A communication bridge between underwater sensors and Unmanned Vehicles using a surface Wireless Sensor Network – design and validation

Artur Zolich, Jo Arve Alfredsen, Tor Arne Johansen
Center for Autonomous Marine Operations and Systems
Department of Engineering Cybernetics
Norwegian University of Science and Technology,
Trondheim, Norway

Kristoffer Rist Skøien
Department of Engineering Cybernetics
Norwegian University of Science and Technology,
Trondheim, Norway

***Abstract*—This paper presents a conceptual design and field test validation of a network of surface nodes providing a communication bridge between underwater sensors and Unmanned Vehicles (UV). Here we describe the combined operations of custom made low-cost buoys and Unmanned Aerial Vehicles (UAV), linked together within one network. Buoys equipped with an underwater acoustic telemetry receiver and water parameter sensors were moored in a Norwegian subarctic fjord and the underwater sensor data and settings were made accessible via the buoys to a surface mesh-type Wireless Sensor Network. The paper describes the design and implementation of buoy hardware and software, as well as results and experiences acquired through field experiments with the system.**

I. Introduction

Long term measurements collected by underwater sensors play an important role in e.g. climate and fishery research. Unfortunately, retrieval of recorded data from spatially distributed sensor platforms located in remote coastal and oceanic sites creates a series of challenges. Limiting factors include crew and equipment risk during vessel operations, lack of mobile and terrestrial network coverage, poor satellite availability and data transmission costs.

The need for frequent data retrieval has been already addressed by the operators of large underwater sensor arrays [1]. Every operation of this type requires involvement of a trained crew, vessels or for some deployments even scuba divers. Increasing interest and developments in the domain of Unmanned Vehicles, both natatorial and flying, accompanied by the progress in Wireless Sensors Network (WSN) technologies, create new possibilities for the underwater sensor data collection [2], [3], [4], [5]. Unmanned Vehicles, designed for 3D work (Dirty, Dangerous, Demanding), may be used during data retrieval campaigns where they can serve as network nodes, relying signals between the surface network and the user station [6]. Alternatively, UVs can serve as data-mules, collecting data from the network, storing it in internal memory and subsequently delivering it when the user station is within range [7]. In such scenarios use of UVs in combination with WSNs can contribute to increased accessibility to remote sensor platforms and retrieval of critical data, previously jeopardized by improper risk of crew and equipment, or limited economic viability.

Although submerged devices usually provide a wired data interface, underwater communication is also possible using acoustic [8], optical [3] and radio [9] transceivers. Each technology is characterized by different capabilities, limitations and economical viability. However, when considering cooperation with the aerial vehicles use of radio-waves brings significant benefits in terms of the system versatility, scalability and costs. Especially, when using an easily accessible license free Industrial, Scientific, Medical (ISM) frequency band radio.

This paper presents a complete chain for the data retrieval from underwater sensors using a custom built surface node and unmanned aerial vehicles. A description of the buoy prototypes and their field evaluation are the main contributions of the paper. The paper provides results from field experiments in terms of data-link performance, as well as a detailed technical description of the hardware and software design. Buoys are carriers for COTS (commercial off-the-shelf) underwater sensor equipment, providing access to their data and control interfaces. Use of easily accessible mesh-type transceivers makes the system suitable to cooperate with different types of UVs and other nodes. Such capabilities can increase performance, reduce crew risk and lower the costs of data collection campaigns in the remote areas, e.g. in the Arctic. Additionally, devices allow for real-time monitoring of underwater sensor status and measurements, giving better insight into the current situation in the research area. Moreover, having access to energy sources, such as sunlight, wind and waves, the surface node can provide power to the underwater equipment and extend their lifetime or maintenance cycle.

The available literature provides few experimental results on cooperative underwater, surface and aerial technologies under a common and complete data retrieval network chain. Palmer et al. [4] proposes an Air-to-Water radio communication system based on custom designed underwater sensors with controlled buoyancy that can cooperate with UAVs using an IEEE 802.15.4 network. The paper describes communication

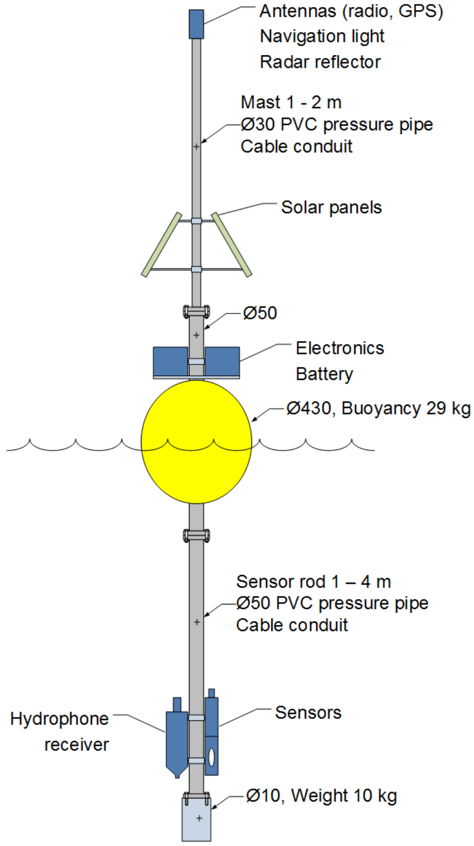

Fig. 1. Overall buoy design

between surfacing nodes and the UAV, providing detailed radio link analysis with practical verification. Teh et al. [10] explores integration of UAVs and WSN, focusing on the UAV trajectory modifications according to sensor node feedback. The paper discusses an airborne system and a sensor node design, provides experimental results for short range communication and data muling. Barbatei et al. [5] propose a custom made, miniature surface sensor node collecting measurements and cooperation with the UAV in terms of data acquisition and relaying.

A section II of this paper describes the details of the hardware and software configuration of the surface node. Section III discusses experimental scenarios and their results.

II. The floating node design

The floating node architecture was created with high energy efficiency, long operating life and low cost as the primary design targets. The device (Fig. 1) consists of three detachable parts. The lower underwater part is a support for a set of underwater sensors and counterweight. The middle part holds an inflatable buoy and a compartment for electronic components including the device control unit and batteries. The top part serves as support for optional solar panels, antennas and beacons.

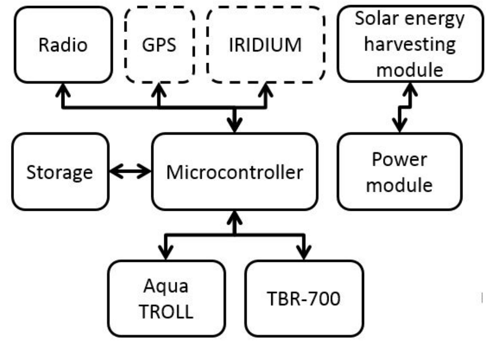

Fig. 2. The floating node hardware architecture

A. The control unit

The core element of each node is the control unit which comprises a microcontroller, a data storage, underwater sensors interfaces, a radio transceiver, and power modules. The unit can be extended with a GNSS or IRIDIUM satellite communication modem (Fig. 2).

The control unit is based on a Silicon Labs EFM32 Gecko microcontroller with a 32 MHz ARM Cortex-M3 CPU core designed for low energy high-performance battery operated applications [11]. In addition, it provides a number of communication interfaces, including multiple USART ports support by RS-485 drivers, suitable for communication with the underwater sensors.

In order to create the surface network between the buoys, and provide communication with Unmanned Vehicles, the system features a COTS Radiocrafts TinyMesh RC1180HP radio module [12]. The radio operates in the 868MHz license free ISM frequency band, which is less influenced by the atmospheric phenomenon than 2.4 or 5.8 GHz frequencies [13]. The module provides up to 76.8 kbit/s data rate, however, actual performance is significantly lower due to compliance with the Listen Before Talk (EN 300 220) regulations. The maximum available transmission power is 27 dBm, while the sensitivity is -96 dBm@100kbit/s. The power consumption during receiving is 24mA@3.3V and 560mA@3.3V when transmitting with maximum power. Entering the sleep mode reduces the consumption to 3.4µA@3.3V. The operating temperature range is -40 to +85°C allowing for operation in demanding weather conditions. The modules establish a self-forming and self-configuring mesh-type network. The number of devices in the network is only limited by the number of available addresses (4 bytes System ID, 4 bytes Unique ID), and link-path supports up to 255 hops. The transmission is secured with AES128 encryption.

The control unit is also equipped with an SD card slot for data storage, two RS485 to TTL-USART converters for communication with underwater sensors, and a power distribution circuit. A prototype of a solar power harvesting module can be used to increase the operating lifetime of the buoy as well as the submerged sensors.

The floating node control unit run a software developed specifically for the current application. It provides support of all described components and can be easily upgraded with new functions. The Fig. 3 presents a flow diagram of the control unit software.

B. Underwater sensors

Two types of state-of-the-art underwater sensors have been included in the system prototype: a receiver for acoustic fish telemetry data (TBR-700, Thelma Biotel AS) and a multi-parameter water probe (Aqua TROLL 400, InSitu), as shown in Fig. 4. The sensors record data on the proximity and migration of acoustically tagged fish as well as water quality parameters, providing insight into the environment and behaviour of fish.

The TBR-700 receives and decodes signals transmitted by acoustic fish tags operating in the 60 - 80 kHz range [14]. The transmitters range from simple ID tags to more advanced sensor tags providing additional data on the fish such as swimming depth, motion/acceleration, dissolved oxygen, salinity, heart rate and muscle activity [15]. The Aqua Troll 400 provides measurements of 12 vital water parameters [16]: (1) actual conductivity, (2) specific conductivity, (3) salinity, (4) total dissolved solids, (5) resistivity, (6) density, (7) dissolved oxygen, (8) ORP, (9) pH, (10) temperature, (11) water level, (12) absolute water pressure.

Both devices differ significantly in terms of communication protocols, power consumption and storage autonomy (Table I). The acoustic receiver is a fully autonomous unit, while the water sensor requires external power, storage and control. These make the pair a perfect showcase of the floating node capability of handling differing sensor requirements.

Device	TBR-700	Aqua TROLL 400
Interface	RS-485	RS-485
Communication protocol	Proprietary	Modbus/SDI-12
Battery life	8-9 months, can be supplied via power-line	no internal battery, has to be supplied via power-line
Data storage capacity	1 500 000 detections	no internal memory

TABLE I
TBR-700 [14] AND AQUA TROLL 400 [16] SPECIFICATIONS

III. FIELD TESTS & RESULTS

Multiple field tests were performed to experimentally validate the functionality and behaviour of the system. These tests were divided into two groups. The initial tests included only one device and were focused on components integration and mechanical structure evaluation. The general behaviour and basic functions of the node were checked when connected to a moving vehicle, both while on land and in the water. The second group of tests focused on achieving more precise measurements of the performance of the data link between two floating nodes and the flying vehicle. During all tests a TBR-700 log were used as a reference data for the transmission performance assessment.

No.	Transferred bytes	Lost blocks	Delivery ratio
Reference data	35455		
1	35455	0	100.00%
2	31595	2	89.11%
3	27543	1	77.68%
4	20040	3	56.52%
5	35325	1	99.63%
6	28114	1	79.29%
7	35455	0	100.00%
8	28153	1	79.40%
9	28541	1	80.50%
10	35455	0	100.00%
11	35455	0	100.00%
12	35455	0	100.00%
Average	31382		96.56%

TABLE II
INITIAL TEST RESULTS – UAV RELAY

A. Initial tests

Initially, an on-shore test was conducted to check proper system operation. The first transfer test showed that a maximum distance between two stationary radio nodes was 485 m. To check if the radio communicates well with moving nodes a fixed-wing Unmanned Aerial Vehicle (UAV) based on an X8 flying platform was used. The ground node was transmitting a TBR-700 log file of 35455 bytes while the UAV – equipped with the second radio-node – was circling around it within Visual Line Of Sight (radius of a few hundred meters), with a speed of 15-17 m/s. 12 data downloads were performed showing good delivery ratio 95.56%, Table II. The radio equipment was therefore deemed sufficient to keeping connection with moving nodes.

Next, the buoy was moored in a fjord (Fig. 5). Because the location was beyond the UAV reach, a motorboat was used as the moving node. For the first time the real time forwarding of underwater records to the surface was demonstrated. The signals from an acoustic fish tag, towed by the motorboat, were received by the TBR-700 and then forwarded via radio to the user station. Radio performance records revealed lower performance than in the flight test in terms of delivery ratio. A file of 55907 bytes was transferred 4 times resulting in the average delivery ratio of 73.16% (Table III). Elevation of the sensor node antenna was approx. 1 m above water surface, while for the motorboat it reached approx. 2.5 m. Regarding link range measurements, the nodes were disconnecting on various distances, usually between 300-400 meters between each other, however once a maximum transmission distance of 800 meters was reached. The exercise revealed a strong need for a dedicated user software and some additional software and hardware modifications of the node itself. However, the good overall integrity and correct floatation of the device was confirmed.

B. Full tests

After applying necessary software and hardware modifications revealed during the initial tests, a second version of the buoy was built. Additionally, a custom user station software,

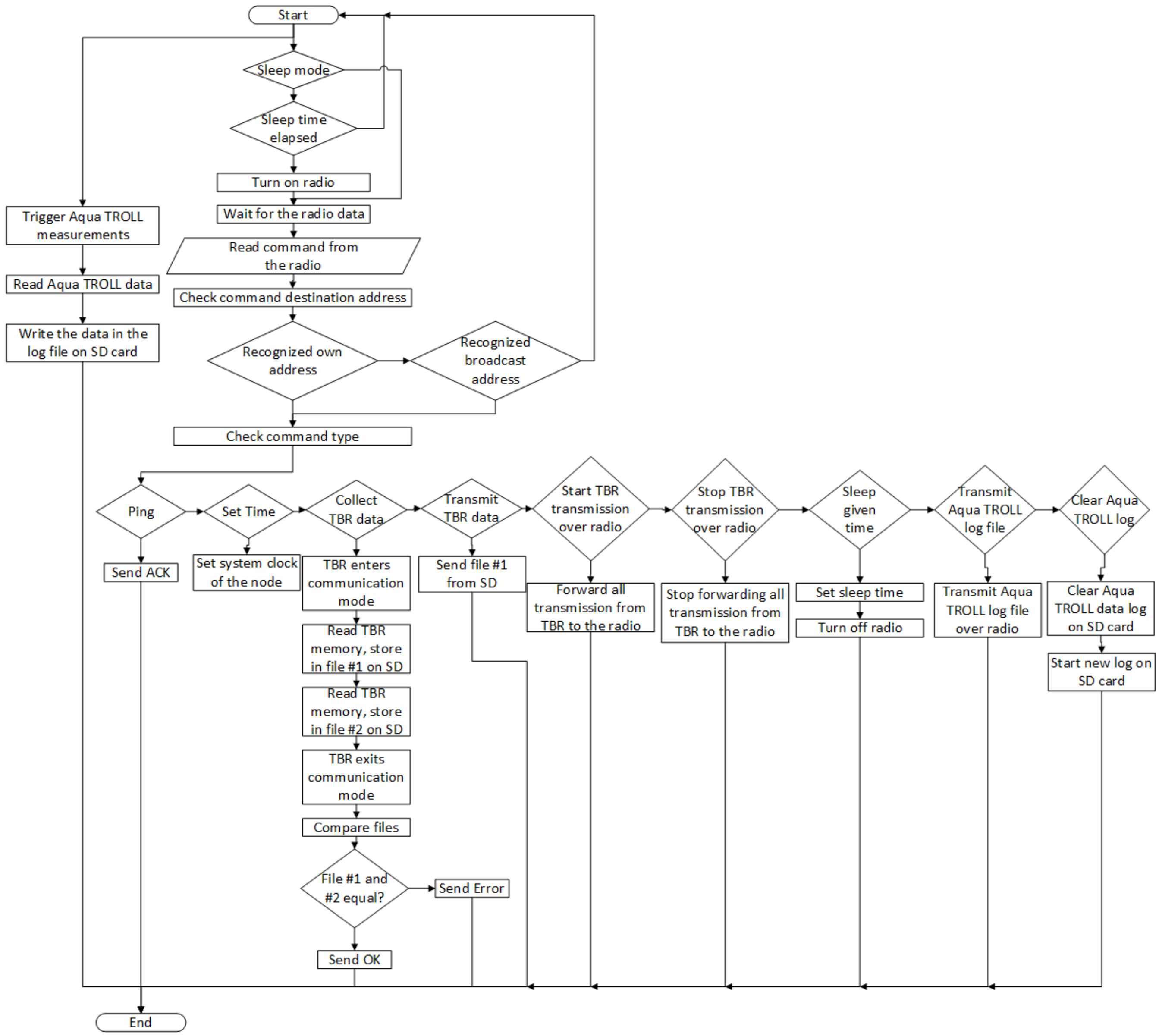

Fig. 3. The software algorithm

No.	Transferred bytes	Lost blocks	Delivery ratio
Reference data	55907		
1	32494	7	58.12%
2	35250	10	63.05%
3	48087	1	86.01%
4	47773	2	85.45%
Average	40901		73.16%

TABLE III
INITIAL TEST RESULTS – MOTORBOAT RELAY

tailored to the test requirements, was developed. The user station provides all control commands and logs data transfer performance with more details.

The full tests (Fig. 6) were performed in a new location in a subarctic fjord and included three scenarios:

- Short range surface to surface
- Short range surface to air
- Long range surface to air

The DJI Phantom quadrocopter was used as the flying node as the test area again was outside the X8 UAV operational capabilities. Results of each scenario are presented in the following sections.

C. Short range surface to surface

The two floating buoys were deployed with a distance of 50m from each other. Later tests showed that the maximum measured distance where two buoys were still able to establish radio contact was 176 m. A third radio-node was attached

No.	Transferred [bytes]	Lost blocks [blocks]	Single bytes lost [bytes]	Total loss [bytes]	Delivery ratio	Transmission time [ms]	Average speed [bps]
Reference file	34699						
1	34699	0	0	0	100.00 %	53974	5143.22
2	34468	1	0	231	99.33 %	66961	4117.14
3	34699	0	0	0	100.00 %	54285	5113.60
4	34699	0	0	0	100.00 %	54760	5069.25
Average	34641				99.83 %	57495	4860.80

TABLE IV
BUOY 1 - SURFACE TO SURFACE COMMUNICATION, SHORT RANGE

No.	Transferred [bytes]	Lost blocks [blocks]	Single bytes lost [bytes]	Total loss [bytes]	Delivery ratio	Transmission time [ms]	Average speed [bps]
Reference file	101925						
1	101778	1	29	147	99.86 %	210817	2541.00
2	101906	0	20	19	99.98 %	197081	4136.61
3	101542	2	25	383	99.62 %	254510	3191.76
4	101519	2	21	406	99.60 %	232526	3492.74
Average	101686				99.77%	223734	3340.53

TABLE V
BUOY 2 - SURFACE TO SURFACE COMMUNICATION, SHORT RANGE

No.	Transferred [bytes]	Lost blocks [blocks]	Single bytes lost [bytes]	Total loss [bytes]	Delivery ratio	Transmission time [ms]	Average speed [bps]
Reference file	58484						
1	58484	0	0	0	100.00 %	91980	5086.76
2	58248	2	0	236	99.60 %	107348	4340.87
3	58484	0	0	0	100.00 %	94477	4952.23
Average	58405				99.87 %	97935	4793.29

TABLE VI
BUOY 1 - SHORT RANGE COMMUNICATION, QUADROCOPTER RELAY

No.	Transferred [bytes]	Lost blocks [blocks]	Single bytes lost [bytes]	Total loss [bytes]	Delivery ratio	Transmission time [ms]	Average speed [bps]
Reference file	125965						
1	101775	N/A	0	N/A	N/A	212189	3837.15
2	123873	12	0	2092	98.34 %	365578	2710.73
Average	N/A				N/A	288884	3273.94

TABLE VII
BUOY 2 - SHORT RANGE COMMUNICATION, QUADROCOPTER RELAY

No.	Transferred [bytes]	Lost blocks [blocks]	Single bytes lost [bytes]	Total loss [bytes]	Delivery ratio	Transmission time [ms]	Average speed [bps]
Reference file	58483						
1	58113	3	16	370	99.37 %	159936	2906.91
2	58207	1	14	276	99.53 %	143225	3251.28
3	58472	0	13	11	99.98 %	115551	4048.29
Average	58264				99.63 %	139571	3402.16

TABLE VIII
BUOY 1 - LONG RANGE COMMUNICATION, QUADROCOPTER RELAY

No.	Transferred [bytes]	Lost blocks [blocks]	Single bytes lost [bytes]	Total loss [bytes]	Delivery ratio	Transmission time [ms]	Average speed [bps]
Reference file	125965						
1	125844	1	2	121	99.90 %	206569	4873.72
2	125692	3	0	273	99.78 %	247060	4070.01
3	124992	6	1	973	99.23 %	234937	4256.19
Average	125509				99.64 %	229522	4399.97

TABLE IX
BUOY 2 - LONG RANGE COMMUNICATION, QUADROCOPTER RELAY

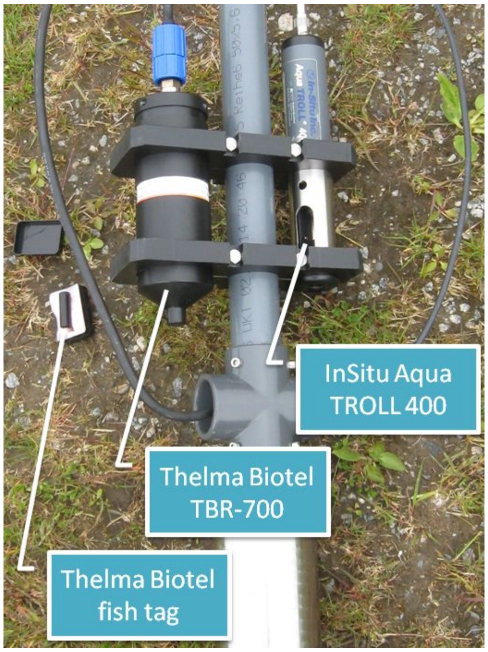

Fig. 4. TBR-700 (left) and Aqua TROLL (right) sensors integrated with buoy

Fig. 5. The buoy moored in a Norwegian Subarctic fjord

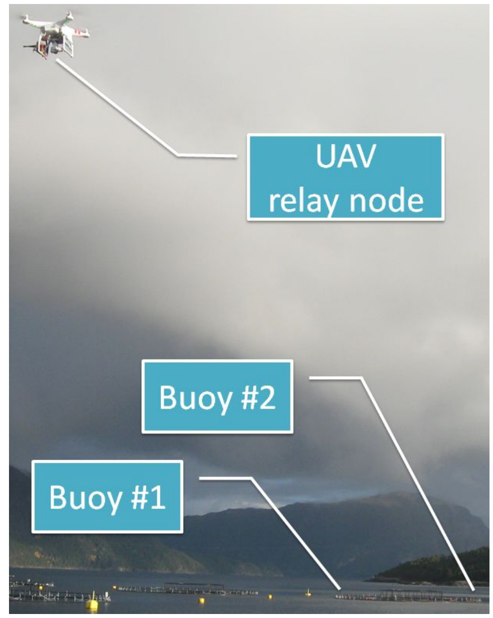

Fig. 6. Data acquisition using the multirotor UAV

Fig. 7. Quadrocopter with the radio payload

to the Phantom quadrocopter (Fig. 7). Having only three TinyMesh radio nodes available (two on the buoys, one in the quadrocopter), the payload had to include a transparent 3DR Point-to-Point 433MHz radio for short range connection between quadrocopter and the user station. Post-mission log analysis revealed some transmission errors caused by this radio, however anomalies can be clearly distinguished from TinyMesh transmission errors. TinyMesh radio transmission errors have a form of lost blocks of bytes, and are marked in Tables IV-IX as "Lost blocks", while 433MHz radio losses are single bytes shown in "Single bytes lost" columns.

The short range surface to surface test was performed to check if the buoys were working properly. Buoy 1 was within a couple of meters from the quadrocopter resting on the motorboat while buoy 2 was approximately 50 m away. A full set of data was downloaded from each buoy 4 times while the user station software was monitoring the transmissions. Results are provided in Tables IV and V as well as in Fig. 8 and 9. For the first buoy the transfer reached the average delivery ratio of 99,83% with average speed 4860.80 bps, and for the second node 99.77% and 3340.53 bps respectively.

D. Short range surface to air

During this test, the quadrocopter with the radio payload attached took-off and hovered 4 m from the buoy 1 and 59 m from buoy 2. A full set of data was transmitted three times from every node. Post analysis shown an error in readout from buoy 2 (on the user station, due to user error) therefore only

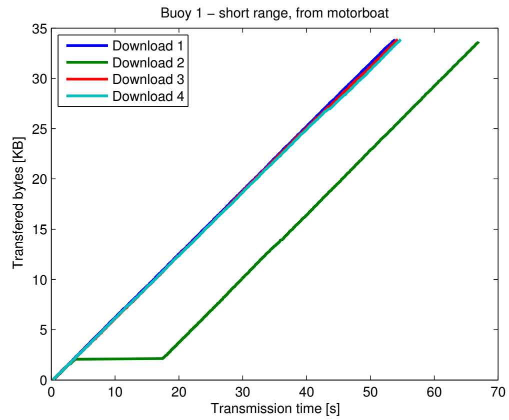

Fig. 8. Buoy 1 - short range communication, motorboat relay

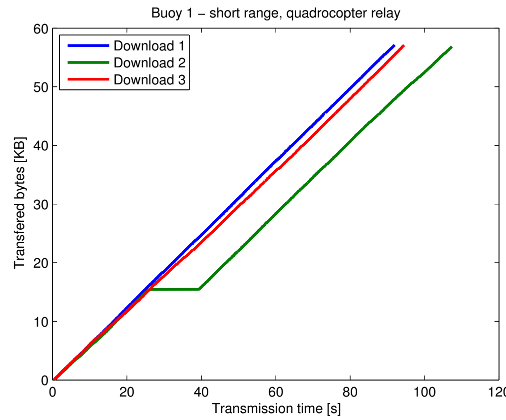

Fig. 10. Buoy 1 - short range communication, quadrocopter relay

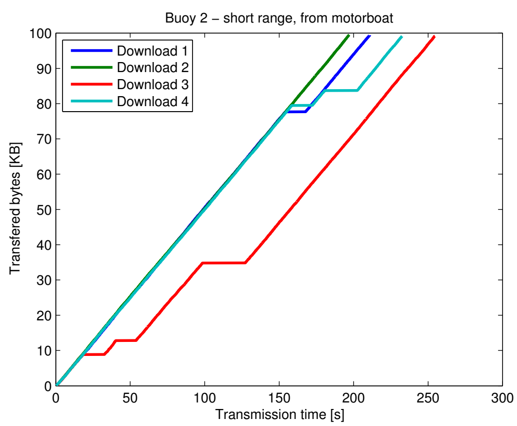

Fig. 9. Buoy 2 - short range communication, motorboat relay

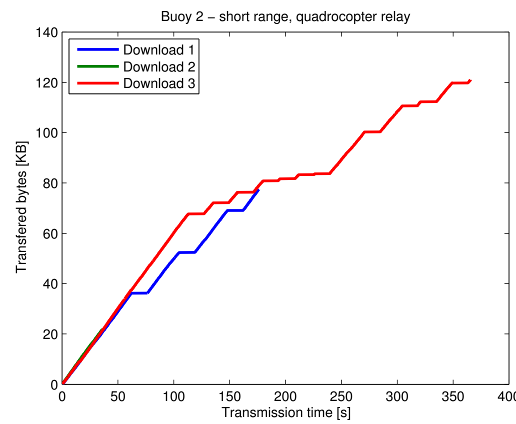

Fig. 11. Buoy 2 - short range communication, quadrocopter relay

one set of data can be used to reliably calculate the delivery ratio, still all collected information can be used to measure average transfer speed.

Results are provided in Tables VI, VII, and in Fig. 10, 11. For the first node the transfer reached an average delivery ratio of 99.87% with average speed 4793.29 bps. For the second node the average delivery ratio cannot be determined due to errors in the log files, however the average speed of 3340.53 bps was achieved.

E. Long range surface to air

The quadrocopter was moved to another location 402 m from buoy 1 and 420 m from buoy 2. Again multiple datasets from each buoy were transferred.

Results are provided in Tables VIII and IX, as well as in Fig. 12, 13. For the first node the transfer reached an average delivery ratio of 99.63% with average speed 3402.16 bps. For the second node 99.64% and 4399.97 bps respectively.

During experiments a maximum data link range of approx. 485 m was achieved, with the DJI flying approx. 9 m above sea surface. This value corresponds to the distance achieved during the initial on-shore tests.

F. Results summary

The experiments confirmed a good performance and high capabilities of presented system. The buoys successfully communicate with different types of moving nodes allowing for real time monitoring of underwater sensor records and status, ensuring that the sensors were operating properly.

The achieved delivery ratio was very high and the average transfer speed got very close to the expected limits of the radio nodes and the LBT regulations. Because the radio protocol supports data retransmission the number of transmission interrupts does not directly determine the number of lost blocks of data.

Quadrocopter flights were performed on maximum safe altitude defined by the pilot. During all flights the quadrocopter was rotated in favor to the antenna radiation pattern, therefore maximizing transfer range and speed. Analysis of quadrocopter flight logs against transmission logs does not show strong correlations between quadrocopter motion and transmission stops or speed.

Although field experiments showed good results, the measured maximum communication range between two floating nodes during the last experiments was not satisfactory and

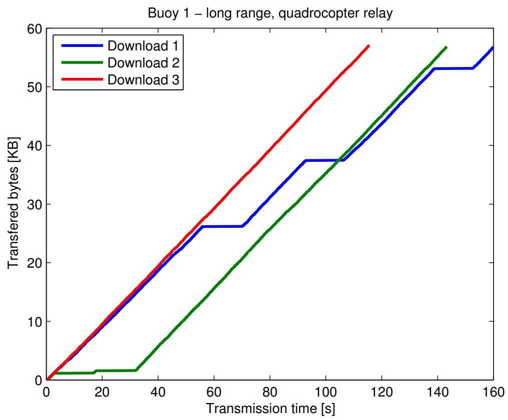

Fig. 12. Buoy 1 - long range communication, quadrocopter relay

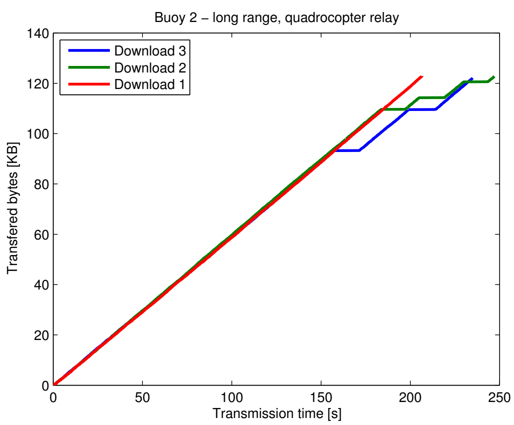

Fig. 13. Buoy 2 - long range communication, quadrocopter relay

requires further attention. Results from the initial water test suggest that lower antenna elevation may be the explanation. During initial tests the second antenna was placed on the roof of the motor boat, approx. 1.5 m higher than what was the case during the final tests.

The experiments provided valuable feedback on the node design and functionality that will serve as crucial input to the design phase of next generation of buoys.

IV. Future work

After the field validation, a new activity has been launched to redesign and upgrade the control unit. The new design integrates major equipment into a single custom made PCB removing all unnecessary elements introduced by the micro-controller and radio prototyping kits employed in the first version of the node. The upgrade also incorporates new useful components, i.e. a GPS for positioning and time synchronization, and an IMU for wave monitoring. Currently the upgraded module is being assembled and tested. Future plans include use of the buoys during a wild Salmon migration tracking and monitoring campaign. Additionally, the devices - equipped with different modules - are going to be used in a set of experiments on heterogeneous, intermittent network routing including high-bandwidth surface-to-air, acoustic underwater, and satellite communication.

V. Conclusions

An increasing interest in oceans monitoring creates new opportunities for underwater sensor systems. However, limited access to remote areas, crew risk and economical viability influence decisions on deployment of new sensors. Providing new methods of data retrieval and extending the sensors maintenance cycle can facilitate the use of state-of-the-art technologies, resulting in better insight into complex environmental processes.

The communication bridge presented in this paper represents a complete chain of information exchange between underwater, surface and flying equipment platforms. Modular design allows for quick integration with other sensors and unmanned vehicles. The concept was tested in the sub-arctic Norwegian fjord, with results showing a radio data delivery exceeding 99% and predicted transmission speeds.

Acknowledgment

This work is partly sponsored by the Research Council of Norway through the Centres of Excellence funding scheme grant number 223254 - AMOS.

References

[1] D. M., "Methods for the deployment and maintenance of an acoustic tag tracking array: An example from california's channel islands," *Marine Technology Society Journal*, vol. 39, pp. 74–80, March 2005.

[2] A. Erman, L. Hoesel, P. Havinga, and J. Wu, "Enabling mobility in heterogeneous wireless sensor networks cooperating with uavs for mission-critical management," *IEEE Wireless Communication*, vol. 15, pp. 38–46, 2008.

[3] V. I., K. K., R. D., D. M., and C. P., "Data collection, storage, and retrieval with an underwater sensor network," in *SenSys'05 Proceedings of the 3rd international conference on Embedded networked sensor systems*, 2005, pp. 154–165.

[4] J. Palmer, N. Yuen, J.-P. Ore, C. Detweiler, and E. Basha, "2015 ieee international conference on robotics and automation (icra)," in *On air-to-water radio communication between UAVs and water sensor networks*, 2015, pp. 5311 – 5317.

[5] R. Barbatei, A. Skavhaug, and T. Johansen, "Acquisition and relaying of data from a floating wireless sensor node using an unmanned aerial vehicle," in *2015 International Conference on Unmanned Aircraft Systems (ICUAS)*, 2015, pp. 677 – 686.

[6] E. Pignaton de Freitas, T. Heimfarth, I. Netto, C. Lino, C. Pereira, F. Wagner, and T. Larsson, "Uav relay network to support wsn connectivity," in *2010 International Congress on Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT)*, 2010, pp. 309 – 314.

[7] J. Isaacs, S. Venkateswaran, J. Hespanha, U. Madhow, J. Burman, and T. Pham, "Multiple event localization in a sparse acoustic sensor network using uavs as data mules," in *2012 IEEE Globecom Workshops*, 2012, pp. 1562 – 1567.

[8] D. Kilfoyle and A. Baggeroer, "The state of the art in underwater acoustic telemetry," *IEEE Journal of Oceanic Engineering*, vol. 25, pp. 4 – 27, Januar 2000.

[9] A. Palmeiro, M. Martin, I. Crowther, and M. Rhodes, "Oceans, 2011 ieee - spain," in *Underwater radio frequency communications*, 2011, pp. 1–8.

[10] T. S. K., M. L., C. P., and H. W., "Australasian conference on robotics and automation (acra)," in *Experiments in integrating autonomous uninhabited aerial vehicles (uavs) and wireless sensor networks*, 2008.

[11] "Efm32 gecko 32-bit microcontroller," http://www.silabs.com/products/mcu/32-bit/efm32-gecko/Pages/efm32-gecko.aspx, accessed February 14, 2016.

[12] "Radiocrafts rc11xx/25xx-tm mesh/multi-hop rf transceiver module," http://www.radiocrafts.com/uploads/rcxxxx(hp)-tm_data_sheet_1_19.pdf, accessed February 14, 2016.

[13] E. Karagianni, A. Mitropoulos, I. Latif, A. Kavousanos-Kavousanakis, J. Koukos, and M. Fafalios, "Atmospheric effects on em propagation and weather effects on the performance of a dual band antenna for wlan communications," *NAUSIVIOS CHORA*, vol. 5, pp. B29–B45, 2014.

[14] "Tbr 700 acoustic receiver," http://www.thelmabiotel.com/tbr-700/, accessed February 14, 2016.

[15] "The thelma biotel acoustic depth transmitters," http://www.thelmabiotel.com/index.php?pageId=559, accessed February 14, 2016.

[16] "Aqua troll 400 multiparameter instrument," https://in-situ.com/wp-content/uploads/2014/11/Aqua-TROLL-400-Multiparameter_Specs.pdf, accessed February 14, 2016.