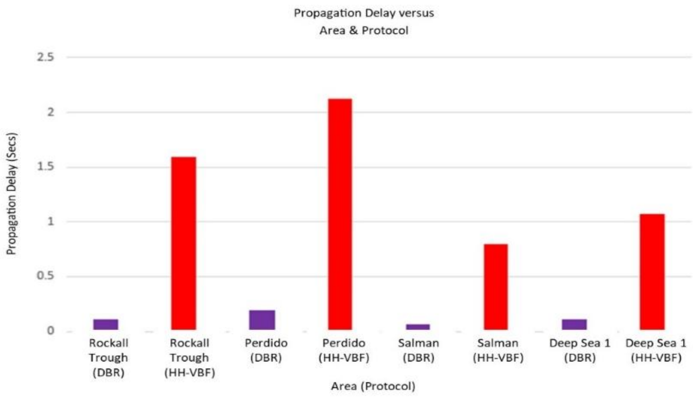

Fig 2. A comparison of propagation delay versus protocol in four different areas

As can be seen in table 4, DBR was proven to operate the quickest of the available routing techniques, in this scenario. DBR was quick to process packets consistently reaching the surface within less than 0.2 seconds processing time within the network, reaching the destination. HH-VBF, however, took considerably more time in those fronts with propagation delays of beyond a second within the same networks. This means that DBR would be preferable for this formation of network as it is consistently quicker than HH-VBF. The speed overall for DBR would be great for these types of services. As can be seen in the reports above, there is a mix of times between problems emerging then manifesting physically. As such, given this robust, quick network response, it is likely that if this network was to have been implemented in one of the given scenarios it would have allowed for interjection quickly at given stages throughout the chain of events and allowed for ample opportunities to prevent disaster. This can be said because the events that unfolded generally took a finite amount of time to propagate between several seconds and minutes, a quick response at one or more of those points could have altered the course of these disasters. Naturally, the quicker the network response and lower the propagation delay, the more chances open from which events can be interrupted.

5. Conclusion

In conclusion, this study effectively demonstrated through simulation how a network could be deployed that allows for sensing and quick or automatic disconnection at the wellhead. A literature review was carried out that looked at disasters such as Piper Alpha and Deepwater Horizon, identifying stages where the deployment of UWSN could have helped carry out proactive maintenance or directly allowed for interjection into the chain reaction that led to the disasters. A 3D layer-based approach to positioning acoustic nodes with a mesh topology was taken to the problem that allowed for nodes to distributed according to the operating range of the modems. This design allowed for the effective range of a modem positioned at the wellhead to be extended to the surface. It was found that data can be transferred quickly, in a matter of seconds, dependent on distance. It discussed how this paradigm could allow for quicker manual or automatic decision making to be made in emergencies, feasibly allowing for valves and blowout protection to be activated remotely in an emergency. This extra input could theoretically be the difference between a small problem remaining solvable or ballooning into a catastrophe like Piper Alpha. Future works considered could be looking into developing an algorithm that reliably identifies when a disaster is possible for this sytstem.

References

[1] L. U. Khan *et al*, "Digital-Twin-Enabled 6G: Vision, architectural trends, and future directions," *IEEE Communications Magazine,* vol. 60, *(1),* pp. 74-80, 2022.

[2] T. Qiu *et al*, "Underwater Internet of Things in smart ocean: System architecture and open issues," IEEE Transactions on Industrial Informatics, vol. 16, (7), pp. 4297-4307, 2019.

[3] Deep Diving for Metals: Visualizing Ocean Mining, Visual Capitalist, August 2021, Available from https://www.visualcapitalist.com/deep-diving-for-metals-visualizing-ocean-mining/

[4] M. Stojanovic and J. Preisig, "Underwater acoustic communication channels: Propagation models and statistical characterization," Communications Magazine, IEEE, vol. 47, pp. 84-89, 2009

[5] WD Cullen "Public Inquiry into the Piper Alpha Disaster", Department of Energy, London, UK, Cm 1310, 1990

[6] N. Hossein Motlagh *et al*, "Internet of Things (IoT) and the energy sector," Energies, vol. 13, (2), pp. 494, 2020.

[7] M. Y. Aalsalem *et al*, "Wireless Sensor Networks in oil and gas industry: Recent advances, taxonomy, requirements, and open challenges," Journal of Network and Computer Applications, vol. 113, pp. 87-97, 2018.

[8] "Deepwater Horizon Investigation Report", BP, 2010

[9] nsnam, March 21, Available from < https://www.nsnam.org/>

[10] R. Martin, S. Rajasekaran and Z. Peng, "Aqua-sim next generation: An NS-3 based underwater sensor network simulator," in Proceedings of the International Conference on Underwater Networks & Systems, 2017, pp. 1-8.

[11] P. Davis and J. Brockhurst, "Subsea pipeline infrastructure monitoring: A framework for technology review and selection," Ocean Eng., vol. 104, pp. 540-548, 2015.

[12] F. J. L. Ribeiro *et al*, "Underwater monitoring system for oil exploration using acoustic sensor networks," Telecommunication Systems, vol. 58, (1), pp. 91-106, 2015.

[13] N. Sönnichsen, "Number of offshore rigs worldwide as of January 2018 by region," Statista, January 2018, Available from https://www.statista.com/statistics/279100/number-of-offshore-rigs-worldwide-by-region/

[14] "Acoustic Modems", EvoLogics, March 2022, Available from https://evologics.de/acoustic-modems

[15] H. Yan, Z. J. Shi and J. Cui, "DBR: Depth-based routing for underwater sensor networks," in International Conference on Research in Networking, 2008, pp. 72-86.

[16] N. Nicolaou *et al*, "Improving the robustness of location-based routing for underwater sensor networks," in - OCEANS 2007 - Europe, 2007, pp. 1-6.

[17] J. Luo *et al*, "A survey of routing protocols for underwater wireless sensor networks," *IEEE Communications Surveys & Tutorials,* vol. 23, *(1),* pp. 137-160, 2021.