Reliability and Delay Analysis of AUV Navigation System Using EM Wave Based Underwater Sensor Network

[1]Muhammad Sabbir Alam, [1]Md. Farhad Hossain, [2]Kumudu Munasinghe, and [3]Abbas Jamalipour
[1]Department of Electrical and Electronic Engineering, Bangladesh University of Engineering and Technology, Dhaka-1000, Bangladesh, [2]Faculty of Education, Science, Technology and Maths, University of Canberra, ACT 2617, Australia, [3]School of Electrical and Information Engineering, University of Sydney, NSW 2006, Australia.
Email: sabbir_alam10@yahoo.com, mfarhadhossain@eee.buet.ac.bd, kumudu.munasinghe@canberra.edu.au, abbas.jamalipour@sydney.edu.au

Abstract—Due to the relatively longer coverage capability, acoustic wave based underwater networks are commonly used for navigating autonomous underwater vehicles (AUVs). However, significantly slower propagation speeds of acoustic waves make the navigation of AUVs prone to substantial operational delay. Though electromagnetic (EM) signal suffers from severe attenuation in underwater environment, it can be useful for short-range networks for faster communications. Considering the need for faster navigation of AUVs, this paper proposes and investigates an EM wave based AUV navigation system using underwater sensor network (UWSN). Extensive simulations are carried out for evaluating the reliability and delay performance of the proposed system for establishing a theoretical foundation of EM wave based AUV navigation systems. Impacts of transmission frequency, transmit power and detection threshold on the navigation performance are thoroughly investigated and critically analyzed. Performance of the proposed system is also compared with that of acoustic based counterpart demonstrating improved reliability and faster operation.

Keywords—AUV navigation; EM communications; reliability; propagation delay; underwater sensor networks

I. Introduction

Underwater sensor networks (UWSNs) enable a wide range of civilian and military applications including tactical surveillance for protecting maritime boundaries, mine reconnaissance, search and rescue operations, assisted navigations, disaster prevention, offshore explorations, oceanography and aquatic applications [1, 2]. Due to the longer communication range capability, today's most underwater wireless networks use acoustic waves as the transmission medium. However, extremely low data rates of around few kbps, considerable impacts of sea water dynamics on acoustic waves, and the adverse impact of these waves on marine lives have limited this technology to be adapted in most modern applications [1], [3], [4]. Furthermore, because of limited bandwidth and comparatively slow speed of acoustic signals (around 1.5×10^3 m/sec in water), transmission data rates are limited and results in larger transmission delay [5]. In contrast, optical underwater networks can offer very high data rates. However, optical signals are susceptible to turbidity and back-scattering from suspended matters [3]. Optical systems also require clear water, line-of-sight propagation and tight alignment between transmitter-receiver pairs, and therefore limited to extremely short distances, often a few meters [6]. On the other hand, although underwater electromagnetic (EM) communications suffer from severe attenuation, it has crucial advantages such as higher bandwidth, faster data rates, lower propagation delays and lesser sensitivity to channel disturbances [1]. These fundamental benefits along with the demand of high speed underwater communications have made EM wave as the most promising candidate for a number of modern applications.

Autonomous underwater vehicles (AUVs) are powerful tools for exploring, monitoring and investigating ocean resources [7]. Therefore, it is extremely critical to plan a path for AUVs and assist them using a navigation (aka localization) system for accurately following the planned path that maximizes the information collected, while minimizing travel time, fuel expenditure, etc. However, as AUVs continue to mature as operational assets, navigation still remains a fundamental technological component that presents unique challenges to researchers. A navigation mechanism named as communication-constrained data collection problem (CC-DCP) presented in [8] plans the AUV's path, which minimizes travel time and maximizes information gathered. Whereas, authors in [9] proposed planning algorithms as well as communication protocols for AUVs designed for collecting data from UWSNs. The problem is modeled as a traveling salesperson problem (TSP) with probabilistic neighborhoods demonstrating a superior performance compared to that of CC-DCP. On the other hand, [10] proposes a hypothesis and grid based technique for improving the long baseline navigation of AUVs. This technique employs a probabilistic model of the environment based on empirical evidence developed by quantifying the quality of subsequent real-time range measurements. Experimental results on the command, control and navigation of AUVs are also presented in [11]. However, all of these AUV navigation schemes investigated in [8]-[11] operate using acoustic waves, which suffers from an inherent long propagation delay as discussed above. As AUV platforms continue to proliferate, becoming commercially available to a wider application range, navigation methods with lower delay and improved accuracy are expected to expand as well [12].

In light of this, this paper proposes an EM wave based navigation system for guiding AUVs in an underwater environment. The proposed navigation network is essentially an UWSN consisting of underwater sensor nodes (SNs), cluster heads (CHs) and a base station (BS) located at the ocean surface. While an AUV moves for a planned task, SNs around the AUV senses its presence, send the signal to the corresponding CHs and subsequently to the BS. The BS estimates the location of AUV for identifying any deviation from the planned path and sends back this to the AUV for correcting its path. Communications between any two network elements are done using EM signals. System performance in terms of network reliability and operation delay is evaluated using extensive simulations. Impacts of transmission frequency, transmit power and EM signal detection threshold on the proposed system performance are analyzed thoroughly. Performance of the proposed system is also compared with that of the acoustic based counterpart establishing a solid theoretical foundation for preferring and further exploring EM wave based AUV navigation systems.

The rest of the paper is organized as follows. Section II describes the proposed AUV navigation system followed by the underwater channel models in section III and performance metrics in section IV. Simulation results are discussed in section V. The paper finally concludes in section VI by summarizing the key findings.

II. Proposed AUV Navigation System

The proposed AUV navigation system using EM wave based communications is presented in this section. This system is designed to guide an AUV to follow a pre-planned path intended for completing a specific task in underwater environment, such as collecting data from aquatic environment monitoring sensor networks, surveying an area for intruder, searching for mines or wreckage, etc.

The network for the proposed system is basically an UWSN consisting of SNs, CHs and a surface BS. SNs and CHs are placed in layers in vertical direction along the designed path of the AUV. Each layer consists of SNs and CHs, which can be positioned according to some fixed patterns or in random nature. A section of a layer of the complete path with some communication links are shown in Fig. 1. Number of such layers depends on the depth of water. For higher depth, higher numbers of layers are required such that the CH located in the upper most layer can lie in the communication range of the BS. SNs are smaller in size, battery operated, and transmit data via radio frequency (RF) modems. In addition to having RF modems, CHs are equipped with relatively longer range directional modems, allowing them to communicate with the BS located at the ocean surface. SNs and CHs are placed in such a way that each SN can communicate with at least one CH. Data transfer between

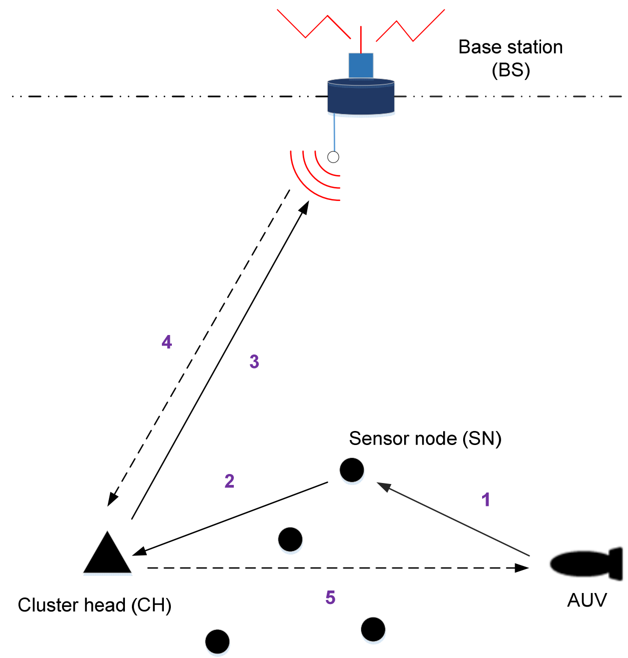


Fig.1. Proposed EM wave based AUV navigation system.

any two nodes in the system can be single-hop or multi-hop. The multi-hop approach is generally more power-efficient, because the signals have to travel shorter distances between two nodes. But the network maintenance and configuration tasks are more complex in a multi-hop case. All communications between AUV-SN, SN-CH, CH-CH (if any) and CH-BS are done using EM waves.

The proposed AUV navigation system operates as follows. While the AUV moves, it periodically transmits a RF signal. The period of transmitting signal is system specific and adjustable. The signal carries the information from which the current location of the AUV can be estimated. SNs within the communication range of AUV receive the signal and forward the signal to the corresponding CH. The CH detecting signal from surrounding SNs then transmits the information to the next CH in the immediate upper layer or to the BS directly if the CH is in the upper most layer. Subsequently, the BS receives the information and estimates the AUV's current position using some specific algorithm. If the BS identifies any deviation of the AUV from designated path, it then sends back the devised information to the AUV through the same network with the instruction to correct its path. After receiving the instruction, the AUV fine-tunes its position accordingly. This procedure continues until the AUV completes its mission. It is worthwhile to mention here that the proposed navigation system is developed independent of the position estimation algorithms and designing such algorithms is also beyond the scope of this work.

III. Channel Model

The proposed AUV navigation system employs EM waves for communications. For the sake of clarity, we also compare the system's performance with that of an acoustic wave based one. This section thus presents both the EM and acoustic wave propagation models in an underwater environment.

A. Underwater Propagation Model for EM Waves

Path loss P_L in dB of EM wave in underwater can be expressed as [13]

$$P_L = L_{\alpha,\epsilon} + L_R \tag{1}$$

where $L_{\alpha,\epsilon}$ is the attenuation loss in water due to water conductivity and complex permeability in dB and L_R is the reflection loss at the water–air boundary in dB due to the impedance mismatch between the two media. But considering all the SNs and a BS communicating terminals immersed into water, reflection loss L_R can be neglected. The propagation constant can be expressed as [14]

$$\gamma = j\omega\sqrt{\mu\epsilon - j\frac{\sigma\mu}{\omega}} \tag{2}$$

where μ is the permeability, ϵ is the permittivity, σ is the conductivity and $\omega = 2\pi f$ is the angular frequency. Thus P_L at a distance D (meter) can be expressed as [15]

$$P_L = L_{\alpha,\epsilon} = \Re(\gamma) \times \frac{20}{\ln(10)} \times D \tag{3}$$

where $\Re(x)$ is the real value of x.

B. Underwater Propagation Model for Acoustic Waves

Propagation path loss P_L for acoustic wave in shallow water expressed in dB can be given by [16]

$$P_L = 10\log(r) + \alpha r \times 10^{-3} \tag{4}$$

where α represents the absorption coefficient in dB/km and r is transmission range expressed in meters. The absorption coefficient α can be calculated using Thorp's expression at frequencies above a few hundred Hz as below [17]

$$\alpha = \frac{0.1f^2}{1+f^2} + \frac{40f^2}{4100+f^2} + 2.75 \times 10^{-4}f^2 + 0.003 \tag{5}$$

where f is frequency in Hz.

IV. Performance Metric

A. Navigation Reliability

In this paper, we ignore the fading effect for evaluating the system reliability. Thus the received signal strength (RSS) denoted as P_{RX} in dBm can be expressed as

$$P_{RX} = P_{tx} - P_L \tag{6}$$

where P_{tx} is source level (transmit) power in dBm. In order to detect the signal correctly by the receiver, the received signal strength should be greater than a detection threshold denoted by D_{th}.

Now, considering that the distances among the network nodes can vary due to water current, movement of underwater objects, ships, etc., the distances are modeled as uniform random variables and thus RSS P_{RX} also becomes a random variable. Let P_i be the probability of receiving the signal for i^{th} link equal to or above D_{th}, i.e.,

$$P_i = \Pr(P_{RX} \geq D_{th}) \tag{7}$$

If there are total n number of links in the round trip path between the AUV and the BS, then the navigation reliability, that is the probability of successful communications between the AUV and the BS can be expressed as

$$P_T = P_1 \cap P_2 \cap P_3 \cap \ldots\ldots\ldots \cap P_n \tag{8}$$

Assuming that the links are independent to each other, navigation reliability can be expressed as

$$P_T = P_1 \times P_2 \times P_3 \times \ldots\ldots\ldots \times P_n = \prod_{i=1}^{n} P_i \tag{9}$$

B. Propagation Delay

Propagation delay of a communication system can be evaluated by dividing the total distance travelled by signal with the propagation speed of the signal.

Though EM signal is severely attenuated in an underwater environment, the speed of propagation is quite high and unaffected by environmental constraints. The propagation speed of EM wave in underwater environment can be represented by the following equation [14]

$$C_w = \frac{c}{\sqrt{\mu_r \varepsilon_r}} \tag{10}$$

where c is the speed of light in free space, μ_r and ε_r are the relative permeability and permittivity of sea water respectively.

On the other hand, acoustic waves may propagate in water through multiple paths, which depends upon various factors, such as the acoustic wave speed structure in the water, locations of source and receiver, etc. Moreover, speed of acoustic waves in water is a function of temperature, water depth, pressure and salinity of seawater, and thus affected by environment unlike EM waves. Considering various factors, speed of acoustic signal in water can be expressed by [18]

$$\begin{aligned} C_a = {} & 1448.96 + 4.591T - 0.05304T^2 + 0.0002374T^3 \\ & +1.340(S-35) + 0.0163z + 1.675 \times 10^{-7}z^2 \\ & -0.01025T(S-35) - 7.139 \times 10^{-13}Tz^3, \\ & 0 \leq T \leq 30^o, 0 \leq S \leq 40, 0 \leq z \leq 8000 \end{aligned} \tag{11}$$

where T is temperature in degree Celsius, S is the salinity in parts per thousand (ppt) and z is depth in meter.

V. Simulations And Results Analysis

A. Simulation Setup

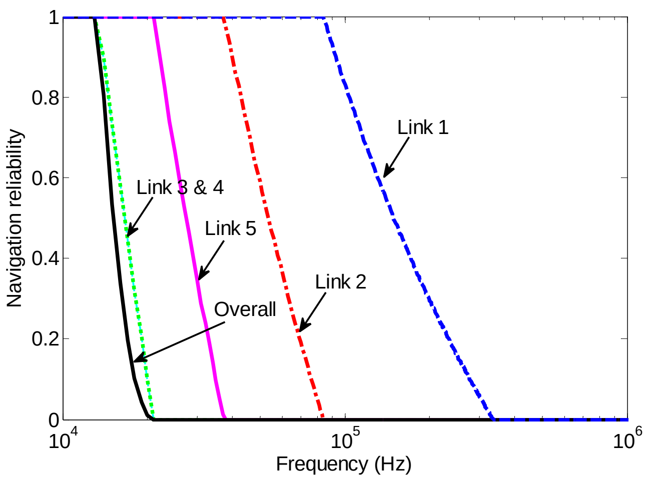
Extensive computer simulations using MATLAB are carried out for evaluating the performance of the proposed AUV navigation system. Each average value presented in the following figures is generated averaging over 10,000 independent simulations. For the convenience of performance demonstration, we simulate a section of the complete navigation path consisting of five independent links between the AUV and the BS as shown in Fig. 1. Since the objective of this section is to illustrate a reasonable comparison between the proposed EM based system with the one of acoustic wave based, simulation results for the specified section provide the sufficient insight. However, simulations for the entire navigation path considering various network scenarios can be completed in a similar way.

Simulations are performed considering a typical salty sea water environment using the constants as σ = 4 S/m [6], μ_r = 1 [14] and ε_r = 81 [6]. On the other hand, the distances between various network nodes are considered to be uniformly distributed over some specific ranges. Specifically, the distances are taken as SN-CH ~ U[2, 3] m, CH-BS ~ U[4, 5] m and CH-AUV ~ U[3-4] m. Without losing the generality, transmission power of all the network elements for both EM and acoustic wave based systems are considered equal. Unless otherwise specified, transmission power = 30 dBm, transmission frequency = 1 kHz, detection threshold D_{th} = 10 dBm, T = 25°C, S = 35 ppt and z = 15 m are used for the simulations.

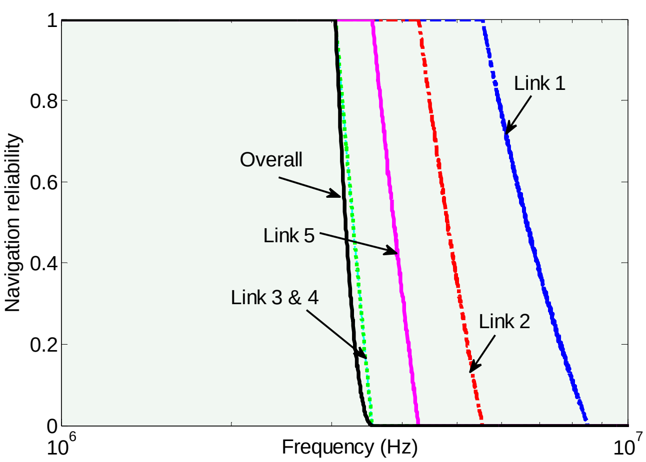
B. Results Analysis

Figs. 2(a)-(b) illustrate the variation of navigation reliability with transmission frequencies for the EM and acoustic signal based systems respectively. Reliability of the individual links as well as the overall system is included in the figures. From both the figures, it is evident that increase in frequency reduces the navigation reliability sharply. However, acoustic signals can be received more successfully for a wider range of frequencies than EM signals. Since the attenuation of EM signals increases more drastically with increasing frequency, at higher frequencies, say 10^6 Hz, it can no longer be used for successful navigation.

On the other hand, Figs. 3(a)-(b) present the impact of transmit power on the navigation reliability. From the figures, it is apparent that increasing the transmit power results in greater probability of successful navigation. Comparing the two figures, it can be seen that EM signal based system works successfully even at a slightly lower transmit power level than acoustic based systems. For example, when the transmitted power is 16 dBm, the overall navigation reliability for EM based system is 1, while it is equal to zero (i.e., no successful navigation) for acoustic based system. This can be explained by the fact that, for short distances, like a few meters in this case, the path loss of acoustic signals is greater than that of EM signals. Hence the EM signal based system navigates more successfully at lower transmission power. Thus, EM wave based system can be more energy efficient for short-range systems. However, with the increase of distance, path loss of EM signals eventually overtakes the path loss of acoustic signals, which is not shown in this paper.

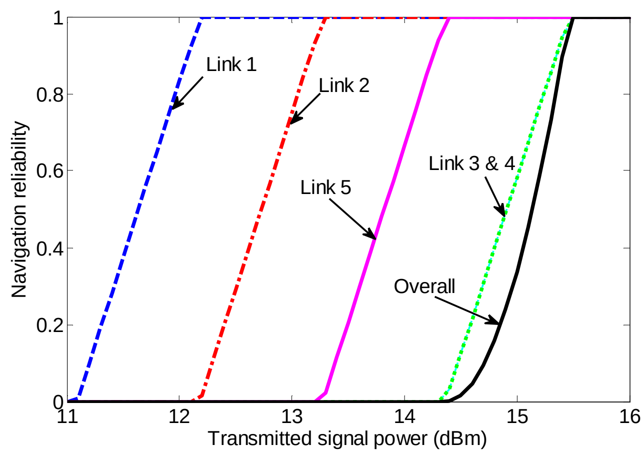


(a) EM wave based

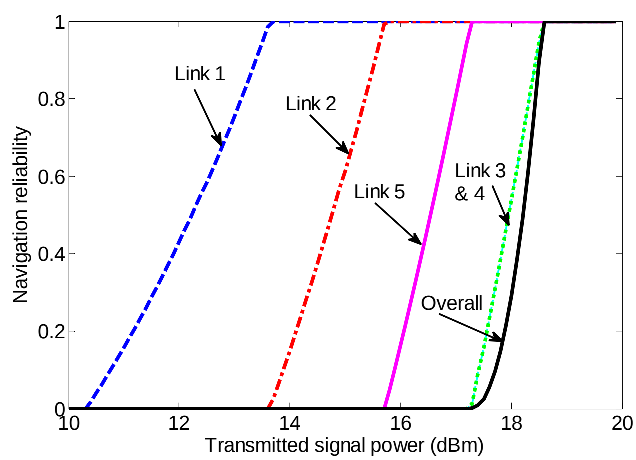


(b) Acoustic wave based

Fig. 2. Navigation reliability with transmission frequency.



(a) EM wave based



(b) Acoustic wave based

Fig. 3. Navigation reliability with transmitted signal power.

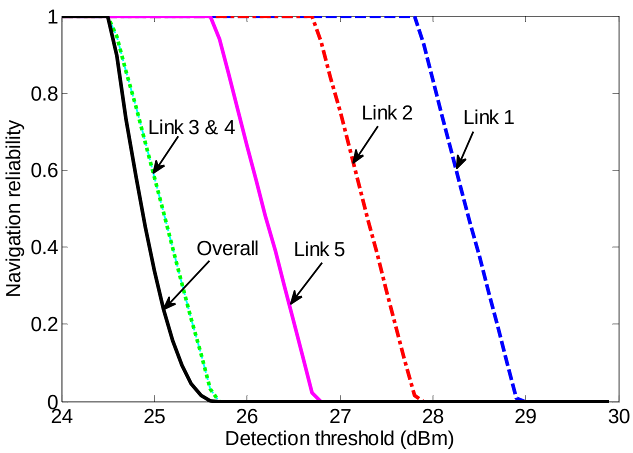
Figs. 4(a)-(b) demonstrate the navigation reliability with the detection threshold for EM and acoustic signal based systems respectively. Comparison of the two plots demonstrates a superior performance of EM based system, that is, the EM signal based system works more successfully with higher detection threshold than acoustic based system. For example, successful navigation in acoustic based system is impossible at a detection threshold beyond 22.5 dBm, whereas the overall probability for successful navigation for EM based system at this threshold is 1. This is attributed to the same reason as explained for Figs. 3(a)-(b) of greater path loss of acoustic signal compared to EM signal at shorter distances. Hence, received signal strength for EM based system is greater than that of acoustic signal, which explains that, EM signals can be detected at higher detection thresholds than that of acoustic signals.

Finally, Figs. 5(a)-(b) present the cumulative distribution function (CDF) of the round trip time and thus compare the navigation delay of EM and acoustic wave based systems. It is clearly seen that the navigation delay for EM signal based system is of several orders of magnitude smaller than that for an acoustic signal. The reason behind this significantly lower navigation delay of EM based system is the fundamental characteristic of high propagation speed of EM waves compared to that of acoustic waves.

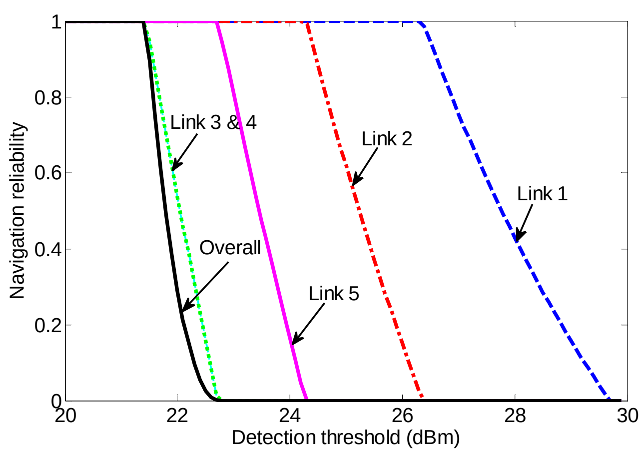
VI. Conclusion

In this paper, we have proposed and investigated an EM wave based AUV navigation system. Performance of the system is evaluated through extensive Monte-Carlo simulations. System performance is also compared with that of an acoustic based system. It is identified that for shorter transmission range, an EM based system shows superior performance in terms of navigation reliability as well as energy efficiency. Furthermore, the navigation delay is found significantly lower for EM based system, which clearly indicates the preference of selecting EM based system over acoustic type for applications requiring fast navigation.

Future works will include the analytical modeling of the proposed system including more complex scenarios. Furthermore, techniques will be developed for improving the EM based navigation performance.

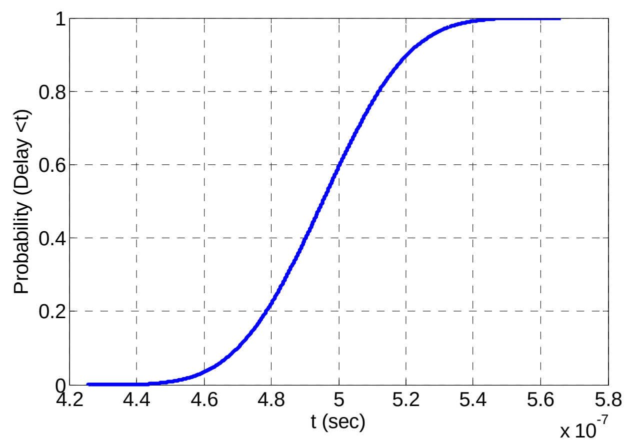


(a) EM wave based

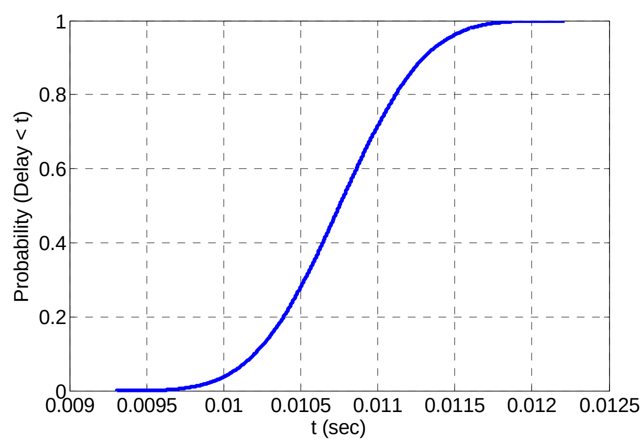


(b) Acoustic wave based

Fig. 4. Navigation reliability with detection threshold.



(a) EM wave based



(b) Acoustic wave based

Fig. 5. CDF of the round trip delay for the EM and the acoustic wave based systems.

References

[1] X. Che, I. Wells, G. Dickers, P. Kear, and X. Gong, "Re-Evaluation of RF Electromagnetic Communication in Underwater Sensor Networks," *IEEE Communications Magazine,* vol. 48, no. 12, pp. 143-151, Dec 2010.

[2] S. Al-Dharrab, M. Uysal, and T. M. Duman, "Cooperative Underwater Acoustic Communications," *IEEE Communications Magazine*, vol. 51, no. 7, pp. 146-153, July 2013.

[3] B. F. Bush, V. K. Tripp, and K. Naishadham, "Practical Modeling of Radio Wave Propagation in Shallow Seawater," *IEEE Antennas and Propagation Society International Symposium*, pp. 1-2, July 2012.

[4] J. Partana, J. Kurosea, and B. N. Levinea, "A Survey of Practical Issues in Underwater Networks," *ACM Mobile Computing and Communications Review*, vol. 11, no. 4, pp. 23–33, Oct 2007.

[5] J. H. Cui, J. Kong, M. Gerla, and S. Zhou, "The Challenges of Building Mobile Underwater Wireless Networks for Aquatic Applications," *IEEE Network*, vol. 20, no. 3, pp. 12-18, May-Jun 2006.

[6] A. I. Al-Shamma'a, A. Shaw, and S. Saman, "Propagation of Electromagnetic Waves at MHz Frequencies Through Seawater," *IEEE Transactions on Antennas and Propagation*, vol. 52, no. 11, pp. 2843-2849, Nov 2004.

[7] R. Headrick and L. Freitag, "Growth of Underwater Communication Technology in the U.S. Navy," *IEEE Communications Magazine*, vol. 47, no. 1, pp. 80-82, Jan 2009.

[8] G. A. Hollinger, S. Choudhary, P. Qarabaqi, C. Murphy, U. Mitra, G. Sukhatme, M. Stojanovic, H. Singh and F. Hover, "Communication Protocols for Underwater Data Collection Using a Robotic Sensor Network," *IEEE GLOBECOM Workshops*, pp. 1308-1313, Dec 2011.

[9] G. A. Hollinger, S. Choudhary, P. Qarabaqi, C. Murphy, U. Mitra, G. Sukhatme, M. Stojanovic, H. Singh and F. Hover, "Underwater Data Collection Using Robotic Sensor Networks," *IEEE Journal on Selected Areas in Communications*, vol. 30, no. 5, pp. 899-911, June 2012.

[10] B. Bingham and W. Seering, "Hypothesis Grids: Improving Long Baseline Navigation for Autonomous Underwater Vehicles," *IEEE Journal of Oceanic Engineering*, vol. 31, no. 1, pp. 209-218, Jan 2006.

[11] D. B. Marco and A. J. Healey, "Command, Control, and Navigation Experimental Results with the NPS ARIES AUV," *IEEE Journal of Oceanic Engineering*, vol. 26, no. 4, pp. 466-476, Oct 2001.

[12] B. Bingham, *Navigating Autonomous Underwater Vehicles*. INTECH Open Access Publisher, 2009.

[13] S. Jiang, and S. Georgakopoulos, "Electromagnetic Wave Propagation into Fresh Water," *Journal of Electromagnetic Analysis and Applications*, vol. 3, no. 7, pp. 261-266, Jul 2011.

[14] M. Sadiku, *Elements of Electromagnetics* (the Oxford Series in Electrical and Computer Engineering). Oxford University Press, USA, 2014.

[15] G. Hattab, M. El-Tarhuni, M. Al-Ali, T. Joudeh, and N. Qaddoumi, "An Underwater Wireless Sensor Network with Realistic Radio Frequency Path Loss Model," *Journal of Distributed Sensor Networks*, vol. 2013, Article ID 508708, pp. 1-9, 2013.

[16] L. E. Kinsler, A. R. Frey, A. B. Coppens, and J. V. Sanders, *Fundamentals of Acoustics*. 4th Edition, Wiley-VCH, pp. 560, Dec. 1999.

[17] R. J. Urick, *Principles of Underwater Sound*. Aug 1996.

[18] K. V. Mackenzie, "Nine-term Equation for Sound Speed in the Oceans," *The Journal of the Acoustical Society of America*, vol. 70, no. 3, pp. 807-812, Sep 1981.