System Architecture for Data Communication and Localization under Harsh Environmental Conditions in Maritime Automation

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Abstract—**This paper shows an initial approach of a system architecture for a wireless sensor network (WSN), addressing the maritime domain. Novel architectures, technologies and prototypes for WSNs have been in focus of researchers and economists for several years. The proposed system architecture is focused on maritime automation - the construction and maintenance of offshore wind farms with their specific requirements. Harsh environmental conditions impede the performance of wireless technologies in onshore and offshore applications, caused for instance by many metal components, wayless terrain, often non-line-of sight (NLOS) connections between mobile motes, and dynamic ground motion for example onto a jack up ship for offshore construction work.**

Furthermore, many approaches for WSN are addressing either communication or localization networks. The proposed system architecture covers both at the same time, based on Ultra Wide Band radio technology (UWB). UWB allows robust distance measurements and communication, in particular in harsh environments.

I. INTRODUCTION

A. Motivation

The establishment and maintenance of offshore wind farms represent a difficult and complex task for people and machines in their environment. With the planned expansion of renewable energy sources, particularly in the offshore sector, there is an increasing need to perform these operations as efficiently and safely as possible. In Germany alone, offshore wind farms are estimated to produce 25 gigawatts of electric power with an investment volume exceeding 75 billion Euros by the year 2030. [1] There are two working offshore wind farms in the North Sea at the time of writing (Alpha Ventus and BARD Offshore I). An additional 26 farms are approved and will follow soon [1].

For this reason, the research project SOOP was created. SOOP stands for Secure-Offshore-Operations and is promoted by the European Regional Development Fund (ERDF).

The main goals of SOOP are to increase personnel safety, to improve the environmental protection, to enhance process reliability and to reduce overall cost through increased efficiency. The objective of SOOP is to realize a sensor-based situation awareness and risk analysis based on human and situation models [2], [3]. Thereby critical situations would be identified through a generic hazard list [4]. The visualization of the missions will be done by a digital mission assistant which aggregates all information about the mission's current state. All these elements should support and optimize maritime operational tasks in on- and offshore projects.

B. Related work

Existing approaches about wireless sensor based control and monitoring systems in on- and offshore applications can be found in the operation of oil- and gas platforms.

In this fields of application WSNs can be used to detect the loss of flow from a well [5], to monitor pipeline leaks and corrosions or the implementation of a fire protection system [6]. Furthermore there some research is conducted about structural health monitoring [7], [8]. This is used to detect any damage or degradation in structures or mechanical systems to ensure the functionality and safety of infrastructure like bridges, dams, towers and offshore platforms [8]. The goal is to have a real-time production flow optimization through an onshore operation center with a field and reservoir management system [9], putting the focus on an industrial process.

In contrast, the system proposed and planned by SOOP, special focus is on the optimization of maritime tasks and personnel safety.

C. System Overview

The structure of the WSN is shown in Figure 1. Each sensor cloud represents a local WSN on or around a vessel including a SOOP-gateway, a mission assistant and many stationary and mobile sensor nodes (hereafter also called *motes*). The sensor-clouds are able to communicate among each other by a GSM or Terrestrial Trunked Radio (TETRA) based connection. This permits the coordination of local missions and missions in remote sensor clouds. These bits of information will be associated to generate and analyze a view of the state of the overall operation.

In practice, a sensor cloud can be a vessel with a mission such as building or maintaining wind turbines. This is illustrated in Figure 1, which shows the transport of wind turbine parts. The vessel and its cargo are equipped with sensor motes to capture sensor data. Inside the navigation bridge there is a SOOP-gateway installed to collect the sensor data from the sensor motes and the mission assistant to monitor the current

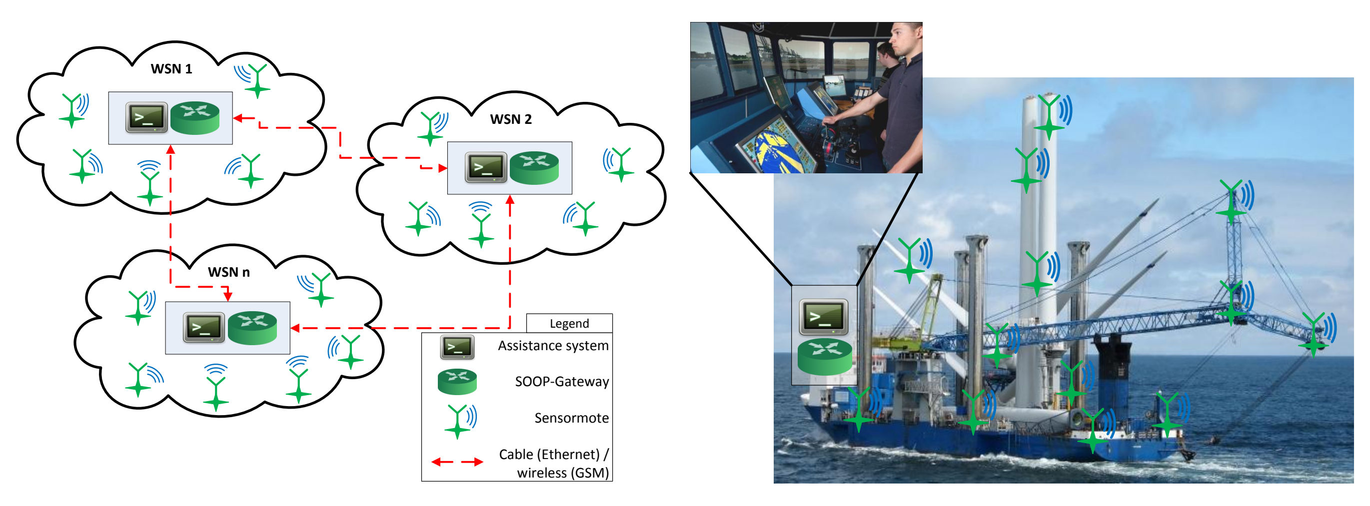

Fig. 1: Left: Structure overview about the wireless sensor network for SOOP; Right: Real-world scenario on a vessel

mission-state. Also warnings are generated in case of critical situations.

Besides the acquisition of sensor data the WSN should be able to locate people, machines and other parts in its environment with high accuracy, which is defined for this application by a measurement accuracy within decimetres.

Thereby the consistence between information and production flow presents a major challenge, and for example it takes therefore a main focus in the FP7-ICT program from the seventh European research program [10], too. Also the conditions on the high seas are to be classified as a particularly difficult, because the maritime environment itself, weather influences, electrical interferences and the reflection of metallic objects must be considered.

D. Requirements for wireless sensor networks in maritime environments

Typical requirements for wireless sensor networks in offshore operations - especially for the proposed system - can be divided into the following items:

1) sensor data acquisition and communication of several physical parameters such as temperature, humidity, illumination and acceleration
2) integrated and highly precise real time locating system (RTLS)
3) processing through an assistance system
4) resistant to harsh conditions in a maritime environment such as bad weather influences, surrounded by salty water and air conditions, vibrations and fluctuations
5) self organizing system architectures
6) limited processing power with low energy consumption for mobile nodes
7) support mobile and static sensor motes
8) be able to recognize and correct a failure from sensor motes
9) observance of the standards in offshore applications

The choice of a suitable wireless communication standard to fulfil all the refereed requirements above represents an essential challenge. Established industry standards are ZigBee PRO, WirelessHART, ISA100.11a and other proprietary solutions such as the DUST wireless communications protocol from DUST Networks [11]. All those approaches are based on the IEEE 802.15.4 standard.

ZigBee PRO is an extension of the ZigBee 2007 protocol stack from the ZigBee Alliance and was especially developed for industrial control applications to increase the robustness and reliability compared to the normal ZigBee standard [11]. WirelessHART is also a part of wireless standards and has become the first recognized standard within industrial automation [11]. After the introduction of WirelessHART the ISA designed a standard (ISA100) to a wider range of applications of wireless control networks. Finally in 2009, the ISA100.11a standard was announced which is based on ISA100. A lot of properties from WirelessHART can be found in ISA100.11a but the ISA standard provides an extended set of options for industrial WSNs [11].

All these standards are actually suited for most of the requirements as defined for the proposed system architecture with the exception of an integrated precise real-time locating system. Therefore it was necessary to search another wireless communication standard - see Section II-B - which fulfils all the requirements. Table I lists the radio standards which have been analyzed regarding communication and localization range, data rate and other characteristics.

II. SOLUTION

A. Components

The approach for a maritime WSN primarily consists of a large number of distributed motes which capture various sensor values from the environment and centralize them within a gateway component (see Figure 2). An example application for analysing the performance of the proposed WSN is an offshore wind energy plant under construction on the high sea.

A network gateway forwards the collected data to other applications for subsequent analysis, e. g. to mission assistants (see Section I-A). The motes of the WSN are technically homogeneous and have a fixed set of sensors. Each of the motes offer an interface for NMEA communication which is the standard interface for instruments in the maritime domain such as compasses, weather stations, GPS devices etc. So the instruments installed on the navigation bridge or any other place in the vessel can be logically included into the sensor network.

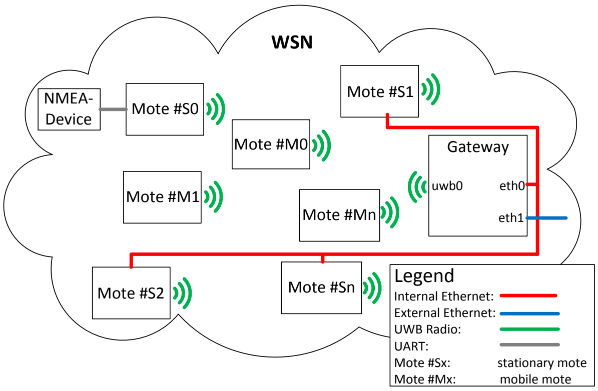

Fig. 2: Overview of the WSN with the gateway, NMEA device and a showcase of some stationary and mobile motes

a) Sensor mote: Figure 3 shows a block diagram of a mote. The current state of development is accordingly an evaluation model to test the functionality (see Picture 4). The hardware can be separated into the following base components: power supply, transceiver module, sensor board and base board. As a power supply the mote is equipped with a LiPo battery power pack which offers 2500 mAh at 11.1 V. This high capacity is required because of the actual power consumption of almost 5 W, in part because the radio module is currently not an optimized ASIC but amongst others a FPGA (Xilinx VIRTEX-6) and an analogous baseband. The hardware and especially the LiPo battery pack is a temporary solution for the evaluation model. LiPo batteries have typically a bad behaviour in lower temperature ranges. The choice of power supply and definition of the target energy consumption are part of further research and development.

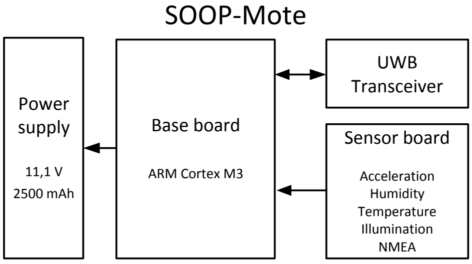

Fig. 3: Block diagram of the basic motes

The base board controls the mote's components, processes the protocols which are necessary for network functionality and executes the functions which acquire and process the telemetry data. The implemented protocols ensure aspects like routing, energy efficiency, self organization and fault tolerance. A microcontroller system with an ARM Cortex M3 is the main part of the base board.

The sensors which are needed to acquire telemetry data with the mote are mounted onto the sensor board. The prototype of the mote contains an initial functional range within an accelerator module, a temperature sensor, a humidity sensor and an illumination sensor. The sensors are connected to the ADC inputs and the I^{2}C interface of the μC. Furthermore the NMEA interface is implemented as component of the sensor board. It is connected to one of the UARTs of the μC. The software for initializing and using the sensors and NMEA devices and purify the sensor data runs on the base board.

The transceiver module is also connected to the base board via UART. The packets which are generated on the base board are sent out with the radio module. The incoming packets whether in the mote's role as a routing point or as destination mote are tunnelled to the base board through the radio module, too.

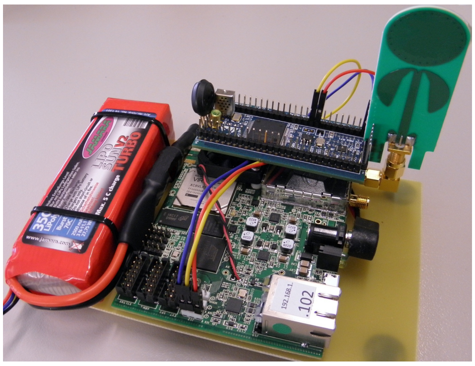

Fig. 4: Picture of the current evaluation model

b) Gateway: The gateway component's hardware consists of an Industrial PC (IPC), suited for installation in a navigation bridge. This IPC is connected to the WSN in two ways. On the one hand, a standard mote is connected via a UART (uwb0 interface in Figure 2), and secondly there is an Ethernet connection to those of WSN motes operated stationary.

Both categories of motes are part of our overall concept (see Figure 2).

The gateway is equipped with an additional Ethernet interface, which is used to transfer data from the WSN to other applications explained in Section I-A.

B. Radio Technology

One of the important parts of a WSN is the used radio technology. There are a several technologies available, which partially meet the requirements (see Section I-D) of the proposed sensor network. Table I shows a comparison between more or less popular radio technologies which seem to be suitable for WSNs.

	UWB (used HW)	ZB PRO	WirelessHART / ISA100.11a	WLAN
Range / m	88	250	220-250	30-100
Low Energy	+	+	+	-
Data Rate	159 kbps	250 kbps	250 kbps	300 mbps
Robustness	+	o	o	-
RTLS	+	o	o	-

TABLE I
COMPARISON BETWEEN DIFFERENT TECHNOLOGIES FOR SHORT RANGE RADIO (SRR)

The relatively low data rate of UWB is sufficient to transmit telemetry data, tiny protocol headers and so on. So the very suitable solution for the refereed requirements is UWB, because only UWB guarantees a precise distance measurement at simultaneous communication in moderate ranges with low energy consumption (in respect to the usage of an optimized transceiver ASIC). We decided to use the Ultra Wideband technology in form of commercial available radio OEM modules.

So the overall wireless communication within the WSN is solved with the UWB radio technology. A radio system belongs to the category UWB when a frequency bandwidth of $B > 500\,\mathrm{MHz}$ is used [12]. The motes are equipped with radio modules which are working in the frequency band $f_L = 3.1\,\mathrm{GHz}$ to $f_H = 5.3\,\mathrm{GHz}$, therefore using a bandwidth of $B_{mod} = 2.2\,\mathrm{GHz}$. With a transmit power of only $P_{tx} = -14.5\,\mathrm{dBm}$ the radio modules are conform to the regulations of the FCC Part 15b. At a distance of 88 m, the raw data rate between these modules is specified with 159 kbps. The main advantage of this broadcast technique is that the informations are not modulated on a carrier wave, but instead they are transmitted as a sequence of pulses. Each pulse has a period of about 500 ps (see Figure 5). That's why there is the broad band in the frequency spectrum.

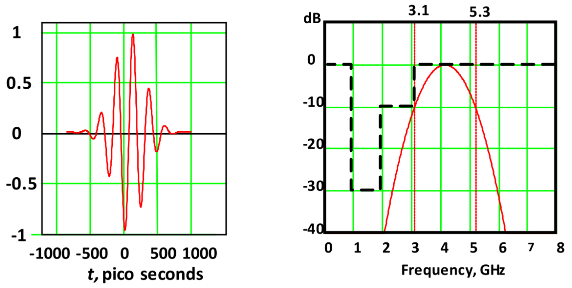

Fig. 5: Example of a Gaussian pulse (left) and the related frequency spectrum (right) which is used by the radio modules (Graphic: [13])

Measurements on offshore oil platforms have shown that UWB is a very suitable technology for communication purposes in harsh environments, especially those which are interfered by large metal components, by electromagnetic devices as well as NLOS connections [14]. The conditions on vessels during the establishment of offshore wind energy plants respectively offshore wind farms are comparable with them on oil platforms. So we expect good results from our system for the live test in offshore conditions in the future.

C. Management and Sensor Data Exchange

The behaviour of the motes can be configured by a central institution, regarding to the context in which they are intended to be used. For instance, the data rate used by the devices to transmit position and telemetry data should meet the specific dynamic requirements of the system to be monitored, without wasting bandwidth.

The latter is an essential prerequisite for an efficient use of available resources. If for example a mote is attached to a crane hook, the required data rate will be significantly higher than if measured on a mostly stationary device.

To handle the large number of sensor motes and especially their generated sensor data, it is necessary to have an organized sensor management system. It should be able to configure sensor properties and control the exchange of sensor data on a higher software layer. Therefore SCAI will be appropriated (Sensor Configuration, Aggregation and Interchange Protocol) as a part of the SCAMPI (Sensor Configuration and Aggregation Middleware for Multi-Platform Interchange) for the planned system [15].

The functionality of SCAMPI is to provide an interface between sensors and applications. To realize a transparent communication between the different layers the SCAI protocol is needed. This allows the exchange of heterogeneous sensor data of different sources through an open and interoperable architecture [15] and helps to solve the challenge of the consistence between information and production flow described in Section I-C. Also the SCAMPI core has the ability of preprocessing the sensor data to aggregate or filter them in a format which is desired by the target application [15]. All these features of the SCAMPI middleware including the SCAI protocol makes the sensor management and data exchange very flexible and easy to use in different types of applications. For all those reasons we have decided to use it for our system.

D. Ranging and Localization

One of the major requirements for the maritime WSN is a sufficiently precise localization of the motes. They can be attached to workers, to materials or for example to crane hooks. The WSN should span a web of located motes over the complete working area of an offshore operation. With these detailed process informations, mission assistants are able to make high quality assessments of the process and personal safety from the operation in real time.

The applied localization algorithms are based on lateration and thus distances between motes. So an important selection criterion of the radio technology is the possibility to derive a very precise distance information between transmitter and receiver from the radio transmission. Due to its transmission method, this is exactly what a UWB system can ensure. By transmitting very short pulses ($t_{pulse} = 500\,\mathrm{ps}$) it is possible to differ the direct path pulse from the multi path pulse, although the amplitude of the multi path impulse is higher than that from the direct path pulse [16]. Hence, there is the possibility to calculate an exact Time of Flight (TOF) and thereby the exact distance between the motes up to an accuracy of a few centimetres. For these distance measurements (also called ranging) the radio modules are using an algorithm called *Two Way Ranging* [17].

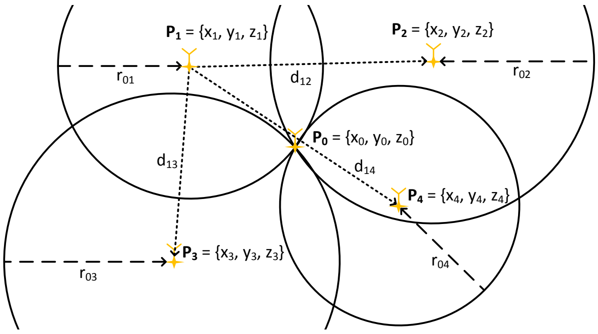

Fig. 6: Geometric dependencies at the localization via quadlateration

Calculating the unknown position $\mathbf{P_0}$ (shown in Figure 6) of a mote is carried out in three phases:

*c) **Phase 1**:* Appropriation of the distances r_{0i} and getting the position $\mathbf{P_i} = \{x_i, y_i, z_i\}$ of the surrounding motes ($i \in \{1, ..., n\}$).

*d) **Phase 2**:* For the lateration algorithm in phase three it is necessary to select $n \geq \textit{to be determined dimensions} + 1 = 4$ suitable motes respectively at least four datasets of the motes from phase one. At the selection in this step the stationary motes are preferred, because they are anchor points with static reference positions and in comparison to the other located motes they have the most accurate position.

Subsequently it is necessary to calculate the distance squares d_{12}^2, d_{13}^2 to d_{1n}^2 towards Pythagoras theorem, which is shown in Equation 1. These are the distances from a previously defined origin reference mote $\mathbf{P_1}$ to the other reference motes.

*e) **Phase 3**:* The last step is executing a quadlateration with the four selected datasets.

The distance square between two points $\{\mathbf{P_i}, \mathbf{P_j}\}$ in a three dimensional space after the Pythagoras theorem is:

$$d_{ij}^2 = (x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2 \tag{1}$$

Based on the geometric dependencies between the known positions of the four reference motes $\{\mathbf{P_1}, ..., \mathbf{P_4}\}$, the unknown position of mote $\mathbf{P_0}$ and the distances between each of them, we get a system of linear equations (see Equations 3 and 2), after linearization.

$$A \cdot x = b \tag{2}$$

$$\begin{bmatrix} x_2 - x_1 & y_2 - y_1 & z_2 - z_1 \\ x_3 - x_1 & y_3 - y_1 & z_3 - z_1 \\ x_4 - x_1 & y_4 - y_1 & z_4 - z_1 \\ \vdots & \vdots & \vdots \\ x_n - x_1 & y_n - y_1 & z_n - z_1 \end{bmatrix} \cdot \begin{bmatrix} x_0 - x_1 \\ y_0 - y_1 \\ z_0 - z_1 \end{bmatrix} = \frac{1}{2} \cdot \begin{bmatrix} r_{01}^2 - r_{02}^2 + d_{12}^2 \\ r_{01}^2 - r_{03}^2 + d_{13}^2 \\ r_{01}^2 - r_{04}^2 + d_{14}^2 \\ \vdots \\ r_{01}^2 - r_{0n}^2 + d_{1n}^2 \end{bmatrix} \tag{3}$$

The method to resolve this equation system with equalization calculation of the measurement uncertainties is the least squares method, shown in Equation 4 [18].

$$\mathbf{P_0} = x = (A^T \cdot A)^{-1} \cdot A^T \cdot b \tag{4}$$

The motes are calculating their position themselves. So this is a decentralized approach for the localization.

The positions of the motes are calculated relatively to a fixed point, for example the gateway located on the ship. If this fixed point has an absolute position e. g. determined by an (D)GPS[1] device, it is possible to conclude the absolute positions of the motes, too.

III. EXPERIMENTS

Our first experiments were concerned with the distance measurement and localization of objects. In addition to a precise calibration of the stationary mote's positions, measuring the distances between motes with a high accuracy is the most important prerequisite for an exact localization.

Fig. 7: Test scenario for non-line-of-sight connections in an industrial environment in the Technikum at the University of applied sciences Emden/Leer to arrange comparable conditions such as those on vessels during offshore operations

So the initial experiment is a distance measurement between two calibrated motes with one line-of-sight (LOS) and two non-line-of-sight (NLOS) scenarios. Within each of the three scenarios we caused our UWB motes to measure the two distances of 1000 mm and 6000 mm, which had been calibrated exactly. Therefore, we received a total of six series of measurements. The LOS test was executed within the laboratory, where there were no disturbing influences. The first of the NLOS tests was performed within a model of a factory hall, placed in the technical center of the University of applied sciences Emden/Leer. In this hall, the so called $Technikum$, there were many large metal constructions like high racks and robots, leading to NLOS connections and to heavy multi path propagation of the electromagnetic waves (see Figure 7).

In the second NLOS test was verified the limiting behaviour of the distance measurement, using a ranging between two

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[1] (D)GPS: (Differential) Global Positioning System - GPS is a satellite based navigation respectively positioning system and DGPS is a method to enhance the accuracy up to a few centimetres.

motes completely separated by a 250 mm reinforced concrete wall.

Table II shows the results of these measurements. For each series, 100 distance measurements have been performed. The first row $Mean$ is the average value of those 100 distance values. $Std.\ Dev.$ shows the standard deviation for each series. The rows Min and Max contain the minimum respectively the maximum value of the measurements. $Failures$ represents the percentage of failed rangings due to various reasons.

	LOS		NLOS (metal)		NLOS (wall)	
Distance / mm	1000	6000	1000	6000	1000	6000
Mean / mm	1010	5991	1056	5941	1369	6289
Median / mm	1027	6000	1102	6017	1398	6292
Std. Dev. / mm	40.9	31.9	78.3	83.8	45.0	18.9
Min / mm	866	5883	772	5519	1273	6199
Max / mm	1039	6037	1125	6055	1425	6319
Failures / %	2	0	0	0	1	1

TABLE II
EVALUATION OF DIFFERENT DISTANCE MEASUREMENTS

IV. PERFORMANCE

The measurements in Section III demonstrate a great performance regarding the reliability of the prototype. Only four of the 600 rangings failed, despite the hard NLOS wall test.

The inaccuracy of the ranging is very small, even within an industrial NLOS environment. However, the results show that the standard deviation of the distances clearly depends on the environment in which the measurements had taken place. For instance, metal components show a significant impact on the standard deviation, but they have only a small influence on the average value. This result gives us a starting point for further research in optimizing the quality of ranging methods.

The third scenario, in which we performed our measurements through a wall of reinforced concrete, shows the limits of this measuring method, caused by the propagation delay and the attenuation of the electromagnetic signal. This results in an almost constant offset (in our case ≈ 30 cm).

V. CONCLUSION

The aim of this paper is to demonstrate an overall system architecture for wireless sensor networks which combines communication and localization for the maritime domain. The proposed approach address in particular the build process of wind energy plants in wind farms. However, the system architecture can easily be transferred to other offshore operations as required on oil and gas platforms. A further transfer to onshore operations like logistical applications or in factory automation is not a long turn either. Therefore, the system architecture presents an universal approach to WSN in harsh environments.

The measured results of the prototypical system in the first lab and shop floor tests are promising. The distances are captured had an accuracy (mean + standard deviation) of only 4 cm in LOS and about 13 cm in metal NLOS environment.

Next steps will be the improvement of the current system and algorithms. Another aspect is the implementation of all the features into prototypical components of the WSN. Furthermore we have to make the components seaworthy and start live testing during offshore operations.

Further work of research will be focused on the analysis of intelligent methods and procedures for increasing the accuracy of ranging and localization, enhancing the robustness and optimizing the energy efficiency of the proposed system. Furthermore, we will continue the development of a self organizing network consisting of intelligent motes which are both network clients and routing nodes.

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REFERENCES

[1] Federal Ministry of Economics, “Energy concept for an environmentally friendly, reliable and affordable energy supply,” September 2010.

[2] J. C. Lenk, R. Droste, C. Sobiech, A. Lüdtke, and A. Hahn, “Towards Cooperative Cognitive Models in Multi-Agent Systems,” in *International Conference on Advanced Cognitive Technologies and Applications*, 2012.

[3] S. Schweigert, R. Droste, and A. Hahn, “Multi-Agenten basierte 3D Simulation für die Evaluierung von Offshore Operationen,” in *Go-3D*, 2012.

[4] R. Droste, E. Böde, A. Hahn, T. Peikenkamp, and J. Lenk, “Security Analysis for Offshore Operations,” 2011.

[5] S. Carlsen, A. Skavhaug, S. Petersen, and P. Doyle, “Using wireless sensor networks to enable increased oil recovery,” in *Emerging Technologies and Factory Automation, 2008. ETFA 2008. IEEE International Conference on*, sept. 2008, pp. 1039 –1048.

[6] M. Akhondi, A. Talevski, S. Carlsen, and S. Petersen, “Applications of Wireless Sensor Networks in the Oil, Gas and Resources Industries,” in *Advanced Information Networking and Applications (AINA), 2010 24th IEEE International Conference on*, april 2010, pp. 941 –948.

[7] P. Wang, Y.Yan, G. Y. Tian, and Z. D. O. Bouzid, “Investigation of Wireless Sensor Networks for Structural Health Monitoring.”

[8] L. Hong-wei, Z. Zhi, and O. Jin-ping, “Offshore Platform Health Monitoring Applications Of Wireless Sensor Network,” 2002.

[9] E. Birkemoe, J.-E. Frey, S. Svensson, and P. Doyle, “How wireless communication supports the lifetime extension of oil and gas production,” *ABB-Review*, 2008.

[10] European Commission, “ICT Updated Work Programme 2011,” July 2011.

[11] R. S. Wagner and R. J. Barton, “Standards-Based Wireless Sensor Networking Protocols for Spaceflight Applications,” 2010.

[12] Federal Communications Commission, “Revision of part 15 of the commissions rules regarding ultra-wideband transmission systems, et docket 98-153, no. 02-48,” April 2002.

[13] Time Domain, *Part Two: UWB Definition and Advantages*, 2011.

[14] H. Li, M. Juan, L. ShuRong, and Z. Zhen, “UWB Channel Measurement and Data Analysis in Offshore Oil Platform,” *International Conference on Communications and Mobile Computing, 2009*, 6-8 Jan. 2009.

[15] C. Busemann and S. Behrensen, “SCAMPI Project Report, Requirements and Final Specification of the SCAI-Protocol,” OFFIS - Institute for Information Technology, Tech. Rep., 2011.

[16] Time Domain, “An Overview of Ultra Wideband,” *3 rd Annual Winter Workshop for U.S. Army Vetronics Institute*, January 15, 2004.

[17] Time Domain , *Part Three: Two-Way Time-of-Flight (TW-TOF) Ranging*, 2011.

[18] W. S. Murphy, Jr. and W. Hereman, “Determination of Position in Three Dimensions Using Trilateration and Approximate Distances,” Department of Mathematical and Computer Sciences, Colorado School of Mines, Golden, Colorado, Tech. Rep., October 1995.