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Underwater Localization using Received Signal Strength of Electromagnetic Wave with Obstacle Penetration Effects

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Abstract: In this paper, we discuss a range sensor model using EM wave attenuation for localizing in an underwater environment with obstacles. Because an acoustic sensor is unsuitable for environment with obstacles due to the multi-path effect and diffraction, we propose a alternative range estimation method using EM wave attenuation. By considering the penetration distortion effect with underwater distance-signal attenuation model, we defined a robust EM wave attenuation function in the environment with obstacles. We performed the several experiments in order to determine the calibration factors according to the material, and the obstacle model is developed. Also, we obtained a robust localization results using the obtained sensor model with obstacle penetration effects.

Keywords: Underwater Positioning, Electromagnetic wave, Localization, EM wave, Sensor.

1. INTRODUCTION

In recent years, autonomous underwater vehicles (AUV) technologies have received great attention from both academic and military fields. However, sensors for underwater localization is limited to acoustic sensors, since an underwater environment is a very difficult condition for conventional sensors due to large signal attenuation and backscatter. Since the underwater sonar sensor has a long range and reliable operation, it is good for infrastructure based underwater positioning schemes. However, sonar has poor performance in dynamic object tracking due to the speed of sound, and also in complicated structured environments due to the multi-path effect and diffraction scattering. Moreover, by increasing the underwater structures, many applications need the precise position estimation in limited environment by obstacles such as offshore plant and docking structure. Therefore, an alternative sensor to use in complex underwater environments is required (Kinsey et al. (2006, 2003); Gordon and Moscrop (1996)).

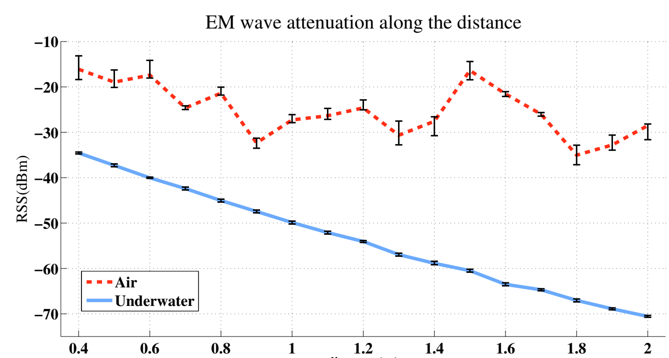

Fig. 1. Plot of RSS values according to the distance (10 mW and 420 MHz).

As an alternative to acoustic sensors, we suggest a method of utilizing electromagnetic(EM) waves and its received signal strength(RSS) values to estimate position in underwater environments. This method used above water many times, but it had large uncertainty due to its susceptibility to surrounding environments rather than distance (Fig. 1). So this sensor is used as a supplementary sensor for relative sensors to correct odometry distance error (Zmuda et al.

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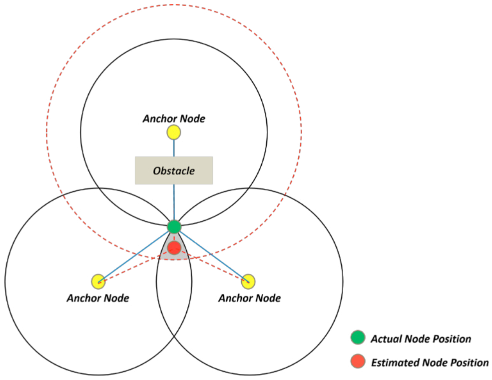


Fig. 2. Biased localization result caused by an obstacle. The obstacle brings about additional EM wave attenuation and it functions as additional distance gap between nodes.

(2008); Tsai (1998)). On the other hand, the EM wave has large attenuation in an underwater environment, thus it is expected to provide accurate high resolution distance measurements as shown in Fig. 1 (Park et al. (2012); Kwak et al. (2011)). In addition, an EM wave can penetrate most underwater obstacles, so a sensor based on the EM wave has more robust performance than an acoustic sensor because it has less multi-path distance error caused by reflected signals from obstacle surfaces.

However, there is no lack of RSS distance model in underwater environment with obstacles. Although we suggested the EM wave RSS model in lossy medium (Park et al. (2016, 2012, 2013)), it is limited to an open space condition between transmitter and receiver. So, if we estimate position in the obstacle-included underwater environment using the old model, the sensor may have bias error due to the additional signal attenuation as shown in Fig. 2. Unfortunately, in many applications, we must estimate the precise position in dangerous or difficult circumstances to install the sensor in open space such as septic tank inspection and nuclear reactor inspection. In this case, we have to consider additional signal attenuation caused by the obstacles. But it is very difficult to consider signal distortion caused by obstacles. Additionally, if the sensor required many sensor properties to estimate the additional signal attenuation, it is inconvenient to use with large complicated operations. Therefore, an underwater RSS distance model considering significant obstacle distortion effect is required.

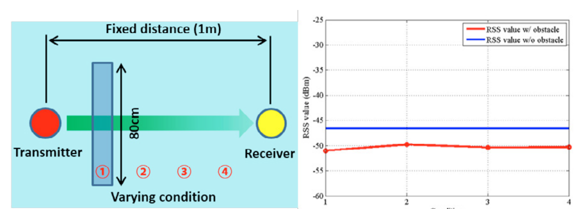
In this paper, we propose an underwater RSS distance model including attenuation due to obstacle distortion. Using feasibility experiments, we propose the obstacle model which considered signal attenuation due to penetration. In order to take account of penetration distortion, we measured several penetration constants which is a unique property to individual materials. And the sensor model with the obstacle effect is verified with localization experiments. The key contributions of this paper can be summarized as follows.

- We consider a novel sensor model which measures distance using EM wave RSS values. In order to enhance the localization performance in environment with obstacles, we consider the obstacle effect between nodes when the EM wave propagates underwater. To make an effective and simple sensor model, only the signal attenuation by penetration is considered. Also, by combining the obstacle model with a previous underwater sensor model that we proposed, a more robust sensor model in environment with obstacles is proposed.(Section II).
- We suggest a method to determine the calibration factors of obstacle materials, and perform the calibration factor experiments for stone, wood and steel (Section III-B).
- We finally set up a 2D localization environment and perform a distributed positioning scheme in ad-hoc networks of sensors in an underwater environment with obstacles to verify the sensor model (Section III-C).

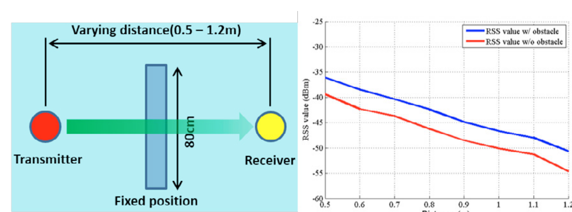
2. DERIVATION OF UNDERWATER SENSOR MODEL FOR ENVIRONMENT WITH OBSTACLES

2.1 Underwater Sensor Model (Park et al. (2016))

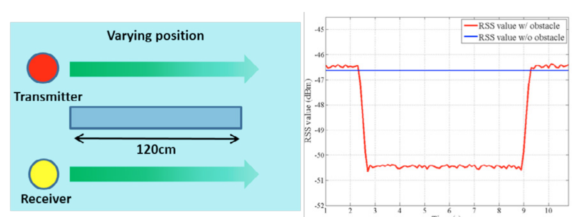
To acquire RSS values for some specific medium for a given distance, we should consider both the antenna and media properties. The sensor model in the air use the Friis Transmission Formula (Friis and Rumson (1971)), which is commonly used to calculate distances for a given received signal strength. However, it is not enough for underwater application due to different signal attenuation characteristics. Therefore, the EM wave attenuation model



(a) Fixed distance between nodes, varying object position



(b) Fixed object position, varying distance



(c) Fixed object position, varying transmitter, receiver position

Fig. 3. Feasibility tests for additional EM attenuation due to the penetration effect. Each result shows a constant EM wave attenuation than open space case regardless of position, distance between nodes and obstacle's relative position.

for underwater environment is developed by modifying the equations an underwater environments.

By applying the Maxwell's attenuation constant formula into the Friis transmission formula, we could derive a combined EM wave formula. In this equation, the EM wave receiving power(S_R), can be described with EM wave transmitting power(S_T), distance(R) and attenuation constant(α) as shown below:

$$S_R - S_T = -20\log_{10} R - 20R\alpha\log_{10} e + \Gamma[\text{dBm}] \quad (1)$$

where the final term Γ is the variation which is not influenced by distance R, but by antennas and environment variables such as polarization loss factor(PLE), transmitter antenna gain(G_T), receiver antenna gain(G_R) and additional unknown attenuation factor(w) as shown below:

$$\begin{aligned}\Gamma_{dipole} =& 10\log_{10}\text{PLF} + 20\log_{10}\frac{c}{4\pi f n} + 10\log_{10} G_T \\ &+ 10\log_{10} G_R + 10\log_{10}\frac{3}{2} + w[\text{dB}]\end{aligned} \quad (2)$$

2.2 Obstacle Model

When an obstacle exists between the transmitting node and the receiving node, it brings about additional attenuation of EM wave. This EM wave distortions can be classified into penetration, deflection and diffraction which are affected by the obstacle's characteristics such as radius, thickness, material property, shape and so on.

However, if a sensor is to estimate all obstacle effects, it becomes infeasible with large complicated models. Therefore, selecting the most significant factors to design an optimal obstacle model is very important. In many applications, distortions by reflection and diffusion depend on variables which can change depending on conditions such as angle of incidence and surface roughness, which are difficult to measure (Ahmed et al. (2010); Zavorotny and Voronovich (2000)).

On the other hand, in order to estimate the signal attenuation due to penetration, it only needs the information about the obstacle's material type and depth (Ahmed et al. (2010)). Also, the penetration effect has constant value regardless of conditions. In order to verify the penetration property, we conducted the three feasibility tests as shown in Fig. 3. These experimental results show that additional power attenuation by penetration has almost constant values regardless of the node's position, distance and obstacle's relative position.

This obstacle model is shown below (Sommer et al. (2011)):

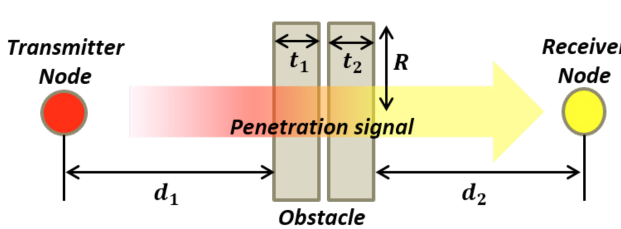


Fig. 4. Influence factors of EM wave attenuation when EM wave penetrating obstacle. The penetration attenuation is affected by obstacle depth and material type.

$$L_{obs} = \beta n + \gamma t_m[\text{dB}] \quad (3)$$

L_{obs} is intended to capture the additional attenuation due to n obstacles with total obstacle thickness t_m, located between the transmitter and the receiver. The first of the two calibration factors, β, is given in dB per obstacle and represents the additional attenuation caused by penetration. The second calibration factor, γ, is given in dB per meter and represents the attenuation factor by material.

2.3 Underwater Sensor Model with Obstacle Effect

By adding the obstacle model that only considers the distortion effect of penetration into the underwater sensor model for EM wave attenuation, we can estimate the transmitter-receiver separation robustly in an obstacle included environment. Subtracting Eq. (3) from Eq. (1), it results as:

$$S_R - S_T = -20\log_{10} R - 20R\alpha\log_{10} e + \Gamma - \beta n - \gamma t_m \quad (4)$$

3. EXPERIMENT

In order to develop and verify the improved underwater sensor model, we carried out two experiments. First, we measured the RSS values in various obstacle conditions to determine the calibration factors β and γ. Second, we performed the distributed positioning schemes in ad-hoc network of sensors to verify the localization performance for environment with obstacles.

3.1 Experimental Environment

To develop and verify the improved underwater sensor model, we set up the experiment in underwater test facility in Korea Institute of RObot and convergence(KIRO). The test bed was 12m long, 8m wide, and 6m deep. In order to prevent EM wave reflection, the antennas were

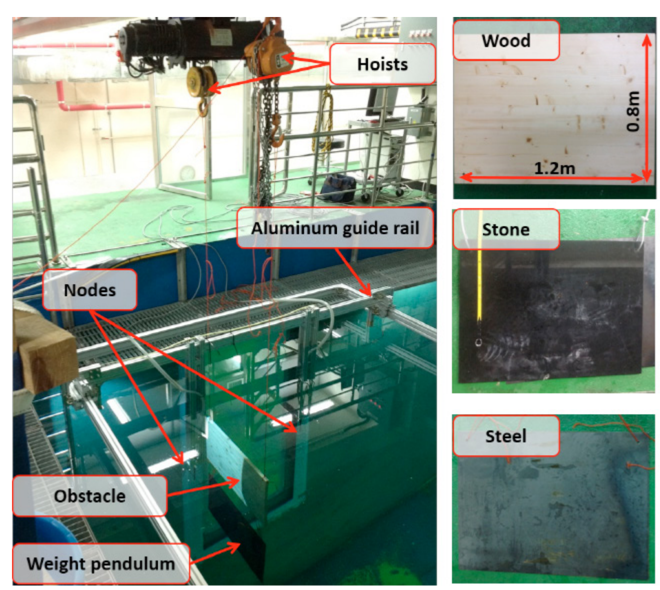


Fig. 5. Experimental condition to determine calibration factors. The obstacle was 1.2m wide, 0.8m long and various thickness with 10mW power at 420MHz.

Table 1. Test environment constants

	Property (symbol)	Values [unit]
Freshwater	Conductivity (σ)	0.075 [S/m]
	Permeability (μ)	1.2566×10^{-6} [H/m]
	Permittivity (ϵ)	7.2797×10^{-10} [F/m]
	Refraction index (n)	8.8
Antenna	Antenna gain in air (G_T, G_R)	3 [dBi]
	Transmission Power (S_T)	10 [dBm]
	Operation frequency (f)	420 [MHz]

separated 1.5m away from the basin wall. The antenna depth between guide rail and the peak of the antenna was 1.5m. The antenna used in the experiment was a dipole antenna with 3dBi antenna gain, and the antenna was considered as a sensor(node). Silicone hoses were used to waterproof the antenna and their cable, while the antenna frames were used to ensure proper alignment between antennas.

The distance between the antennas, R, was measured by measuring the distance between the antenna frames. The medium inside the basin is assumed to be fresh water. The EM wave generation and signal reception was done with a National Instruments signal generator(NI5660SA) and signal analyzer(NI5670SG). In order to prevent crosstalk, we used coaxial cables. In addition, we checked the shielding performance. The transmission power was set to 10mW with 420MHz frequency. The experimental parameters used in this experiment are shown in Table 1.

3.2 Calibration Factor Experiments

The calibration factors are determined based on the material of the obstacle. Because most of the underwater obstacles and the facilities consist of stone, wood and steel, we conducted the calibration factor experiment using these materials.

Experiment Condition and Procedure The experimental environment was shown in Fig. 5. The obstacle was 1.2m wide, 0.8m long with various thicknesses. The obstacle was deployed between nodes, and it was hung on two hoists. Also, additional weight was attached to the obstacle for buoyancy compensation. The distance between nodes was 1m.

The experiment was performed as follows. First, we measured the RSS values without obstacle $S_{w/o}$. And then we repeated these experiments according to the various obstacles and thicknesses $S_{w/}$. The material types were wood, stone and steel. When n was greater than 1, we kept

Table 2. Calibration Factor Experiment Condition

	n	d_m[m]	L_{obs}		n	d_m[m]	L_{obs}
Wood	1	0.015	2.0906	Stone	1	0.02	2.996
	1	0.024	2.9292		1	0.03	3.4173
	2	0.03	4.0958		2	0.04	6.5826
	2	0.039	5.1298		2	0.05	6.9262
	2	0.048	5.9621		2	0.06	7.3574
Steel	1	0.002	43.4537				
	2	0.004	43.5414				

Table 3. Experiment Result for Calibration Factors

	β [dB/n]	γ [dB/m]
Wood	0.6332	96.3408
Stone	2.3101	45.1200

a 5mm gap between obstacles using support. L_{obs} could be solved using $S_{w/o}$ subtracted by $S_{w/}$. Finally, the β and γ values are calculated using least squares. The experiment conditions are shown in Table 2.

Experiment Result In case of steel, since EM wave can not penetrate due to its conductivity, L_{steel} was the largest value despite the small thickness. Thus, L_{steel} can be considered as another distortion effect such as diffraction and reflection, and the effect of other distortions was trivial. The calibration factors according to the materials is shown in Table 3.

3.3 Localization Experiment in Environment with Obstacles

Experimental Condition and Procedure In order to check the obstacle model performance, the random node localization was conducted in environment with obstacles. The experimental environment consisted of three anchor nodes(have specified localizations, and their position informations are known) and three random nodes(has randomized positions, and their positions are unknown) with 2.58m long and 2.58m wide square test bed as shown in Fig. 6. The anchor nodes were fixed near the edge of the test bed, and their position information was known. The random nodes were located on the inner area of the test bed, and received signal from anchor nodes. The obstacle was hung on the two hoists, and was located almost perpendicular to the random nodes. To check the node localization performance, all of the nodes were measured using a laser distance measuring instrument. We assumed the EM wave signal become weaker due to the penetrating obstacle only, and the obstacle thickness and the material were known.

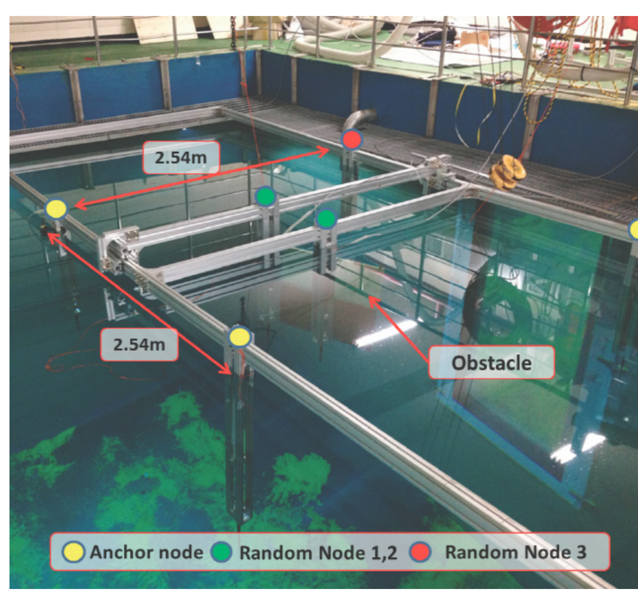


Fig. 6. Random node localization condition in environment with obstacle.

Table 4. Random Node Localization Conditions and Results

Dimension [m]

	Random node 1	Random node 2	Random node 3			
			Random node 3 (Wood)		Random node 3 (Steel)	
			w/o model	w/ model	w/o model	w/ model
Actual Position	[1.0200, 1.4700]	[1.2700, 1.2700]	[2.5400, 2.5400]			
Estimating Position	[1.0194, 1.4693]	[1.2698, 1.2696]	[2.7136, 2.6799]	[2.5585, 2.5629]	[2.6949, 2.6579]	[2.5619, 2.5568]
Maximum Error	0.0038	0.0020	0.2262	0.0322	0.1980	0.0311
Minimum Error	0.0003	0.0001	0.2194	0.0276	0.1913	0.0244
RMS Error	0.0014	0.0008	0.2230	0.0296	0.1947	0.0277

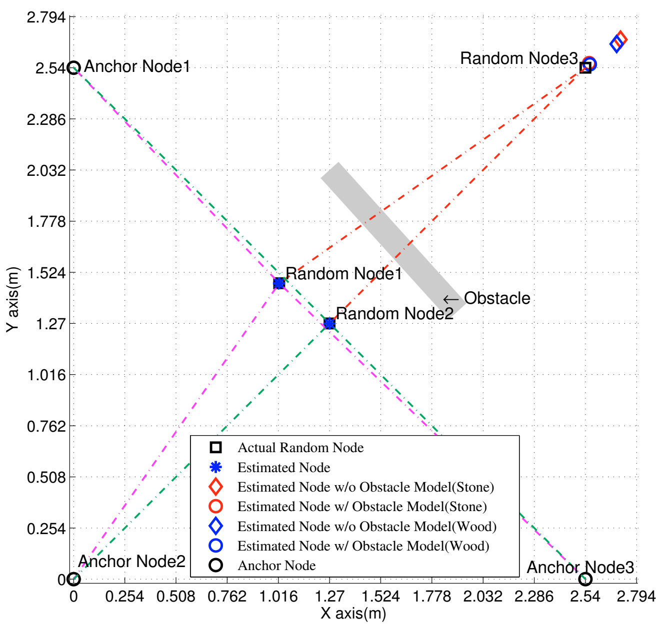


Fig. 7. Random node localization condition and result

The experimental procedure was as follows: in order to verify the sensor model performance for non-obstacle environment, the random nodes were estimated. The anchor nodes transmitted EM wave with different frequency bands, so we knew the identity of each anchor node. Nodes 1 and 2 received the signals from the anchor nodes, and estimated the distance using the sensor model, and then each node estimated theirs positions. Next, to verify the sensor model performance for environment with obstacle, random node 3 was estimated. Random node 1 and 2 broadcasted their own estimated positions on different frequency bands. Random node 3 received the signals from the two random nodes, and then estimated its own position. In order to check the obstacle model performance, a different sensor model was used. One is the sensor model without additional loss factor for obstacles, the other is the sensor model with additional loss factor.

Localization Result The localization result are shown in Fig. 7 and Fig. 8. First, the localization results of random node 1 and 2 were shown in Fig. 8(a) and Fig. 8(b). These figures shows good position estimation results, and the estimated positions were inside of the covariance ellipse with a small error. It means that the localization result had good performance for non-obstacle environments. The localization performances according to the obstacle material were shown in Fig. 8(c)(stone) and Fig. 8(d)(wood). Regardless of using the obstacle model, the localization results had a gap from actual position. This may be caused by additional distortion of EM wave or environmental effect. However, the performance of the sensor with the obstacle model is significantly improved from that without the obstacle model. In Table 4, the RMS errors were decreased by 90%.

4. CONCLUSION AND FUTURE WORKS

In this paper, to overcome the effect of an underwater obstacle, we proposed a sensor model considering obstacle effects. By considering only the penetration effect, we designed an optimal obstacle model. Finally, we verified the sensor model in environment with obstacles by combining the obstacle model with the distance model.

In order to determine the penetration model according to the material, calibration factors were verified by experimental results with a number of different material and obstacle thickness, and we have discovered β and γ. Finally, we conducted a random node localization experiments using the sensor model for environment with obstacles. The random node localization showed the improved position estimation results with the improved sensor model. In summary, the experiment results showed robust localization performance from the proposed obstacle model in underwater environment with obstacles.

In the future, we will expand the distributed positioning schemes in more wider environment with obstacles using the sensor network techniques. Also, we will conduct an obstacle tracking using the proposed sensor model.

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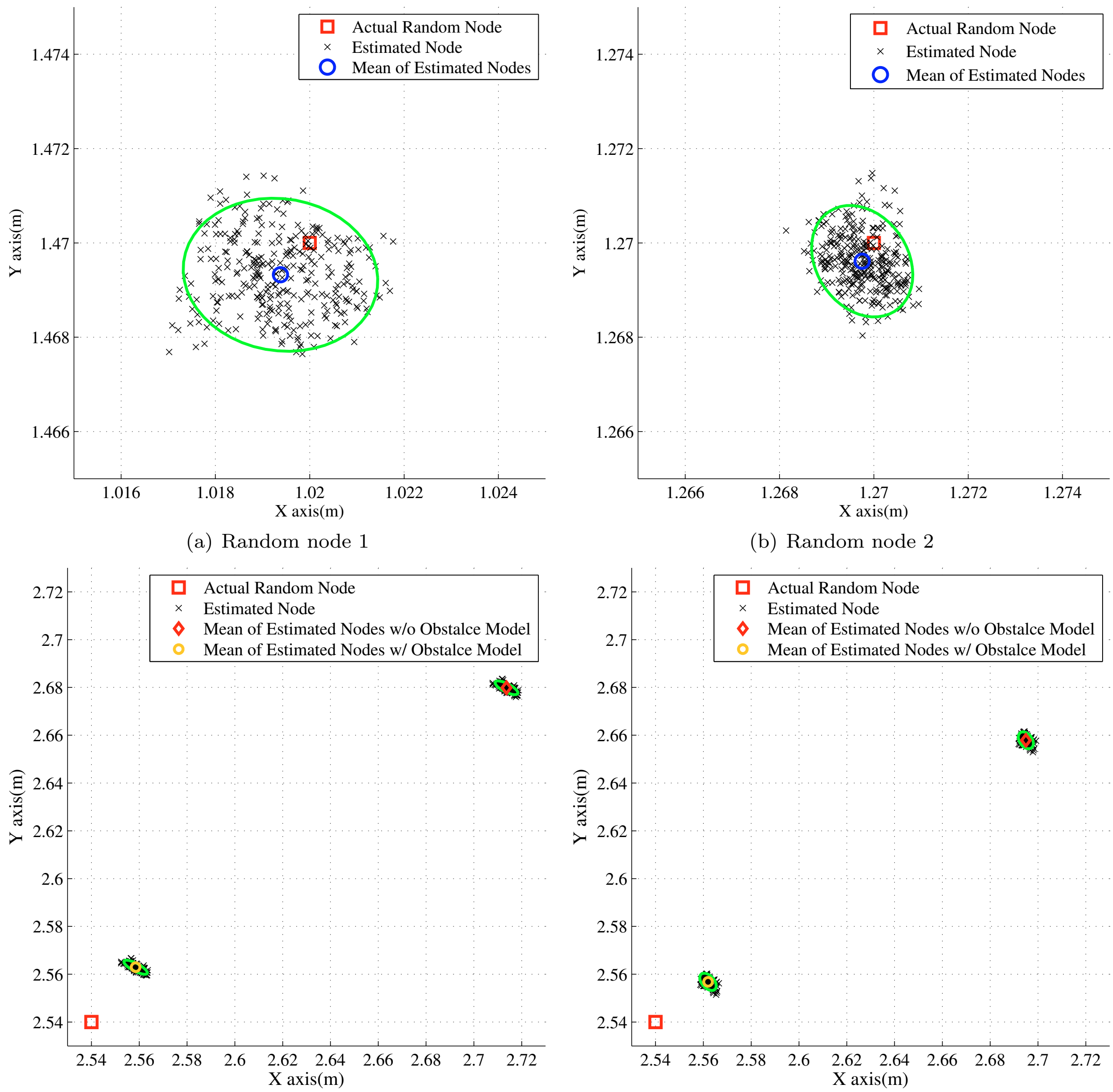

(a) Random node 1

(b) Random node 2

(c) Random node 3 with obstacle (Stone)

(d) Random node 3 with obstacle (Wood)

Fig. 8. Random node localization results

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