exeley INTERNATIONAL JOURNAL ON SMART SENSING AND INTELLIGENT SYSTEMS

Article | DOI: 10.21307/ijssis-2020-015

Issue 1 | Vol. 13 (2020)

Implementation of a low cost, solar charged RF modem for underwater wireless sensor networks

Mohammad M. Abdellatif*, Salma M. Maher, Ghazal M. Al-sayyad and Sameh O. Abdellatif

Electrical Engineering Department, Faculty of Engineering, and FabLab, Centre for Emerging Learning Technologies (CELT), The British University in Egypt, El Sherouk City, Suez Desert Road, Cairo, 11837, Egypt.

*E-mail: Mohammad.Abdellatif@bue.edu.eg

This paper was edited by Md Eshrat E. Alahi.

Received for publication May 11, 2020.

Abstract

Underwater communication (UWC) has become an attractive research field over the past few decades. This is mainly due to the increase in underwater applications such as exploration, monitoring, and warning systems. Traditional communications techniques face many obstacles when used underwater. Optical communications require line of sight which is not always maintained underwater due to turbulence. Acoustic communication does not suffer from that, however, it can only operate with very low rates. While radio frequency (RF) communication can only operate over short distances due to the attenuation from the water, it can deliver relatively high data rates and does not require line of sight nor affected by turbulence. Additionally, it does not suffer much when crossing the air–water boundaries. Moreover, underwater nodes require a new method of powering as it is not feasible to change their batteries when they are depleted. And so, we have investigated underwater solar power harvesters as a means to power the underwater nodes. In this paper, we design, implement, integrate, and test a low cost solar powered RF underwater modem to be used as a building block of an underwater wireless sensor network. The system was tested with multiple nodes to allow multi-hop communications in order to increase the communication distance. Results show that the network operates with a moderate to high throughput from end to end.

Keywords

Underwater communications, Solar power, WSN, RF transceivers, Monocrystalline solar cells.

Underwater communication (UWC) is a booming research field as it serves many applications (Hu et al., 2019). It is used by oceanographers in navigation and exploration of deep seas; by military in protection and guarding of the water borders and to detect underwater mines; by divers to communicate with their host ship; and by governments as an early warning system against floods or earthquakes (Kao et al., 2017). Since a large number of devices has to be used in order to create an underwater network, cost, and reliability become really important. Hence, it is important that the underwater devices used allow reliable and fast data transmission while being cost effective, small, and easy to deploy.

In literature, UWC is mainly done using one of three technologies: optical communications (Sawa et al., 2019), radio frequency (RF) communications (Kamal et al., 2019; Maher et al., 2019), and acoustic communications (Sanchez et al., 2011, 2012; Sendra et al., 2016; Zia et al., 2018). Although, acoustic is the primary underwater technology due to its water turbulence immunity and the ability to operate without line of sight. It can only operate reliably with very low data rates, high latency, and very limited bandwidth (Sendra et al., 2016). On the other hand, optical communication technology can sustain very high data rates even with the high attenuation from the water.

However, is highly affected by water turbulence and it requires line of sight which is not always available, therefore making it unreliable and hard to implement, not to mention expensive (Saeed et al., 2019). Finally, there is RF technology. RF communications can be used to transfer data with moderate data rates over short distances and can cross air/water boundary smoothly. This along with multipath propagating was found to be a benefit in many different types of waters (Garcia et al., 2011; Ali et al., 2019). Additionally, RF devices are very cheat and small in size when compared to both optical and acoustic communication devices (Awan et al., 2019).

Many studies were conducted on UWC and several commercial modems are currently available in the market by various suppliers. In 2019, a team published the implementation of an optical modem with 20 Kbps operating within a range of 100 m. This was done using a bidirectional prototype and is currently being improved to support omni-directional directivity along with an axis error compensator (Sawa et al., 2019). However, it requires a line of sight to operate, which our proposed RF modem does not need. Zia et al. (2018) developed an acoustic modem that was adjusted for short range implementations; they were able to achieve data rates of 300 bps at 1 m. Furthermore, according to Sanchez et al. (2011), they have developed a low cost acoustic modem that could reach a maximum distance of 100 m with data rate of 96 bps with FSK modulation technique. The modem consumes 12 mW at the transmitter, while maintaining an idle power of 3 μW. Moreover, the study group continued developing acoustic modems; they studied the effect of modulation techniques on the transmission in water. They developed a modem that uses BPSK which was found to enhance the data rate to 80 kbps, but shorten the range of transmission to 50 m (Sanchez et al., 2011). On the other hand, Garcia et al. (2011) also established an acoustic modem that could work with 200 bps at range with 750 Mw transmitter power and 35 mW idle power.

From the industry point of view, one of the leading companies that sell underwater nodes for navigation is Sonardyne that was founded in 1970 (BlueComm, 2020). They produce three optical underwater modem set, Bluecomm 100, 200, and 100UV priced at £37,679.00 GBP, £72,891.00 GBP, £79,891.00 GBP, respectively. Our proposed modem cost much less than the aforementioned modems. The Bluecomm 100 operates at maximum of 10 meters at 1 to 5 Mbps, it is mainly optimized to accommodate all lighting conditions. Moreover, version 200 operates at 150 meters with 2 to 10 Mbps optimized to achieve maximum rate, whereas 200 UV is similar to the previously discussed version except with a shorter range, it is mainly operating in conditions where wireless underwater video recording is required. The company also sells acoustic modems, one of the most selling is Underwater Acoustic Modem 6, which could deliver 9 Kbps and maximum range of 1 km. It could also stand without recharging for 35 days when on standby conditions (Sendra et al., 2016). On the other hand, LinkQuest Inc. sells several acoustic modems. For instance, UWM1000 is the modem with least specifications. It could deliver 7 kbps and could transfer data up to 350 m (LinkQuest Underwater Acoustic Modems, 2020a, 2020b). The modem has a sleep mode power consumption of 8 mW and a dimension of 87.2 mm × 126.2 mm with a weight out of water of 4.2 kg (LinkQuest Underwater Acoustic Modems, 2020a, 2020b). Whereas the modem with the highest qualifications, UWM10000, has a data rate of 2 kbps operating at a range 7,000 m in omni-directional mode and 10,000 m at directional mode (LinkQuest Underwater Acoustic Modems, 2020a, 2020b). It has a 9 mW sleep mode power consumption with circular housing of 150 mm diameter and 580 mm high. To the best of our knowledge, there are no developed UWC solutions using RF technology that are available for commercial use. Additionally, the aforementioned modems operate on either replaceable batteries or require external power source.

In this work, we introduce a robust, sustainable, and, most importantly, low cost RF underwater modem with energy harvesting capabilities that can be used as a building block of an underwater wireless sensor network where each device is a node. Monocrystalline solar cells are used to create an energy harvesting subsystem in order to recharge the battery.

The intention is to build a system that could be deployed for monitoring the turbulence and floods as the system will be a standalone where no human interaction is needed. The modems will be powered by the solar cells during the day and through the charged batteries during night, which means it can be used to create a sustainable underwater monitoring network. Results show that the total communication range almost doubles for each added node when the handover mode is enabled. Additionally, experiments were done in order to test the performance of the overall network in terms of overall throughput.

The rest of the paper is organized as follows. The second section presents the modem design. The third section shows the integrated node that combines both the communication subsystem and the harvesting subsystem. The fourth section describes the experiments performed. The fifth and sixth sections present and discuss the results, respectively. Finally, the sixth section concludes the paper.

Rf modem design

The proposed modem is developed using RF technology, as an extension to our previous work published in the studies of Maher et al. (2019, 2020), Kamal et al. (2019), Nasser et al. (2019), Mahmoud et al. (2018). In the study of Maher et al. (2019), two RF modules were tested, one operating at a frequency 433 MHz, while the other is operating at 2.4 GHz. Multiple tests were performed in order to select the most suitable frequency in the proposed setup. Throughput, end–end delay and packet loss were tested in air–air, air–water, and water–water scenarios. Results showed that using 433 MHz as the operating frequency gave the best result and for the longest distance.

Figures 1 and 2 show the server node schematic, and the terminal node schematic, respectively. The proposed topology is that the server node will be placed on a ship or a buoy, while the terminal node(s) will be submerged. An Arduino Nano microcontroller was used to manipulate the data and add the required overheads for transmission in order to achieve a more reliable communication. The microcontroller is based on ATmega328P, which has an 8 bit RISC processor core (Arduino Nano, 2020). In order to use energy, using the concept of the microcontroller could also provide sleep mode for the system. The RF modules used are the FS1000A transmitter and XY-MK-5V receiver modules. They operate at 433 MHZ RF, the transmission power is 10 mW to 40 mW, which allows the communication range to reach 20 to 100 meters outdoors, according to the datasheet. By default, they come with no external antenna, however, a simple antenna can be added to increase the gain and, in turn, the range. In the proposed system, temperature is selected as the physical parameter to be measured and communicated through the network. The temperature sensor used was a DS18B20 one wire digital temperature sensor that can measure a temperature range from −55°C to 125°C with accuracy of ±5 (Electrosum DS18B20 Temperature Sensor, 2020). Moreover, the server modem is further equipped with a Wi-Fi module, ESP8266 low cost module used with full TCP/IP stack, in order to upload data to an online server. This helps the user to monitor data from an offshore workstation. ThingsSpeak was chosen to be the online platform for visualization of data.

The modem is powered through a rechargeable battery charged by a solar cell and a charging circuit. A Lithium Battery Charger Module (TP4056) With Battery Protection is used with charging current of 1 A and as fully charged voltage of 4.2 V connected to a DC–DC Step-up Module (cf. Figure 3). Additionally, monocrystalline solar cells, 'IXYS Corporation',

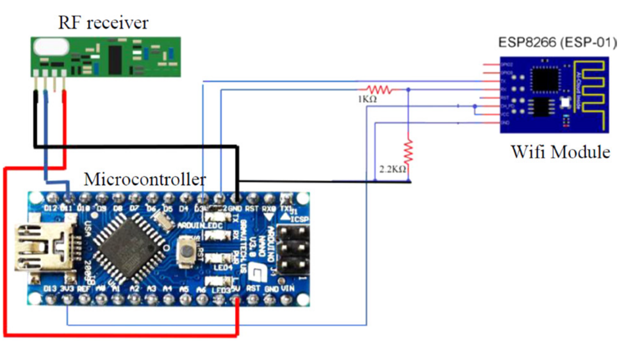

Figure 1: Server node schematic. The RF transceiver is used for UWC, while the Wi-Fi module is used for communication with the server.

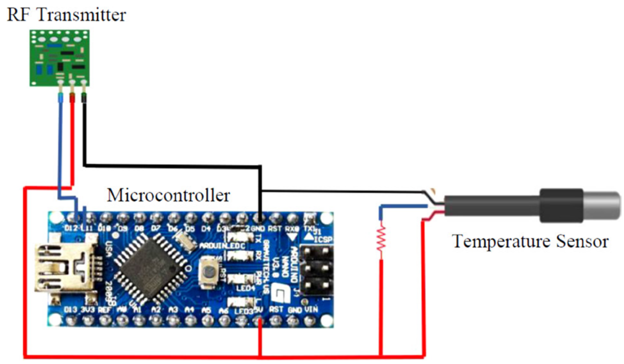

Figure 2: Terminal node schematic. The temperature sensor is used to collect data to be sent of the server.

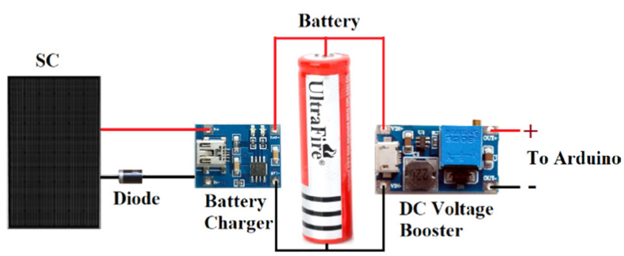

Figure 3: Solar charging circuit connection. The circuit is used to self-power the underwater node.

were used as solar energy harvesters. A complete simulation study as well as experimental analysis for the performance of solar cells under diffused light was already demonstrated in our previous work in Kamal et al. (2019). A customized solar simulator (Sanad et al., 2019) is used to estimate the captured power per cell under various water depth (Kamal et al., 2019)

Integrated modem

A printed circuit board was developed to combine the modem components, i.e., the communication subsystem and the energy harvesting subsystem. The circuit was printed to have a minimum size of 50 mm × 80 mm, which is the minimum size achieved by a single side. However, the circuit was mounted in a container of size 103 mm × 70 mm × 41 mm with the antenna kept external to avoid any absorption of waves by the material. Figure 4A, B shows the open and closed look of the final form. The modem is powered though a battery that is charged through a solar cell, it consumes 57 mA in normal operation, whereas in sleep mode it could consume about 6 μA, see Appendix A, for more information about the modem power budget. The sleep mode was proposed in order to reduce the energy consumption when the nodes are idle, which can be most of the time for sensor node. Based on a detailed cost analysis, see Appendix B, the overall cost of the modem was calculated to be $33.5, which is still much cheaper than other alternative commercial modems.

Experimental setup

The proposed modem can be deployed in an underwater wireless sensor network using one of two setups: a normal mode where each terminal node sends directly to the server node; and a handover mode in which intermediate nodes can be used as relays to forward the date to the server node. The two modes are described next.

Normal mode

Based on the configuration shown in Figure 5, a server node, above water, is used to communicate with two underwater terminal nodes. The data are sent at a rate of 2 kbps with overheads including bits for training preamble, start symbol, byte count, and FCS. Sleep mode is achieved by disabling the processing of many applications that consume power in the microcontroller processor such as the ADC and BOD; followed by enabling the sleep mode internally configured in the microcontroller. The sleep mode is activated using a watchdog timer; this timer resets the system if not interrupted. The system is configured to be active to get data only during 2.5 min per hour as the expected data change rate is low. However, this could be modified for different applications. As the network grows, more efficient sleep/wake periods management protocol should be implemented as well as a technique to achieve synchronizations between the nodes. This is to be done in the future work.

Handover mode

The normal mode is simple to implement. However, it can only reach sort distances due to the attenuation of the water. And so, it needs to be modified in order to extend the range of transmission. The terminal nodes could be used as parts of a relay network employing amplify and forward technique to explore underwater and extend the depth, where information could still be recovered. In this case, the server node above water as well as the first layer relay modem will be powered through the solar cells, whereas any modem at a depth below 4 m will be powered solely from the battery therefore will have to be replaced

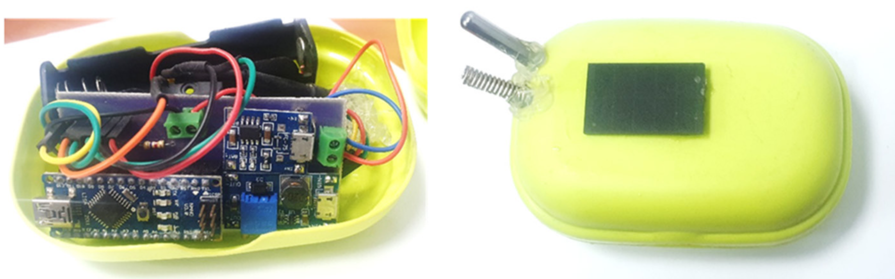

Figure 4: (A) Printed circuit board used in combing RF modem, (B) modem final form showing the antenna, the temperature sensor, and the solar cell.

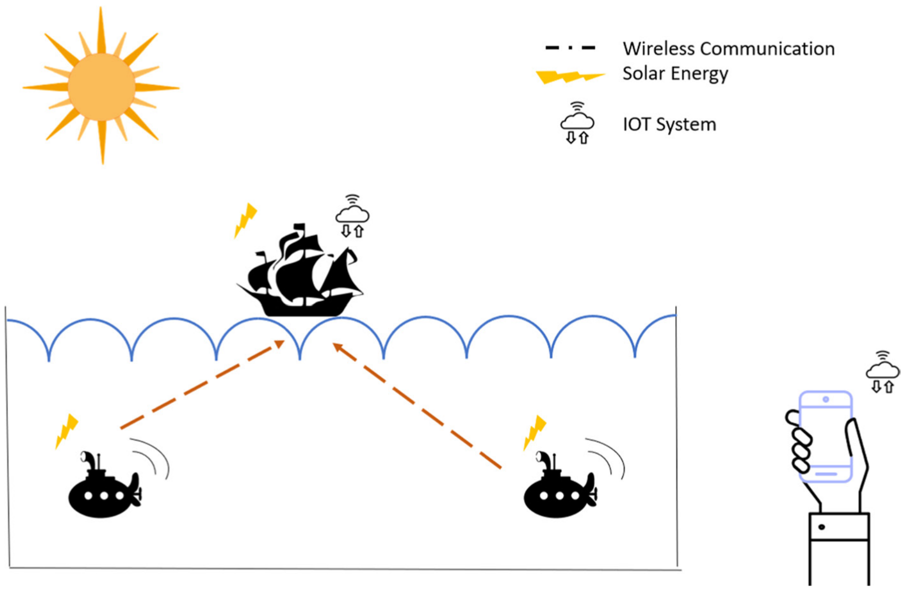

Figure 5: Wireless sensor network configuration for the normal mode.

when the battery goes dead. However, due to the deployed sleep mode the lifetime of the node could be prolonged to several days. Here, the proposed system is optimized to obtain a communication scheme that is reliable for a very long range. An experiment was made to test the reliability of the setup, as demonstrated in Figure 6.

In Figure 6, a star topology was suggested using the same three nodes presented in the previous mode. As indicated in Figure 5, the system operates under the star topology when the moving terminal node is at a distance between 0 cm and 300 cm. After exceeding the 300 cm the moving terminal node almost loses its connection with the server node;

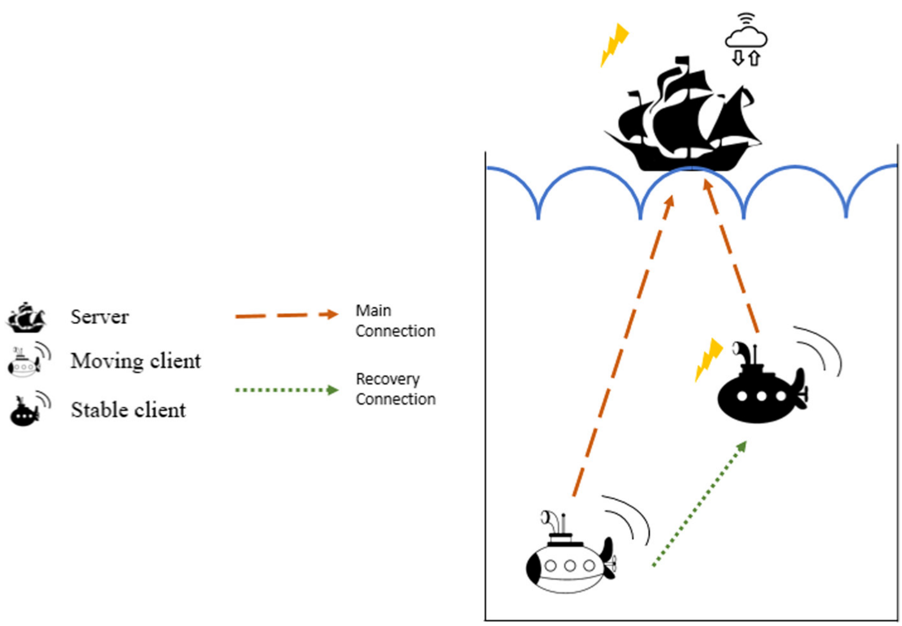

Figure 6: Wireless sensor network configuration for the handover mode.

therefore, the information gathered by the moving node will be relayed through the stable terminal node.

Results

Through utilizing the two operating modes described in the previous section, a series of experiments have been conducted. A server node was placed on the surface of the water in a swimming pool, and two terminal nodes were submerged to depths of 3m. Terminal nodes were programmed to measure the temperature of the water, and send these results periodically to the server node. The server node in turn forwards these measurements to Thinkspeak portal. Figure 7 shows the ThingSpeak portal visualizing the temperature readings. The graph specifies the node readings as well as a gauge calibrated to range 0°C to 50°C. These readings were taken in the normal mode where only one node was working without sleep mode deployment.

The performance of the system in both modes was testing using the throughput as a metric. Figure 8 shows the throughput of the received data at the server node vs. the depth of the node using both the normal mode and the handover mode.

In the normal mode experiment, the server node was placed on the surface of the pool, while the terminal mode was submerged gradually in 50cm steps. The normal mode throughput, blue curve, was maintained constant for two successive steps before decreasing almost linearly after 200cm. The first interval takes place from 0cm to 50cm, where the throughput was maintained at 1,700bps. Consequently, it was reduced to 1,400bps till 200cm. After 200cm the decrease is almost linear with a slope of – 6bps/cm. The system achieved a throughput of 100bps before the signal was completely lost at about 350cm.

In the handover mode experiment, the server node was placed on the surface of the pool, one terminal node operating normally was maintained submerged at a depth of 300cm in order to act as a relay when needed and for it to have a stable connection to the server node. While the other terminal node was submerged gradually is 50cm steps. As we can observe from the figure, the handover mode throughput shows a similar trend to the normal mode but with lower throughput. We attribute this reduction to the addition of a new terminal node to the system that introduces more processing time at the server's end. The throughput remained constant with almost 1,400bps when the moving terminal node was between the server and the stable server node. This is accepted as the lost data were relayed through the stable end node causing hardly any packet loss in the system. Moreover, after 300cm the system turned to

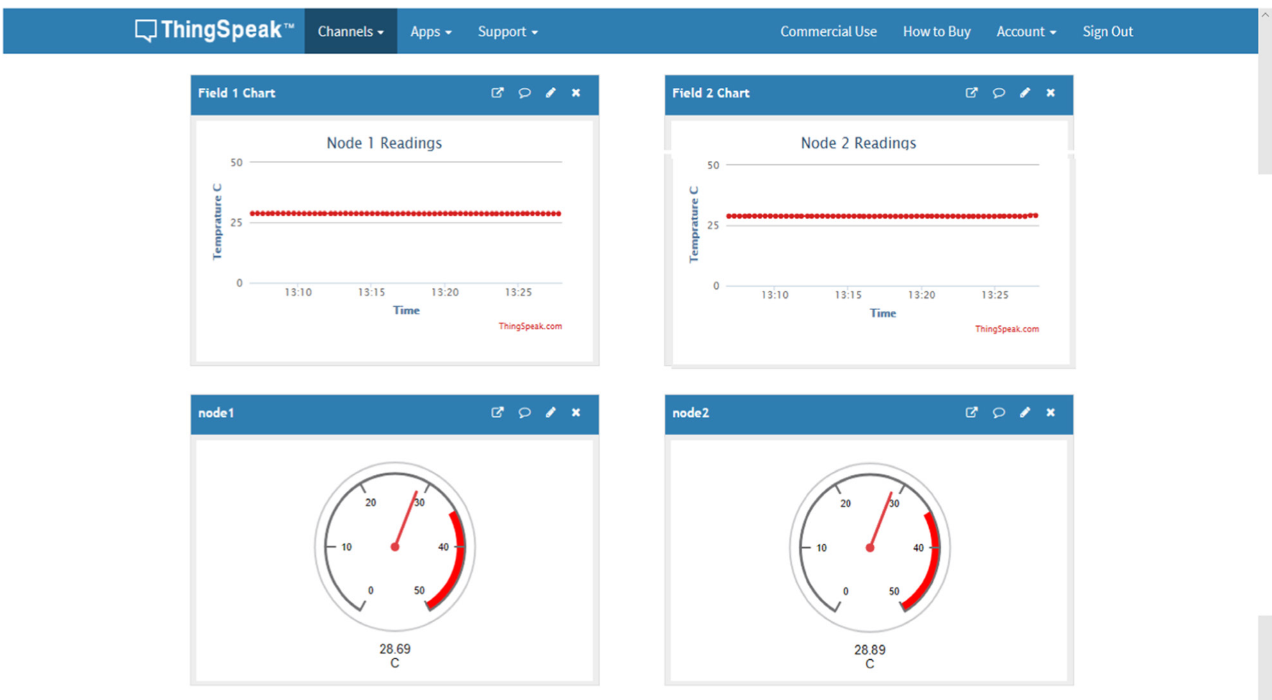

Figure 7: ThingSpeak platform visualization for temperature measurements under normal mode.

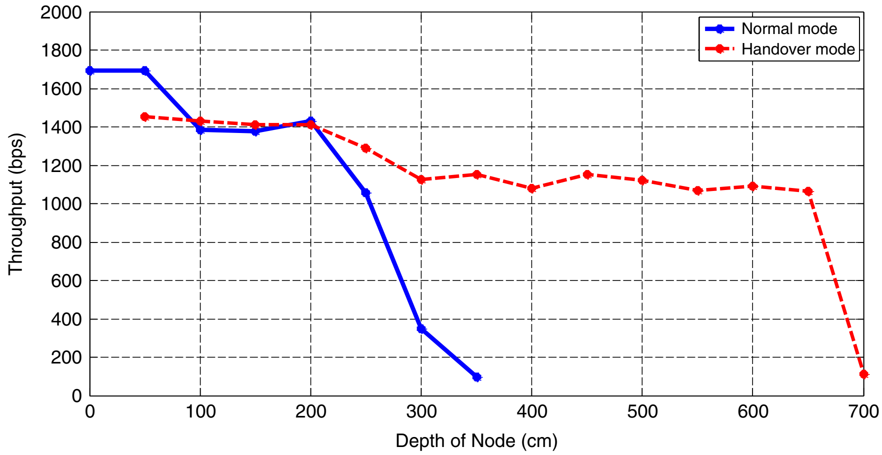

Figure 8: Throughput vs. depth in normal mode and handover mode.

line topology, where the data at the moving terminal are always relayed through the stable node as it could not reach the server directly. The throughput decreased because at this point the packet could be lost due to error from either of the two paths; between moving and stable terminal nodes, or between stable node and server node. The throughput between the interval 300 cm to 650 cm was averaged to be 1,100 bps. At 700 cm, the system could still detect the signal but with a very slow and unreliable rate of 100 bps after which the signal is completely lost.

Discussion

In the results section, the data throughput for both normal mode and handover mode have been presented. In spite of the reduction in the throughput for the handover mode with respect to the normal mode for relatively low distances, an overall nearly doubled distance can be reached using the handover technique. The results demonstrated in this work provide the applicability of utilizing RF technology in underwater transceiver modems. The implemented modem has an overall dimensions of 103 mm × 70 mm × 41 mm, with a dual operation modes. An active operation power of 240 mW is needed during data transmission, 4% of the time, while only 25 µW are consumed in the time remaining due to sleep operation. Consequently, the capability of having a self-powered modem was discussed in this paper. Light harvesters operating under diffused light were examined and integrated in the modem in order to elongate the operation lifetime. From data communication prospective, a maximum distance of 7 m using one hop was recorded with an acceptable throughput, while operating the modem under the handover mode. The range can be increased by adding multiple hops to the system. Considering all the above mentioned findings, we can promote the proposed RF modem for commercialization.

Conclusions

The aim behind this paper is to develop an integrated, low cost, solar powered underwater modem with radio frequency transceivers. This modem is to be used as a building block to create and underwater wireless sensor network. The underwater sensor network can be deployed in any underwater environment to allow underwater communications, underwater monitoring, or underwater early warning systems.

Experiments were made to test the throughput and range of the communication. Results showed that the modem can reach up to 3 m in a single hop with a moderate throughput. This range was increased when using a multi-hop network, handover mode, while maintaining the same throughput more or less. On the other hand, we have also showed that by adding solar powering capabilities to the nodes, we can extend their life time greatly. Not to mention removing the hassle of having to replace the nodes' batteries whenever their depleted. Each modem costs about $33.5, which is very low compared to the other commercially available devices.

For Future work, we intend to improve the performance of both the communication system as well as the solar charging system in order to be able to cover a larger underwater area and further increase the lifetime of the network. Additionally, a more efficient sleep/wake periods management protocol or radio duty cycle (RDC) should be implemented as well as a technique to achieve synchronizations between the nodes.

Acknowledgments

The author would like to acknowledge the STDF as all the experiments implemented for the solar cells performance under diffused light was a part of the STDF funded project ‘Mesostructured Based Solar Cells for Smart Building Applications’, Project ID No. 33502. Additionally, the authors would like to thank Professor Hani Amin Ghali, Director of Centre of Emerging Learning Technologies (CELT), as all the experiments have been hosted by the FabLab, managed by CELT.

Literature Cited

Ali, M., Jayakody, D. N., Perera, T., Sharma, A., Srinivasan, K. and Krikidis, I. 2019. Underwater communications: recent advances International Conference on Emerging Technologies of Information and Communications (ETIC). March 8-10, pp. 1-6.

Arduino Nano. 2020. available at: https://store.arduino.cc/usa/arduino-nano.

Awan, K. M., Shah, P. A., Iqbal, K., Gillani, S., Ahmad, W. and Nam, Y. 2019. Underwater wireless sensor networks: a review of recent issues and challenges. *Wireless Communications and Mobile Computing 2019*, Art. no. 6470359, pp 1–20.

Bluecomm. 2020. BlueComm Underwater Optical Communication-Sonardyne, available at: https://www.sonardyne.com/product/bluecomm-underwater-optical-communication-system/.

Electrosum DS18B20 Temperature Sensor. 2020. available at: https://electrosome.com/temperature-sensor/ds18b20-datasheet.

Future Electronics. 2020. Copyright © 2020, Future Electronics Egypt, available at: https://store.fut-electronics.com/.

Garcia, M., Sendra, S., Atenas, M. and Lloret, J. 2011. Underwater wireless ad-hoc networks: a survey. *Mobile Ad hoc Networks: Current Status Future Trends* Boca Raton, FL: CRC Press, 2011:379–411.

Hu, K., Song, X., Sun, Z., Luo, H. and Guo, Z. 2019. Localization based on map and pso for drifting-restricted underwater acoustic sensor networks. *Sensors* 19(1): 71–92.

Kamal, S., Al-sayyad, G. M., Abdelmoteleb, R., Abdellatif, M. and Abdellatif, S. O., In submerged solar energy harvesters performance for underwater applications. 2019 International Conference on Innovative Trends in Computer Engineering (ITCE), IEEE, 444–449.

Kao, C. -C., Lin, Y. -S., Wu, G. -D. and Huang, C. -J. 2017. In a study of applications, challenges, and channel models on the Internet of Underwater Things. 2017 International Conference on Applied System Innovation (ICASI), IEEE, 1375–1378.

LinkQuest Underwater Acoustic Modems. 2020a. UWM1000 Specifications, available at: https://www.link-quest.com/html/uwm1000.htm.

LinkQuest Underwater Acoustic Modems. 2020b. UWM10000 Specifications, available at: https://www.link-quest.com/html/uwm10000.htm.

Maher, S. M., Ali, Z. M., Abdellatif, S. O. and Abdellatif, M. M. 2020. Enhancing the performance of 433 MHz underwater WSN using handover mechanisms. *Journal of Communications* 15(1): 88–94.

Maher, S. M., Ali, Z. M., Mahmoud, H. H., Abdellatif, S. O. and Abdellatif, M. M. 2019. In performance of RF underwater communications operating at 433 MHz and 2.4 GHz. 2019 International Conference on Innovative Trends in Computer Engineering (ITCE), IEEE, 334–339.

Mahmoud, H. H., Ismail, T. and Abdellatif, S. O. 2018. In energy efficient topology control algorithm and dynamic management scheme for underwater IoT applications. 2018 IEEE Global Conference on Internet of Things (GCIoT), IEEE, 1–5.

Nasser, S., Alashram, A., Hani, A., Fathy, K., Mahmoud, H. H., Ayman, D. and Abdellatif, S. O. 2019. In implementation of underwater communication system powered by solar energy harvesting. Proceedings of the 2019 8th International Conference on Software and Information Engineering, ACM, 156–161.

Saeed, N., Celik, A., Al-Naffouri, T. Y. and Alouini, M. -S. 2019. Underwater optical wireless communications, networking, and localization: a survey. *Ad Hoc Networks* 94(101935): 1–35.

Sanad, M. F., Abdellatif, S. O. and Ghali, H. A. 2019. Enhancing the performance of photovoltaic operating under harsh conditions using carbon-nanotube thermoelectric harvesters. *Journal of Materials Science: Materials in Electronics* 30(22): 20029–20036.

Sanchez, A., Blanc, S., Yuste, P. and Serrano, J. 2011. In a low cost and high efficient acoustic modem for underwater sensor networks. OCEANS 2011 IEEE-Spain, 2011: 1–10.

Sánchez, A., Blanc, S., Yuste, P., Perles, A. and Serrano, J. J. 2012. An ultra-low power and flexible acoustic modem design to develop energy-efficient underwater sensor networks. *Sensors* 12(6): 6837–6856.

Sawa, T., Nishimura, N., Tojo, K. and Ito, S. 2019. Practical performance and prospect of underwater optical wireless communication. *IEICE Transactions on Fundamentals of Electronics, Communications Computer Sciences* 102(1): 156–167.

Sendra, S., Lloret, J., Jimenez, J. M. and Parra, L. 2016. Underwater acoustic modems. *IEEE Sensors Journal* 16(11): 4063–4071.

Zia, M. Y. I., Otero, P. and Poncela, J. 2018. Design of a low-cost modem for short-range underwater acoustic communications. *Wireless Personal Communications* 101(1): 375–390.

Appendix A. Load analysis and power budget.

In this section, all calculations related to the modem power consumption the overall power budget based on the added solar cells are presented. The load requirements for each node in the system was calculated as the controller's load (Arduino) and the attached sensors and modules' loads. The measured load size is listed below:

- Load volt: $V^L_{OC} = 9V$
- Load current: $I^L_{SC} = 57mA$

So, the maximum load power drawn from every node is:

$$P_L = V^L_{OC} x I^L_{SC} = 9V x 0.057 = 0.512W = 513mW \quad (1)$$

Working periods and intervals of the system depend on several factors such as the data transmission time, sensor, and Arduino operation time and the rate of change of the factors to be measured such as the water temperature. In this prototype, 2.5 working minutes each an hour was assumed. Therefore, the system will work for:

$$t_{per\ day} = 2.5 x 24 x \frac{1}{60} = 1 hour\ per\ day \quad (2)$$

Then, the energy consumed per day is calculated as:

$$E_L = P_L x\, t_{per\ day} = 0.513 x 1 = 0.513WH = 513mWH \quad (3)$$

The load is divided into two types: night load E_L^n and morning load E_L^m, each of 12 hr:

$$E^m{}_L = E^n{}_L = \frac{E_L}{2} = \frac{513}{2} = 256.5mWH \quad (4)$$

Night load is directly supplied by the battery. The ampere hour (capacity) required is calculated as the total required load divided by the used battery's capacity:

$$C_{battery} = \frac{E^n{}_L}{V_{battery}} = \frac{0.2565}{3.7} = 69.32mAH \quad (5)$$

The used battery is of 5,000 mAh which is much higher than the required capacity and therefore the nodes could work in night depending on the battery used. However, the battery energy losses should be compensated and taken in consideration during the morning period.

Morning load is directly supplied by the battery. However, morning period should be exploited in order to recharge the battery and compensate the losses occurred due to the system loads. Therefore, at this period, it is required to energize the batteries with 513 mWh. By choosing the monocrystalline solar cell to be used in this prototype, assuming the cell absorption is constant during the day. Then, the number of silar cells required for each node N is calculated as:

$$N = \frac{E_L}{E_{SC}} = \frac{513mWH}{I^{max}{}_{SC}\, x V^{max}{}_{OC}\, x 12 hours} = \frac{513mWH}{10.1mA\, x\, 6.9V\, x\, 12hours} = 0.61 \quad (6)$$

Therefore, to energize the system, only one solar cell will compensate the power losses and overcharge the battery with higher than the required battery. This is more reliable since environmental conditions that lower the efficiency of the SC will not affect the absorption except when those losses cause the absorption to drop to 66.67%, which is of a very low probability.

Appendix B. Cost analysis.

This section illustrates the cost analysis for the implemented system consists of a server modem as well as two underwater modems. All the mentioned expanses are listed in Egyptian pound (EGP), however, the final price is converted in US dollars to facilitate the comparison with other commercial or research-based modems published in the literature. The cost analysis for the server modem is listed in Table B1 (Future Electronics, 2020).

The cost of the server node is found to be reasonable, as the higher amount of the cost is represented in the RF transmitter and the receiver as well as the PCB fabrication. The rest of the components were not of much cost. For the underwater terminal modem, the cost is listed in Table B2 (Future Electronics, 2020).

The overall system has many components. Thus, the prices of the components were selected based on a criterion to ultimately minimize the cost. Some of the components had to be bought and shipped from abroad, some were bought from the local market, and specific things such as the water tank had to be made specifically to serve the experiments needs. Overall, the whole system's cost is found to be reasonable, cf. Table B3 (Future Electronics, 2020). To sum up, the overall system cost was found to be $252 with $33.5 dedicated for the underwater terminal modem. This cost represents 28% cheaper than the corresponding commercial modems.

Table B1. Cost analysis for sever modem.

Components	No. of components	Cost per component (EGP)	Cost (EGP)
Diodes	1	0.75	0.75
T blocks	2	2	4
Arduino Nano	1	90	90
RF Tx/Rx pair	1	120	120
Wi-Fi Module (ESP8266)	1	35	35
DC–DC	1	65	65
Lithium battery charger module	1	35	35
Battery	1	50	50
Battery holder	1	10	10
PCB Implementation	1	100	100
Total			509.75 (about $33)

Table B2. Cost analysis for underwater terminal modem.

Components	No. of components	Cost per component (EGP)	Cost (EGP)
Diodes	1	0.75	0.75
T blocks	2	2	4
Arduino Nano	1	90	90
RF Tx/Rx pair	1	120	120
Waterproof temperature sensor	1	60	60
DC–DC	1	65	65
Lithium battery charger module	1	35	35
Battery	1	50	50
Battery holder	1	10	10
PCB implementation	1	100	100
Resistors	1	0.25	0.25
Total			535 (about $34)

Table B3. Cost analysis for the overall system.

Components	No. of components	Cost per component (EGP)	Cost (EGP)
Diodes	3	0.75	2.25
T blocks	6	2	12
Arduino Nano	3	90	270
RF Tx/Rx pair	2	120	240
Waterproof temperature sensor	2	60	120
Wi-Fi module (ESP8266)	1	60	60
DC–DC	3	65	195
Lithium battery charger module	3	35	103
Battery	3	50	150
Battery holder	3	10	30
PCB implementation	3	100	300
Resistors	4	0.25	1
Water tank	1	2000	2000
Tank requirements	1	600	600
Total			4083 (about $260)