Design Challenges in Application-Aware Wireless Sensor Networks

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Abstract— **The deployment of Wireless Sensor Networks at sea provides on-site, distributed sensing of specific events. They can be complementary to existing satellite and airborne radar monitoring, providing continuous and real-time data feed. Of particular interest is chemical spill, such as oil slick. As unexpected occurrences, it is not possible to predict the location, size or weather conditions affecting the region.**

We present a simulation framework for a large-scale sensor network deployment at sea. Our main objective is to develop communication algorithms for localized maritime monitoring using realistic channel and weather models. The design choices are based on the application scenario description, through a bottom-up approach. Wireless channel and physical layer are fundamental for trustworthiness of results, thus particular focus is given to their model selection. The network architecture is based on a cluster protocol with application-specific decisions. The aim is to provide the best compromise between energy consumption, message delivery and network connectivity under dynamic environments.

Keywords: Wireless Sensor Networks, Application, Simulation

I. INTRODUCTION

Wireless Sensor Networks (WSNs) envision circumstances where devices are rapidly deployed in remote or nearly inaccessible locations [1]. Their objective is to track objects, detect events, or simply to monitor physical aspects of the environment. Typical application examples include: battlefield monitoring using devices the size of dust particles to collect information about the environment or track enemy troops; industrial environments sensing and actuation, with devices strategically positioned to identify when unpredictable events become potentially dangerous; environmental monitoring, with sensors deployed in natural habitats to study geophysical events or assess the impacts of human presence; and healthcare, where the physiological activities of patients are being continuously monitored for prevention or during recovery [2, 3]. The variety of applications makes it impossible to assume the existence of an infrastructure to support operations, leading nodes to self-organise and form a network capable of sharing information across devices [4, 5].

The WSN concept is achieved with the development of wireless communication, sensing devices, and low power hardware. WSNs consist of small, inexpensive devices called nodes. A WSN can consist of thousands of nodes deployed over a region, cooperating with each other for distributed sensing and processing.

One of the main issues with WSN development is the division of literature in two main areas, as argued in [6]: (1) algorithms and protocols, and (2) application-centric system design. The authors claim that there is a lack of work combining the two areas, leading to three methodological flaws:

- The application scenario description is simplified or even inexistent, often leading to incorrect design decisions.
- Design choices are simplified without correct assessment of their implications, missing out complex challenges described in the literature.
- The parameter selection for the evaluation of protocols is not fully justified. This is a consequence of improper application description.

In this paper, we propose a framework for the development of a WSN to monitor localised maritime events. We describe the features and challenges related with a network deployment at sea, and which parameters are required for a realistic simulation. From these challenges and parameters, we derive the basis for a simulation framework, describing and justifying the decisions taken.

II. LOCALISED MARITIME MONITORING

Sea surface monitoring is essentially performed by satellite image processing and airborne remote sensing, using infrared/ultraviolet, laser and Synthetic Aperture Radars (SAR) [7]. Local monitoring can be done using the Argos transmitters [8] or the Genesis alert system [9]. However, each method has its limitations. Airborne monitoring relies on aeroplanes or helicopters, with limited flying time, while Argos and Genesis were developed for small-scale deployments.

WSNs can be a complement to satellite and airborne monitoring. A WSN can be quickly deployed over a region where chemicals such as oil slicks have been spilled. The nodes start communicating immediately with each other, organising themselves into a network that provides means of continuously sending sensed data (i.e. thickness, chemical composition) across the network, to a sink node. The sink node combines and processes the received data and transmits it over to a remote location for further analysis by operators to assess the best cleaning strategy. Figure 1 illustrates a simplified example of a WSN deployed at sea, where the devices represented in yellow are nodes monitoring and tracking the oil slick.

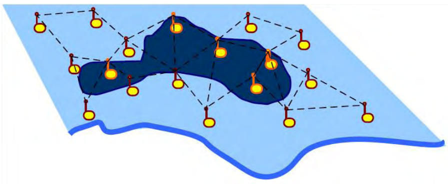
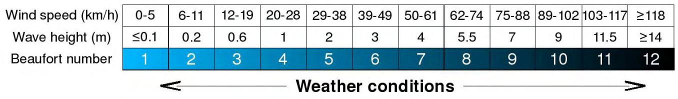


Figure 1. Example of a WSN at sea

A WSN for maritime monitoring has further advantages, not achievable with remote or single-point sensing: while cleaning the slick, the network provides continuous, real-time data about its thickness and dispersion rate in different locations, assisting the procedures. Furthermore, if dispersants are used, the network can detect the depth of oil particles and whether the amount of dispersants used is sufficient or not.

Weather plays an important role in localised monitoring. Weather conditions can quickly change, demanding robustness and adaptability from communication and sensing modules. At the two extremes, and according to the Beaufort scale, the wind can go from a light breeze, with winds below 1 kilometre per hour, to hurricanes, where winds blow at speeds over 118 kilometres per hour resulting in different wave heights, as shown in Figure 2.



Wind speed (km/h)	0-5	6-11	12-19	20-28	29-38	39-49	50-61	62-74	75-88	89-102	103-117	≥118
Wave height (m)	≤0.1	0.2	0.6	1	2	3	4	5.5	7	9	11.5	≥14
Beaufort number	1	2	3	4	5	6	7	8	9	10	11	12

Figure 2. Beaufort scale

A. *Challenges*

Using a WSN for maritime monitoring presents a unique combination of requirements and challenges, due to deployment methods, weather conditions, and oil slick size, shape and expansion rate. Furthermore, nodes must drift with the slick to avoid coverage gaps, additional deployments and node losses.

Ideally, a WSN would be capable of monitoring the whole slick with a resolution at least comparable to that of SAR, i.e. one node every 50 metres or less [10]. To achieve this number, the WSN requires at least 400 nodes per km^2, distributed uniformly. Considering the worst-case scenario of slicks extending over several hundreds of square kilometres, a single network can easily be composed of thousands of sensors, even with partial monitoring.

Murray [11] showed that the oil slick dispersion follows a known pattern, initially linear and later parabolic; hence, its influence in the deployment is predictable. Nevertheless, sea currents can re-shape and break the slick into smaller parts. On the other hand, surface waves can interfere with communication in two ways: they can block the line of sight between sender and receiver, and by tilting the sensor nodes.

Radiofrequency is highly attenuated when by obstacles, particularly when transmitting at 2.4 GHz through water. Nevertheless, 2.4 GHz radios provide faster data rates, allowing more nodes to communicate within the same time interval, while using less energy for each transmitted message. One simple solution to avoid waves is to raise the antenna. However, packaging will limit the antenna height above water level, as a raised antenna moves the centre of mass upwards and increases node tilting. On the other hand, antennas usually have the transmission power concentrated on a small angle (approximately 15 to 20 degrees), and any steep inclination will make the node transmit towards the water or up into the sky. Careful antenna design will expand this aperture, yet the power concentration is inversely proportional to the transmission angle, hence node range will be lower. Using more than one antenna will increase energy consumption, reducing node lifetime. Understanding waves is therefore of major importance, as their size and frequency will have direct effect on network connectivity. Avoidance of high waves (i.e. above antenna height) requires further understanding of nodes' drifting characteristics and dynamic route set-up under unpredictable conditions.

Cost is a common issue with WSN, deriving mostly from the number of devices, and resulting in fundamental decisions to can affect the success of the network. Inexpensive nodes rely on lower spec hardware, thus resulting in limited storage and shorter battery lifetime. Other challenges derive from the WSN paradigm. Traditionally, node lifetime is measured in months or even years, and although the oil slick is expected to be cleaned within days or weeks, energy conservation is still an important factor to address, as it will result in better hardware performance. Physical challenges also cause concerns about network scalability and robustness. The expected number of nodes and the random waves will affect packet delivery rate and latency. Furthermore, it will demand that nodes either seek alternative routes or wait for a clear line of sight towards the destination. On the other hand, with clear weather and flat sea the transmission range increases, thus the number of neighbours for each node and the probability of collisions increase with it.

Node and network location is essential to track and correctly infer where readings are being taken from, and it is assumed that nodes have resources (hardware and firmware) to correctly identify their relative and absolute location.

The challenges described lead to decisions regarding the best node design within the scope of this research, including communication hardware and protocol decision. In addition, they also lead to the trade-off between essential requirements and their relative importance. For example, if one of the essential premises is to keep the latency low while guaranteeing message delivery, the energy consumption will increase, since the network will demand robust protocols, with more frequent retries to overcome dropped packets.

Figure 3 provides a summary of the challenges related to the WSN development for maritime monitoring.

III. RELATED WORK

There are examples of WSN deployment on the ocean. The SECOAS project [12] used fixed sensors distributed through an offshore wind farm to study the sedimentation and wave process and its effect on the wind turbines. The network consisted of 6 sensor nodes equipped with 173.25 MHz radios. Despite variable weather conditions, going from very calm to heavy rain, strong winds and 3 metre high waves, the radios successfully sent their messages to a base station located 3 km away. This proves the usability of a radio transceiver in different weather conditions, independently of using a different frequency to what is common in WSNs. Another project using WSNs on the sea was developed by [13]. The objective of the project was to deploy sensor nodes on the ocean surface to track and monitor ocean currents in near real-time scale, however, as a preliminary study, it has no significant results from the deployment trials. A different set of variables was used in [14], where the central issue was the dispersion of nodes and whether to compensate it with mobile nodes to cover the gaps. There were further considerations regarding wind, salinity, reefs and temperature to model uncontrolled mobility, yet since the deployment was done on a lake, there were no concerns with waves.

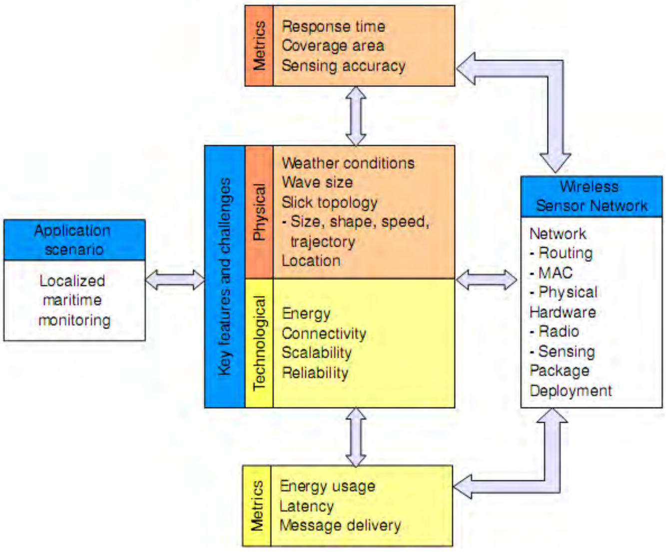


Figure 3. Challenges in localised maritime monitoring

IV. NETWORK SIMULATION AND DEVELOPMENT

Simulation is the most efficient alternative to develop a network prior to its deployment in remote environments. It allows foreseeing and minimising the effects of obstacles and challenges, as well as discovering unexpected issues to assess and modify algorithms accordingly. WSN simulators are grouped in three different categories: custom-built, general-purpose and OS-specific. Custom-built simulators are solutions purposely designed for a particular set of algorithms. They are detailed in specific areas of interest to the development and simplified in other areas. Their advantages are in the detail essential models to the simulations. However, the over-simplification of non-essential areas and the highly customised interface and output makes it difficult to realistically compare with other mainstream solutions.

General-purpose simulators are flexible and support different algorithms, protocols and environments. Their objective is to provide standard inbuilt models of existing protocols that can be customised to fit the demands. The most widely adopted simulators are NS-2 [15] and OMNeT++ [16]. NS-2 is built on a free, open-source platform that allows users to develop new modules (such as algorithms, protocols or propagation models) and share them with the community. Its acceptance as a tool for WSN development means that it is possible to find complete implementation of routing algorithms. The biggest drawbacks arise due to the simplified energy model, overly complex nodes, limited scalability and the potentially distorted results due to the number of modified modules. OMNeT++ is a component-based, modular simulator built for wired networks and later incremented with wireless extensions. Like NS-2, OMNeT++ is an open-source, general-purpose simulator with contributions from the community.

We chose to design a custom-built simulator for this work, since it provides a greater flexibility and focus in the development of algorithms and solutions for the particular application scenario described above.

V. SIMULATION

The simulation is based on a modular approach, where every module represents a different component of the network: nodes, sink and communication channel. In addition, a Real-Time Clock (RTC) and packet handler are required to provide the correct simulation environment. Figure 4 provides a simplified diagram of these modules and their interactions.

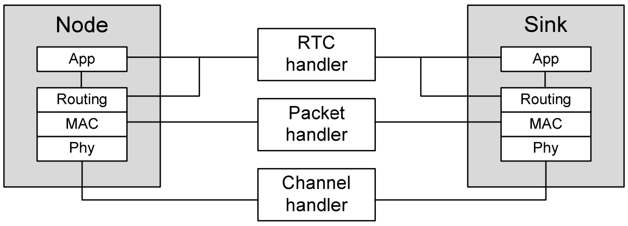


Figure 4. Simulation diagram

Sink nodes have more computational power, memory and energy reserves than standard nodes. This allows them to remain listening continuously for the duration of the deployment. Furthermore, if the network uses a hierarchical algorithm, the additional processing power allows it to manage the network, storing routing tables and schedules. The RTC handler works as a discrete, pseudo-real-time clock, where each new action is stored as a pair <*nodeID, time*>, making its operation closer to that of an internal timer. Each node is triggered sequentially, and once the RTC reaches its time. Each node decides its following task and status individually, according to stored triplets <*time, node, nextStatus*>, where *time* is the event absolute starting time, *node* is the destination of the next event, and *nextStatus* identifies the type of event, whether reply, transmission, or relay. To simplify the communication process, improve simulation speed and reduce memory footprint, all active packets are stored in the Packet handler. The channel handler deals with each individual transmission over the wireless channel.

Both Physical (PHY) and Medium Access Control (MAC) layers are derived from IEEE 802.15.4 standard [17] and are common to all devices in the network. As such, interoperability between nodes and sinks is assured. Furthermore, the standard also describes the expected channel Path Loss (PL) equation, adopted in this simulation, with variable PL exponent.

A. Wireless channel

The communication model is an essential part of simulation: depending on its detail, it can provide a correct understanding of how the packets are sent across the network. Due to random obstacles and variable path losses, broadcasts are calculated on a per-node basis, while simultaneous transmissions are considered independently with additive effect.

In a network every node is a receiver, as long as the transmission signal is strong enough to be decoded correctly. The receiver checks signal strength through the Signal-to-Interference-to-Noise Ratio (SINR). If the signal is strong enough, it is compared with the noise and interferences from other nodes. This is done at bit level: when decoding the signal, a node calculates the Bit Error Rate (BER) probability and, if below a pre-defined sensitivity, it discards the message as being too prone to have errors.

Water molecules resonate at approximately 2.4 GHz, therefore a signal is strongly attenuated if a wave blocks the line of sight, to the point that no transmission gets to the receiver with enough strength to be decoded. A simplistic approach is to consider waves as perfect sinusoidal curves. In these conditions, it can be said that the probability of a node receiving a packet is $p_{Rx} = h/H$, where h is the antenna height and H is the wave height. If a wave is higher than the antenna, there is the probability of blocking the signal. As there is no direct ratio between wave height and length, it is not possible to estimate if this probability is dependent on distance. PL, noise and interference are dependent on the transceiver used. In the case of an IEEE 802.15.4 compliant transceiver, the standard provides equations to estimate these values.

B. Medium Access Control

Distributed network management allows greater speed and flexibility to accommodate unpredictable network behaviour. Clustering algorithms are theoretically more scalable than flat or other hierarchical approaches. Clusters are physically divided from each other and have an independent schedules and management policies, controlled by Cluster Heads (CHs). As such, the network has a better bandwidth distribution. Furthermore, CHs can reduce bandwidth demands though data aggregation and compression when transmitting across to sink nodes. The CH coordination of subscribed nodes also reduces, distributes and parallelises tasks, when compared with the single coordinator alternative. Varying the number of CHs with the number of sensing nodes improves scalability, while correct hardware and protocol selection (along with cross-layer optimisation), and the possibility of node address re-use, improves structural scalability. Clustering also provides increased energy savings. Theoretically and when compared to non-clustered networks, address distribution and route negotiation can be further simplified, reducing overhead [18, 19]. Another advantage comes from the possible network fragmentation due to currents, where clusters become separated and following different trajectories. The distributed management solution provides resources to maintain network operation.

In practise, the decisions taken while setting up the network will be fundamental to assist this statement. Having independent tiers and hierarchies can lead to different routing algorithms in each. A central issue with clustering is the ratio between CHs and sensing nodes. Increasing the number of clusters provides reduces the load management in the lower tier, transferring it to upper tiers. Fewer, larger clusters, on the other hand, reduce the network management and overhead in upper tiers, at the cost of increasing contention and collision inside each cluster. In this work, we will consider the use of amplified transceivers, such as the RFM [20] with a theoretical outdoor range of 1000 metres under low PL. Network algorithms provide means of further improving usability and performance through careful design and adaptation to the application requirements.

1) Cluster formation

The ideal cluster formation would have a uniform CH distribution and transmission range, allowing the creation of a cell-like CH displacement. However, with maritime monitoring, scenario nodes and CHs are expected to be thrown from an aeroplane, hence it is unlikely that they will be perfectly located. Cluster overlapping allows a degree of freedom at the best location, at the cost of added collision in overlapping areas. Figure 5 shows an example of a random network deployment. It uses the $\sqrt{3}.R$ ideal distance between CHs to form a perfect hexagonal cluster, with a maximum deployment error of 150 metres around the ideal location. The deployment consists of 2500 nodes with 1000 metres communication range, randomly deployed in a square area with 7000 x 7000 metres. The number of sensor nodes used in the figure serves only as example for visibility purposes, where a real deployment is expected to have a denser deployment. Nodes in overlapping areas transmit to the closest CH.

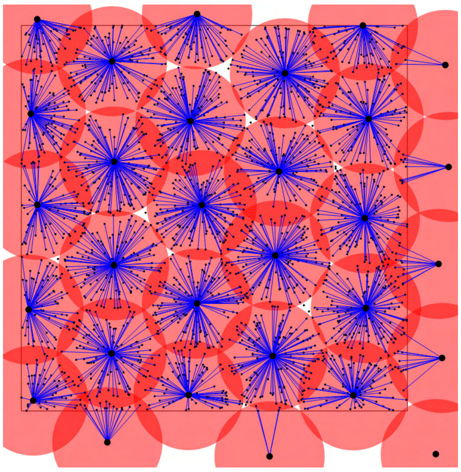


Figure 5. Example of a cluster formation and node-CH connectivity on a 7000 x 7000 metre area

2) Intra-cluster communication

Using transceivers with extended range results in an increased number of nodes subscribing each CH. As such, fixed assignment algorithms with centralised (such as TDMA or FDMA) become unpractical or difficult to maintain, at best. Contention based mechanisms are prone to collisions due to the decentralised schedule and random access, however channel listening, handshaking and ACK can improve delivery. Nevertheless, and as argued in [21], by balancing transmission time with the number of nodes in the cluster it is possible to reduce the probability of collision and minimise its effect in network performance. For this initial stage, nodes avoid collisions by listening to the channel prior to the transmission, and no back-off and retry strategy is used.

C. *Routing*

Clustering allows the use of different routing algorithms inside and outside the cluster. Nodes subscribing a CH will be using a routing strategy defined by it. Single-hop routing is used to test the simulation and weather effects over the communication. It is the simplest routing algorithm where nodes transmit directly to the CH. Considering the CH deployment and coverage, all nodes (with minor gaps expected, as shown in Figure 5) are able to transmit to a CH. Single-hop also gives an insight regarding the energy usage across the network. Routing will consist of two messages: one from the CH, advertising itself and the amount of time nodes have to send back a reply with sensed data; and another from the node, transmitting its sensed data to the CH. The routing algorithm receives the CH advertisement message from the MAC layer and, after a random delay, prepares a message with updated data.

As support for additional routing algorithms, all nodes can receive incoming packets and process them locally. The decision process is done at Routing level and it leads to either dropping the message or search for an adequate receiver. In the case of the CH, if the message has sensed data, it is stored for either inter-cluster or inter-network transmission.

VI. RESULTS

To test the simulator, experiments were conducted on a cluster level, by randomly displacing 300 nodes around a CH, within 1000 metres circular area. The simulation time is 1 hour, during which the CH broadcasts one advertisement every 40 seconds, requesting nodes to send data back within 30 seconds of receiving the advertisement message. The PL exponent was set between 2 (clear weather) and 5 (harsh weather, comparable to indoors communication), while the wave height changed between 0.2 and 2 metres. Since the communication is single-hop, there is no considerable latency between origin and destination.

Figure 6 shows the variation of packet delivery with variations in PL exponent and *H*. It is visible how packet delivery is affected by weather changes. Between PL=2 and PL =3 the number of delivered packets decreases between 28% and 36% (for *H*=0.2m and *H*=2m, respectively). The steeper delivery loss occurs between PL=3 and PL=4, with a decrease of nearly 70%. This greater difference comes from node distribution: while peripheral nodes are divided between adjacent overlapping clusters, intermediate range nodes contact a single CH, making this the area with higher impact on cluster density. Nodes closer to the CH are fewer in number, hence the difference between PL=4 and PL=5 suffers a smaller loss, since the number of nodes is naturally smaller. On the other hand, the difference between wave heights is consistently lower for higher waves, due to the reduced time nodes have with clear line of sight to the CH.

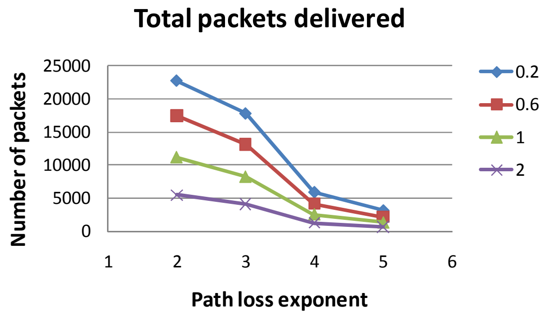


Figure 6. Total packets delivered with different wave heights

Another way to understand the simulation behaviour and cluster communication is through average transmission range between nodes and CH. Figure 7 shows how the transmission range changes with PL and *H*. The curve follows a trajectory similar to that of packet delivery. The differences between maximum and minimum range for a given PL were minimal, with approximately 7% maximum variation between values. This proves that that range is completely independent from wave height. On the other hand, range is severely affected by PL, going below 60 metres for PL=5. Using this knowledge along with effect of path loss in range, we can estimate the routing algorithm effectiveness when affected by different environmental factors. The total estimated delivered packets for a uniformly distributed network is

$$\sum Delivered = \frac{h}{H} 80^{\frac{5.88}{PL}} . \qquad (1)$$

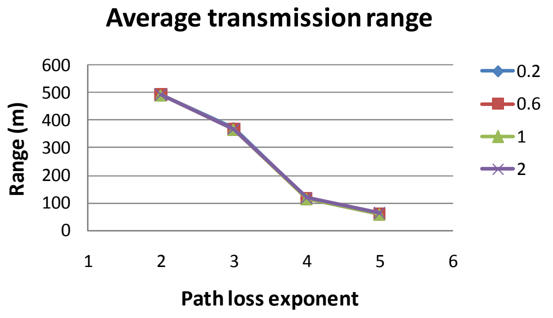


Figure 7. Average transmission range for the delivered packets

Considering (1), we can estimate the packet delivery loss due to collision or back-off, as shown in Figure 8. With lower *H*, the packet delivery rate is 85% of the theoretical maximum, mainly due to contention and collisions. The drop with PL=3, with a minimum of 65.7% when *H*=0.2 shows that for the particular distribution, the network was not uniformly distributed, and the number of peripheral nodes was greater than what would be theoretically expected.

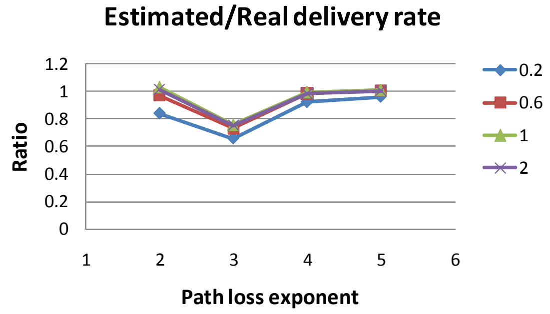


Figure 8. Ratio between maximum estimated and delivered packets

VII. DISCUSSION AND CONCLUSIONS

As mentioned above, one of the main flaws in WSN research and development is the shortage of work that combines algorithm and protocol design with application-centric system design. In this paper, we presented the framework for localised maritime monitoring which, departing from application-specific challenges, leads to the design and development of an infrastructure for communication algorithms using WSNs.

Simulation of WSNs is a fast and effective mean of testing and optimising network. This work describes the simulation development with focus on the communication process. The modular approach provides the basis for the development of routing algorithms and communication models, while the use of independent noise and interference sources lead to a more realistic outcome. Water and waves is another relevant issue for node communication. When a wave obstructs the line of sight, then the signal is considered too weak to be decoded.

Cluster algorithms provide a reliable, distributed infrastructure for network management. Furthermore, as CHs act as local sinks, they can aggregate and compress received messages, minimising bandwidth usage when transmitting them to a destination outside the cluster. Another advantage of clustering is its scalability. As the network size is unknown prior to the deployment, it is only possible to estimate its size. Varying the number of clusters with the network size and density allows each cluster to accommodate a predictable number of subscribing nodes, thus its behaviour is stable independently of the overall network size.

Results show that the single-hop algorithm works well with clear weather, yet it is sensitive to both path loss and obstacles. Although packet delivery is close to the theoretical maximum expected under the weather conditions, the number of delivered packets is low. Multi-hop algorithms are expected to overcome this limitation, by increasing the network range through packet relaying. Furthermore, multi-hop can provide nodes with different route alternatives, allowing them to seek more suitable routes when the CH is not in line of sight.

Further work will look into adaptive network behaviour through MAC and Routing algorithm development and optimisation. This development will consider both network and environmental aspects and, through parameter input and performance estimation, adjust the network behaviour to better suit the immediate network requirements.

VIII. BIBLIOGRAPHY

[1] D. Culler, D. Estrin, and M. Srivastava, "Guest Editors' Introduction: Overview of Sensor Networks," Computer, vol. 37, pp. 41-49, 2004.

[2] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless sensor networks: a survey," Computer Networks, vol. 38, pp. 393-422, Mar 15 2002.

[3] C. R. Baker, et al., "Wireless sensor networks for home health care," 21st International Conference on Advanced Networking and Applications Workshops/Symposia, Vol 2, Proceedings, pp. 832-837, 2007.

[4] D. Estrin, R. Govindan, J. Heidemann, and S. Kumar, "Next century challenges: scalable coordination in sensor networks," presented at the Proceedings of the 5th annual ACM/IEEE international conference on Mobile computing and networking, Seattle, Washington, United States, 1999.

[5] G. J. Pottie and W. J. Kaiser, "Wireless integrated network sensors," Communications of the Acm, vol. 43, pp. 51-58, May 2000.

[6] B. Raman and K. Chebrolu, "Censor networks: a critique of "sensor networks" from a systems perspective," SIGCOMM Comput. Commun. Rev., vol. 38, pp. 75-78, 2008.

[7] N. Robbe and T. Hengstermann, "Latest trends in airborne pollution surveillance," Sea Technology, p. 4, October 2007.

[8] Cobham Tracking & Locating Ltd. (2008, RF-700C2 - Combo Oil Spill Tracker. Available: http://www.seimac.com/

[9] I. EnviroWatch Global Enviro Network. (2002, Genesis Alert System Available: http://www.genalert.com/

[10] I. Maciejewska, "Real Time Oil Spill Detection and Tracking Based on Air-Born and Satellite Remote Sensing Technologies," 2007.

[11] S. P. Murray, "Turbulent Diffusion of Oil in Ocean," Limnology and Oceanography, vol. 17, pp. 651-660, 1972.

[12] M. Britton and L. Sacks, "The SECOAS Project: Development of a Self-Organising, Wireless Sensor Network for Environmental Monitoring," presented at the Second International Workshop on Sensor and Actor Network Protocols and Applications (SANPA 2004), 2004.

[13] S. Nittel, et al., "A drift-tolerant model for data management in ocean sensor networks," presented at the Proceedings of the 6th ACM international workshop on Data engineering for wireless and mobile access, Beijing, China, 2007.

[14] J. Luo, D. Wang, and Q. Zhang, "Double mobility: coverage of the sea surface with mobile sensor networks," SIGMOBILE Mob. Comput. Commun. Rev., vol. 13, pp. 52-55, 2009.

[15] The Network Simulator NS-2. Available: http://www.isi.edu/nsnam/ns/

[16] OMNeT++ Community Site. Available: http://www.omnetpp.org/

[17] I. W.-L. T. Group, "Standard for part 15.4: Wireless MAC and PHY specifications for low rate WPAN," ed: IEEE Computer Society, 2006.

[18] C. Chen, J. Ma, and K. Yu, "Designing Energy-Efficient Wireless Sensor Networks with Mobile Sinks," World-Sensor-Web at SenSys, 2006.

[19] N. Vlajic and D. Xia, "Wireless sensor networks: to cluster or not to cluster?," in World of Wireless, Mobile and Multimedia Networks, 2006. WoWMoM 2006. International Symposium on a, 2006, pp. 9 pp.-268.

[20] RFM Monolithics Inc. (2008, RFM 802.15.4 network devices. Available: http://rfm.com/products/802154.shtml

[21] P. Barbosa, N. M. White, and N. R. Harris, "Medium Access Control in Large Scale Clusters for Wireless Sensor Networks," 2009 International Conference on Advanced Information Networking and Applications, pp. 771-777, 2009.