Development of Underwater Acoustic Channel Model for Wireless Sensor Network in Tank

Sweta S Panchal, Ved Vyas Dwivedi, Jayesh P Pabari

Abstract*: The physical quantity of interest can be detected using wireless sensor network. The concept of wireless sensor network used to explore difficult areas to access is extended to underwater applications. Efforts are made to focus on design and development of reliable, feasible and robust system for communication in underwater environment. The scenario of communication is completely different for terrestrial and underwater environment. Underwater wireless communication is accomplished by transmission of acoustic signal. Requirement exists to develop a model governing basic equations for acoustic frequency range for underwater acoustic communication. With excess quantity of sodium chloride in a underwater tank, the physical properties of the channel changes which alternately effects the communication. Using soft computing technique, the attenuation model is simulated which is a basic physical property taking change during underwater acoustic communication. The topology of sensor network in water is another challenging task because behaviors of acoustic sensor in underwater are completely different than terrestrial sensors. Thus the efforts are made to devise a model of acoustic frequency environment in water using basic relationships of various physical phenomena. The Channel propagation model is devised that helps to understand percentage area coverage for the received signal strength of the transmitted acoustic signal. Thus the underwater acoustic signal channel propagation model is presented which helps to focus on communication scenario in water and proceed for application.

***Keywords* : Acoustic signal, Attenuation model, Soft computing, Channel propagation model, Underwater acoustic communication.**

I. INTRODUCTION

Wireless Sensor Network is typical technology that acts as the powerful resource for terrestrial as well as underwater exploration. An Underwater Acoustic Sensor Networks (UAWSN) consists of wireless sensors which are deployed and designed to perform collaborative task for a given specific area. In order to achieve its aim, sensors are efficient enough to self-organize and adapt in the harsh environment of water. The physical and chemical properties of underwater environment make it more challenging to fulfil faithful communication. The Underwater Acoustic Channel is very complicated and time-varying, no universal models are available for analysis Underwater Acoustic Channel. Various different methods are available to characterize the acoustic channel in water. The underwater acoustic models are developed to study predictive behavior of the UAWSN. Parastoo Qarabaqi and Milica Stojanovic [1] developed a model for statistical scenario for UAWSN which is extended for fast fading observed due to multipath propagation of acoustic signal caused due to reflections. Another model was designed using experimental data which characterize channel with time varying delays, physical parameters with fluctuations in amplitude and frequency [2]. For shallow water applications, the time-varying and frequency shifts for stationary deployed communicating devices. In wireless communication systems the signal travels among transmitter to receiver through wireless channel, the basic part of wireless communication system. Various factors affect the propagation of wireless signals in any propagating environment. This factor occurs due to interference, obstacles, refractions, diffractions, scattering, reflections etc. All these factor imposes constraint that highly affects acoustic signal transmission. The Acoustic signal model is a mathematical formula having empirical type developed with the purpose to study the propagation patterns for given frequency of operation, distance of communication and other environmental conditions. Thus path loss is predicted when an acoustic signal propagates through underwater with specific constraints. This provides the reason for engineers to develop propagation models as they are essential tool for design of wireless communication system for all underwater applications. As the complex physical characteristics of water and disadvantages imposed by radio frequency and optical transmission, the acoustic wave is only media available for underwater wireless communication at any distance. As ocean is highly conductive, the amounts of losses are more. But for communication in raw water like tank, it is less conductive compared to that of sea. But the acoustic wave has low absorption in water compared to radio waves and also acoustic wave do not scatter at high frequencies like optical waves. So the acoustic wave propagation is primary choice for underwater propagation. Development of propagation model requires transmission range for communication between sensors acting as transceiver. The primary interest is to develop wireless sensor network capable of operating in shallow bounded environment of underwater tank with chemical constituents as sodium chloride as prime constituents. The content of sodium chloride is considered 4.66% in raw water containing pure water 95.34% [3].

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The existing models developed for sea water as channel cannot be applied directly to tank medium as the communication environment is different in both. Also bounded environment has more multipaths compared to sea and distance of communication is short. The UAWSN (Underwater Acoustic Wireless Sensor Network) developed in sea are costly, so direct applicability to tank is not possible. Also the losses observed are different in tank than sea. Zoksimovski et al., 2012 suggested use of radio frequency are very short range (<1 m), short range (<100 m). Some theoretical models were developed like Porter and Lie, 1994 [4] attempted to develop model based on ray tracing. Tindle, 2002 developed wave-front based model. The effect of physical parameters like propagation effects and scattering of acoustic signal in shallow water channels were shown by Van Walree, 2013 [2]. The comparative study was developed for short- to medium range communications and low-data rates [5]. Based on the literature survey, the lack of development of channel propagation model for UAWSN for tank which helps to estimate the received power for amount of transmitted power by sensor node is observed. This inspired us to carry work for designing of channel model for propagation of acoustic signal.

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II. ATTENUATION LOSS MODEL

An underwater acoustic signal experiences attenuation due to absorption and other losses. The absorption co-efficient for underwater acoustic frequencies in the channel which consist of raw water saturated with sodium chloride can be calculated using formula defined in $\alpha_{overall}(\frac{dB}{m})$ as function of frequency of f (kHz) Eq.(1) [3].

$$\alpha_{overall} = 0.9534\alpha_{water} + 0.0466\alpha_{NaCl} \quad (1)$$

$$\propto_{water} = A * P * f^2 \quad (2)$$

$$P = 1 - 3.83 * 10^{-5}z + 4.9 * 10^{-10}z^2 \quad (3)$$

$$A = 4.937 * 10^{-4} - 2.59 * 10^{-5}T + 9.11 * 10^{-7}T^2 - 1.5 * 10^{-8}T^3 \qquad T < 20℃ \quad (4)$$

$$A = 3.964 * 10^{-4} - 1.146 * 10^{-5}T + 1.45 * 10^{-7}T^2 - 6.5 * 10^{-10}T^3 \qquad T > 20℃$$

(5)

$$\alpha_{Nacl} = (0.0225 * f^2/2\rho v^3) \left[(4\eta/3 + \eta^v) + \tau\left(\frac{1}{C_p} - \frac{1}{C_v}\right)\right] \quad (6)$$

where attenuation due raw water is given by α_{water} in dB/m [6] which is affected by hydrostatic pressure P in bar [6], z is depth of water medium in meters, T is temperature in ˚C and A is atmospheric pressure which is constant till 20℃ . α_{NaCl} is the attenuation due to sodium in dB/m, f is frequency in kHz, ρ is density g/m^3, v velocity in m/s, η^v is volume viscosity, τ is thermal conductivity, C_p and C_v are specific heat constants at constant pressure and constant temperature [7][8].

The mentioned model is applicable to the channel consisting of 95.34% of raw water saturated with 4.66 % of sodium chloride [9]. The concentration of sodium chloride corresponding to 4.66% is approximately 3 moles/liter. The model for attenuation due to raw water is valid for temperature 20°C , hydrostatic pressure of 1 bar and depth of tank 100m [10]. The attenuation co-efficient is dependent on distance between transmitter and receiver. As the transmission range increases, the attenuation of acoustic signal as function of acoustic frequency ranges also increases.

III. MULTIPATH SIGNAL DISTRIBUTION

Fading is the random process of variation in attenuation of signal in reference to change in various parameters like geometrical position, frequency, etc. Fading occurs due to multipath propagation of acoustic signal. Several methods are used for fading channel modeling. For an underwater acoustic channel as tank which shallow water channel, there can be dominant path and several other multipaths that helps the acoustic signal in propagation from transmitter to receiver. Requirement is to find the best fit distribution model for fading due to multipath propagation in shallow water like tank. The instantaneous signal which appropriate strength is received at receiver. Receiver signal strength is determined using Fading distribution model like Ricean, Rayleigh, Weibull models as suggested in [11]. Rayleigh distribution considers multipath components and does not allow direct path. Ricean Distribution considers direct as well as multipath components. Communication is bounded shallow underwater tank is expected to be line-of-Sight as well as multipath components due to reflections from channel and tank symmetry. Therefore Ricean Distribution is considered as most suited given by [11].

$$f(x|v,\sigma) = \frac{x}{\sigma^2}\exp\left(-\frac{(x^2+v^2)}{2\sigma^2}\right) I_0\left(\frac{xv}{\sigma^2}\right) \quad (7)$$

Where I_0 is modified 0^{th} order Bessel function and value of a depends on direct component. Ricean function is expresses in terms of carrier-to-multipath ratio k as

$$k = \frac{c}{m} = \frac{\propto^2}{2\propto^2} \quad (8)$$

Where c and m are strengths of carrier and multipath components respectively. For large values of k, the received signal strength increases and p(r) becomes Gaussian.

A. Multipath Components

The acoustic signals get reflected from water surface, water bottom and side walls of underwater tank, after transmitted and from due course of its emergence from arrival. The distance between transmitter and receiver plays important role in number of reflections and hence multiple paths it has to travel. Therefore as distance changes, the reflections taking place also changes. This reflection that leads to multiple paths give rise to multipath propagation [12]. Consider channel geometry and bounded medium of tank as infrastructure geometry as shown below with multipath propagation of acoustic signal in tank.

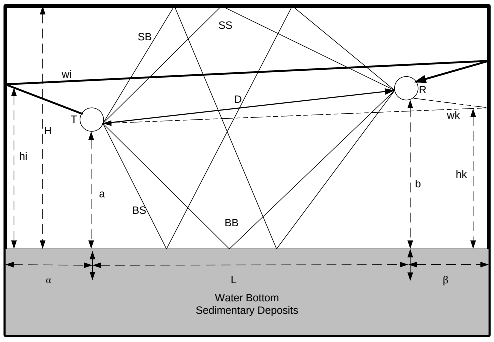

Fig. 1.Multipaths due to reflections from channel geometry and tank geometry

The distance between transmitter and receiver is L. The number of multipath components depends on reflection of transmitted signal from various parts of communication medium in an underwater tank as medium of transmission. The distance between sensors employed for transmission as well as reception also plays vital role for finding number of multipath components. The bandwidth of communicating device plays vital role for number of multipaths [12]. The specifications of the sensors like bandwidth, operating frequency, sensitivity, dynamic range etc. are important for underwater acoustic communication in tanks. The number of multipath can be evaluated according to maximum propagation delay of the reflected signal and bandwidth of the sensor in use. The maximum propagation delay from the calculation is utilized as τ_{max} . Thus the number of multipaths can be calculated using Eq. (9) [13].

$$\delta = [2\tau_{max}B] + 1 \tag{9}$$

where τ_{max} is maximum propagation delay of the various reflected signal from various reflection undergone in due course of its propagation as shown in figure (1) for specific distance between communicating devices, B is the bandwidth of operating frequency ranges of communication.

As distance between transmitter and receiver changes, the number of reflections and ultimately number of multipaths are changed. For a particular communicating set of devices, the number of multipath for the acoustic wave propagating through underwater tanks depends on distance between transmitter and receiver. The expression representing relation between distance between communicating devices and number of multipaths is given by Eq. (10) [14] .

$$\delta = 4.17e^{0.224}d \tag{10}$$

Number of multipaths δ can be calculated using Eq. (10) till distance of 20m between transmitter and receiver for bounded shallow medium of communication like tank.

IV. PHYSICAL PHYNOMENON IN UNDERWATER TANK

The terrestrial models cannot be directly applied to underwater tank applications due to difference in physical and chemical properties as well as different communication scenario. Various physical phenomena occurring due to wave propagation in underwater tank are examined and applied to signal propagation in underwater tank. All such physical phenomena are given and combining them to derive propagation loss model.

Acoustic wave propagation is similar to propagation of radio waves with only low frequency range of acoustic signal compared to radio signal. If the transmitted power is P_t, the distance of receiver from transmitter is L and line-of-sight propagation, and then the receiver power intensity of Omni-directional radiator is assumed other angle of radiation taken into consideration. The received power is

$$P_r = \frac{A_r P_t}{4\pi L^2} \tag{11}$$

Friis transmission equation is used to estimate the transmission range similarly as transmission power (12)[15]. The radiated energy is Omni-directional and received power is given by Eq. (4),

$$P_r = \frac{P_t G_t G_r \lambda^2}{16\pi^2 L^2} \tag{12}$$

Where, P_t is power transmitted and P_r is power receiver, G_t and G_r are gain of transmitter and receiver antennas respectively, λ is wavelength of operating frequency and L is distance between transmitter and receiver. Eq. (12) is the fundamental loss to communicate in underwater acoustic wireless sensor network. Various losses occurring due to phenomena undertaking in due course of communication, needs to be investigated.

A. Reflection

The propagation of acoustic signal is limited by interfaces of water medium and tank geometry. The propagation of signal is limited due to successive reflections from the interfaces of water medium and tank structure. Unlike terrestrial communication where the factors like steady and moving reflectors, atmospheric absorption etc leads to reflection of signal; the reflection in underwater tank is due to water medium and tank structure.

In underwater tank, the reflection of acoustic signal is from the water surface, water bottom and side walls. The geometry of tank and reflections from various parts are as shown in figure 1. Thus multipath signals are induced in propagation of acoustic signal and due to multipaths the signal arriving receiver will vary with direct path. Few expected multipath components are to be considered in tank model due to high propagation delay offered by certain multipath components. Signal wavelength depends on frequency of operation of wireless transmission which is larger and ultimately results in reflection. The signal strength obtained using reflection co-efficient is given in Eq. (13),

$$P_r = \frac{P_t G_t G_r \lambda^2}{16\pi^2 L^2} . |1 + \Gamma \exp{(j\emptyset)}|^2 \tag{13}$$

Where, Γ is reflection co-efficient of the reflected signal, ∅ is phase shift introduced due to reflected signal, $\lambda = c/f$ is wavelength of transmitted signal, c is sound speed in water which is considered 1500 m/s. f is operating frequency of sensor used with horizontal polarization of transmitting device.

The reflection at the water surface is due to impedance mismatch between water surface and air, which makes water surface as good reflector. The reflection co-efficient is evaluated using Bechmann-Spezzichino model as proposed by Coastes, 1988 [16] . The magnitude of reflection co-efficient independent of grazing angles is given by Eq. (14).

$$|r_s| = \sqrt{\frac{\left(1+\left(\frac{f}{f_1}\right)^2\right)}{\left(1+\left(\frac{f}{f_2}\right)^2\right)}} \qquad (14)$$

$$f_2 = 378\, w^{-2} \qquad (15)$$

$$f_1 = \sqrt{10} f^2 \qquad (16)$$

Where, f is operating frequency in kHz, w is wind speed in knots. The impedance mismatch occurs at the surface when the acoustic signal reflects between water surface and air and induces phase shift of π i.e reflection co-efficient of -1 is induced due complex surface pressure co-efficient. The wind speed is considered 9.7 knots, which is makes f_2= 4.017 kHz. Thus the corresponding surface signals reflection co-efficient is 0.49.

For bottom reflected wave BB as shown in Fig 1, the reflection co-efficient can be evaluated. Due to impedance mismatch between water bottom and bottom of tank reflects the acoustic wave incident. The bottom reflected signal is angle dependent given by Rayleigh reflection co-efficient Eq. (17) for the tank having smooth bottom.

$$|r_b| = \frac{m\cos\theta - \sqrt{n^2 - \sin^2\theta}}{m\cos\theta + \sqrt{n^2 - \sin^2\theta}} \qquad (17)$$

Where, $m = \frac{\rho_1}{\rho}$, $n = \frac{c}{c_1}$; ρ and c are density and sound speed respectively of water and ρ_1 and c_1 are density and sound speed of water bottom of tank respectively.

Similarly, the magnitude of reflection co-efficient of various multipath signal as shown in figure 4.2 due to combined pressure loss of repeated surface-bottom reflections [16] is as given in Eq. (18),

$$|r_{sb}| = -|r_s|\,; \quad |r_{bs}| = |r_s| \qquad (18)$$

The direct path of transmitted signal is important because for short distance of communication line-of-sight is received with good signal strength and less delay compared to multipath signals.

B. Diffraction Loss

Diffraction happens when an obstacle with height larger than signal wavelength blocks the direct line of sight signal between transmitter and receiver. The signal is scattered by the obstacle's edge and attenuated when the target is in obstacle's shadow is defined as diffraction loss. Diffraction from knife edge bends signal towards obstacle. The bending of signal allows the signal strength behind knife-edge obstacle considered greater than that behind rounded obstacle [17]. For LOS, diffraction loss takes place on the edge of an obstacle when an obstacle of wavelength comparable to the transmitter or receiver is present. Upon entering the receiver, the signal can be dispersed and attenuated. Diffraction from the knife edge obstacle results in signal bending and this signal bending causes higher signal strength than rounding. Diffraction loss occurs due to knife edge object with finite effective length of obstacle with infinite width is in the path of transmitter and receiver. If the communication environment is sea, such obstacles may be seen which causes diffraction losses. But for the underwater tank environment, such obstacles are not available, so the signal attenuation due to diffraction loss is zero.

C. Reflection Scattering

When the transmitted signal is reflected from a rough surface, the energy of reflected wave will be scattered. This is known as scattering reflection. It was observed and reviewed by Gibson [18]. Also suggested that the surface roughness can be classified according to Rayleigh criterion.

$$h_c = \frac{\lambda}{8\cos\theta_i} \qquad (19)$$

Where, θ_i is the angle of incidence and h is deviation of mean bottom height. For smooth surface, the minimum to maximum protuberance h is smaller than h_c and for rough surfaces, the protuberance h is larger than τ_{max} h_c.

The proposed model for attenuation is developed for the underwater tank filled with raw water saturated with sodium chloride and no sedimentary deposits at the bottom of tank. In the underwater tank, mostly plane smooth surface is observed hence no scattering losses occur in water tank.

D. Refraction

Multipath formation in the water medium is due to two reasons; acoustic wave reflection and acoustic signal refraction. Later is due to the spatial variability of sound speed in water. The bending of acoustic signal in non-uniform medium like water in which the sound speed is function of spatial co-ordinates. The bending of sound signal in non-homogenous medium is towards the low sound velocity. This process is due to propagation of sound wave over longer distances. According to Snell's law, the sound signal bends towards low propagation speed. As the temperature and pressure are constant near surface, the sound speed is also constant, so no refraction is observed at surface. But with increase in depth of water level, the temperature decreases and pressure increases leads to refraction of acoustic signal.

The underwater tank is the small medium of propagation of acoustic signal. The depth of water medium remains same as the medium is uniform. In uniform medium with constant depth, temperature remains constant from water surface to water bottom. The pressure is also maintained constant as the depth is constant in uniform channel for propagation. Thus the sound speed does not change as the propagating acoustic signal moves from transmitter to receiver. This leads to only reflections and no refraction in tank. Thus in the channel medium of tank, the propagating acoustic signal does not suffer from refraction losses.

V. WIRELESS PROPAGATION MODEL FOR UNDERWAER TANKS

The wireless propagation model designed for underwater tank takes path loss, reflection losses, attenuation loss into consideration. The wireless propagation model designed for underwater tank takes path loss, reflection losses, attenuation loss into consideration. . The reflection of acoustic signal leads to multipath propagation in various directions of tank before it reaches to receiver. The number of multipath is suggested in previous section by Eq. (10) as function of range of transmission. The following mathematical model for acoustic signal propagation is suggested as in Eq. (20).

$$P_r = \frac{P_t G_t G_r \lambda^2}{16\pi^2} . \Big| \propto_{overall} \frac{1}{d_d} \exp(-jkd_d) +$$
$$\Gamma_1(f) \frac{1}{d_1} \exp(-jkd_1) +$$
$$\Gamma_2(f) \frac{1}{d_2} (\exp(-jkd_2) + \cdots +$$

$$\Gamma_n(f)\frac{1}{d_n}(\exp(-jkd_n)\Big|^2 \quad (20)$$

Where, $\propto_{overall}$ is the proposed attenuation suggested in Eq. (1) applicable to the medium of water tank saturated with sodium chloride, d_d is the direct path of communication, d_1, d_2 ... d_n are the δ number of multipaths. The maximum number of multipath for particular range of communication is shown in Eq. (10). The path lengths of d_1, d_2 ... d_n are length corresponding to multipaths SS, BB, BS, SB, ...respectively till δ number of multiple paths. k is phase constant, $\Gamma_n(f)$ is the nth wave reflection loss of which the frequency of operation is f=30 kHz. The phase of each multipath signal is determined by $\exp(-jkd_n)$ component, where d_n is the distance of nth ray travelling and corresponding reflection-co-efficient, which is equal to sum of transmitter and receiver distances from the reflected signal.

A. Tank Dimension

The study of acoustic signal propagation in UASWN in bounded shallow medium like tank, the channel propagation model was designed as shown in Eq. (20). The wireless sensor network consists of set of transmitter and receiver to fulfill communication. Each individual transmitter and receiver act as transceiver used as node. Each node used is coupled with transducer. Underwater acoustic sensor used simulation of tank WSN works in acoustic frequency range. Various acoustic sensors are available working frequency range of 10 kHz to 120 kHz, for testing of model BII-8085 acoustic sensor is used. Thus the typical operating frequency is f=30 kHz sensor can be coupled with transceiver BII- 7640 used [19]. The marine acoustic transducer and hydrophones can be used to pair for transceiver for electrical signals and acoustic signal transmission and reception vice-versa. The Underwater acoustic transmitter-receiver used Benthowave Inc. with BII 8080 limited to the bandwidth of 10kHz [20] . Other models with wide bandwidth and higher operating frequencies are also available. The sensor node operating at 30 kHz of operating frequency, 10 kHz bandwidth, 0 dBm as transmitted power and sensitivity of the underwater acoustic receiver node is -80 dBm.

The dimensions of tank shown in figure 1 are fixed by 20 m of height of channel medium, 20 m of range of communication between transmitter and receiver. The medium of communication is the raw water saturated with 3 moles/L of sodium chloride. With the pressure maintained constant at 1 bar and temperature of 20°C. As the height of water medium not changes, there are no changes in temperature and pressure. The proposed model of attenuation can be used for such medium for propagation of acoustic signal.

B. Bounded Coverage Area

The bounded area coverage is defined as the area where power of -100 dBm to the total coverage area of site region. For the mentioned tank model, the total coverage area is 20m X 20m of square site. The coverage for tank is 31.9% of the total dimension of the model. The portion of tank receiving more than sensitivity of acoustic sensor -80 dBm of power are identifies as the area with maximum reception of power possible. Thus the percentage coverage of tank model with assumed square topology will helps to know possibility to place sensor node so that maximum power can be received.

VI. RESULTS AND DISCUSSION

The transmitter is located at middle left wall of tank with dimension of 20m X 20m which represents the middle possible according to the coverage area of transceiver. The transmitted power of 0 dBm. The parameters required to model channel propagation as shown in Eq. (20) is as per Table 1.

Table-I: Parameters values for channel propagation model of Underwater tank

Parameter	Value
Dimension of tank	Length= 20m, Height=20m
Operating frequency	F=30 kHz
Bandwidth	B=10kHz
Speed of sound	c=1500 m/s
Transmitted power	Pt=0 dBm
Radiation pattern	Omni-directional
Transmitter location	Middle left of tank

The channel propagation model of Eq. (20) is simulated using MATLAB. The results suggest the received power at various location of receiver according to the coverage area of the model. It helps to place the receiver at appropriate location so that appropriate amount of power is received. With increase in distance of receiver from transmitter, the amount of power received decreases.

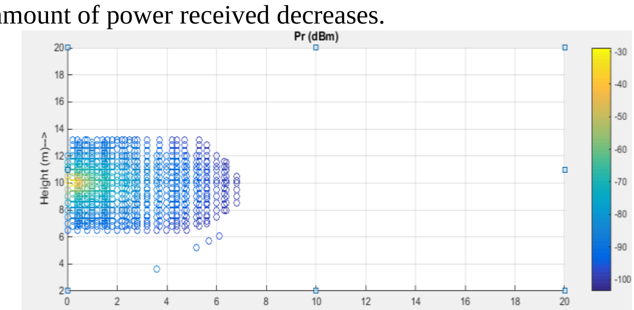

Fig. 2.Results for Channel Propagation for Tank

Fig. 2 shows the result of MATLAB simulated channel propagation model for tank using dervied model of Eq. (20). The result shows the length, height and received power as three axis of tank derived for specified site coverage area. The propagation model is simulated by passing parameter values as transmitter sensor node with operating frequency 30 kHz, transmitted power of 0 dBm and receiver node has sensitivity of -80 dBm. The tank dimensions are fixed as 20m X 20m and chemical constituents fixed by the proposed attenuation model. The result indicated useful area for sensor placement in the tank such that received power is appreciable amount.

VII. CONCLUSION

In this paper, it is investigated that existing channel propagation model cannot be directly applied to shallow bounded underwater applications. Thus the wireless channel propagation model is developed for bounded shallow water like tank containing sodium chloride as prime chemical constituent. All the phenomenon losses are considered in model, which are observed in tank.

Acoustic signal coverage patterns for tank are presented using tank model of fixed dimension. For simulating model, transmitter node is fixed to middle left position of tank and maximum coverage area of the site is calculated with the receiver maximum sensitivity. The position of receiver is varied according to coverage area and received power is calculated. Received power at each position of receiver in tank is calculated by transmitting 0 dBm of power. For the tank with fixed chemical composition of sodium chloride with concentration 3 moles/L and raw water and dimension fixed to 20m X 20m. The result suggests the various position of receiver in the tank where the amount of power is received by receiver node. Apart from the percentage area coverage, the other place in the tank does not receive the sufficient amount of power.

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