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Characterization of RF signals in Different Types of Water

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Abstract

Underwater communication at microwave frequencies overcome the data rate and bandwidth limitations of acoustic communication and the environmental problems associated with optical-based underwater networks. It has several applications in underwater sensors networks. In view of potential applications to 5G, we conducted experimental tests and computer simulations to investigate the propagation losses encountered by microwave signals in the licensed and license-free frequencies (up to 2.6 GHz) in freshwater and seawater. Our results indicate the feasibility of microwave communication in freshwater at the licensed mobile frequencies.

1. Introduction

The earth is a water planet, with over 70% of the surface covered by water. There are several applications demanding the ability to transfer electromagnetic signals through water, including pollution control, marine research, underwater sports, monitoring water quality for agriculture, industrial and domestic uses, etc. Hence, it is most auspicious to investigate how to conduct wireless communication in water. In addition, there is an increasing need to exploit natural resources underwater; the ability to do this without the limitations of wires cannot be overemphasized. However, wireless underwater communication is difficult to implement due to the hostile nature of underwater environments to radio signals.

The unique properties of underwater channels allow wireless communication using only three schemes: acoustic waves, radio frequency and microwave signals, and optical signals [1]. Acoustic waves are by far the most popular and preferred scheme for underwater communication due to their low attenuation in water that guarantees a long propagation range. However, acoustic signals suffer from low propagation speeds and low bandwidths and are unsuitable for use in shallow waters due to time-varying multipath propagation [1] [10]. Acoustic underwater communication is also susceptible to environmental changes, spreading and multi-path fading, and power constraints [2]. In addition, they cannot be used for real-time communication due to their low speeds and limited bandwidths. Optical communication overcomes most of the challenges inherent in acoustic communication. It offers extremely high bit rates, high security and low latency, and is scalable and flexible [3]. However, the range of optical communication underwater is severely limited and it is susceptible to environmental changes and requires precise alignment of the optical transceivers, which is difficult to achieve in the ocean.

Underwater radio frequency communication offers a performance that is midway between those of acoustic and optical communications. They offer high propagation speeds to overcome Doppler shifts-related problems and also possess high enough bandwidths to support real-time applications. Underwater RF communications achieve moderate transmission ranges, depending on the nature of the water medium and the frequency employed for communication. However, microwave signals are severely attenuated in seawater due to the high salinity of seawater which leads to high conductivity, thus, limiting the propagation range. Generally, lower frequencies are preferred for underwater radio communication as they achieve longer range [1]. The disadvantage is that low frequency radio waves have limited bandwidth. Underwater radio propagation is also affected by temperature. In seawater, conductivity increases with temperature due to increased ionization, leading to higher losses with increasing temperature, whereas in freshwater, the loss factor decreases as temperature increases [4].

Most available research in underwater radio frequency and microwave communication have been limited to RF propagation under 100 MHz. Despite the challenges associated with underwater communication, freshwater is a low-loss medium that offers low propagation losses [1], making it possible to achieve reliable high-speed communication.

In this work, we conducted practical experiments and computer simulations to investigate the attenuation of wireless signals from 100 MHz to 2.6 GHz in different types of water. In particular, we examined pathloss and signal propagation characteristics at the licensed mobile frequencies, as well as license-free frequencies up to 2.6 GHz. To the best of our knowledge, this is the first work that involved practical investigation of electromagnetic signal propagation underwater at the licensed microwave frequencies. Our examination of RF propagation underwater in licensed frequencies is with a view towards 5G applications. Since 5G must offer ultra-reliable and low latency as well as massive machine-type communications, including for devices operating underwater, it is imperative to examine radio propagation for sensing and actuation underwater.

2. Methodology

2.1 Microwave Signal Propagation in Water

The ratio of electric conductivity to dielectric permittivity, called *transition frequency*, defines the boundary behaviour of EM waves in a given medium. The dielectric permittivity comprises real permittivity (the ability of a material to be polarized by an external electric field) and imaginary permittivity (the efficiency with which the electromagnetic field is converted to heat). EM waves whose frequencies are higher than the transition frequency will be propagated while those whose frequencies are lower will be absorbed [1]. However, absorptive losses increase with frequency for propagating waves, thus limiting how far they can travel. Our evaluation was only concerned with the propagation of electromagnetic waves in water, that is, we did not evaluate losses due to transmission from air to water, which have already been covered in [9].

Most existing literature on RF and microwave communication in freshwater assume that the losses encountered are frequency-independent [1,5-7]. However, practical experiments and simulations indicate that there are frequency-dependent power losses in both freshwater and seawater. This result is expected since the attenuation of electromagnetic signals in water (including freshwater) is a function of the complex relative permittivity of water, ε_r, which is frequency-dependent [8], according to the Debye model shown in Equation (1) below for a fixed temperature.

$$\varepsilon_r(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + j\omega\tau} \quad (1)$$

where $\varepsilon_r = \varepsilon'_r - j\varepsilon''_r$ is the frequency-dependent complex relative permittivity of water; ε'_r is the real part of complex relative permittivity, $j\varepsilon''_r$ is the imaginary part of complex relative permittivity (accounts for heating). ω represents angular frequency, ε_s represents dielectric permittivity at low frequency, ε_∞ is the dielectric permittivity at high frequency and τ represents the relaxation time [4].

For freshwater, the attenuation, α of the microwave signal per meter is given by [16]

$$\alpha = \omega\sqrt{\mu\varepsilon}\left\{\frac{1}{2}\left[\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2} - 1\right]\right\}^{1/2} \text{ Np/m} \quad (2)$$

where $|\alpha\ (\text{Np/m})| = \frac{1}{8.68}|\alpha(\text{dB/m})|$ (3)

and μ, ε, σ represent permeability, dielectric permittivity and electrical conductivity, respectively. The propagation loss in water at a depth, d is therefore given [9] by

$$\alpha_p = 10log_{10}(e^{-2\alpha d}) \text{ dB.} \quad (4)$$

2.2 Experiments and Simulations

We conducted practical experiments and performed computer simulations to test the behaviour of microwave signals in different types of water. Plane wave propagation model was assumed.

Our practical experiment was conducted using a Samsung Galaxy S9 smartphone running Network Signal Info, a commercial software for network signal strength analysis. We performed the experiments using plastic containers of different sizes, as well as in a standard bathtub and in a 6-lane by 25 metre indoor swimming pool. The mobile phone was secured to a plastic metre rule (used to calibrate depth in water) and lowered into water. The signal strength was measured at approximately 5 cm depth ranges. In addition, the immersed phone was dialled from a mobile phone above the water surface to ascertain the depth at which the mobile signal is completely lost. To test propagation in seawater, sea salt was added to the freshwater at a proportion of 35 g per 10 litres of water to make up the equivalent salinity of seawater, which is 35 ppt. Fig. 2.1 shows one of the practical demonstration environments.

(a) (b)

Fig. 2.1. Practical experimental environment and device: (a) bathtub (b) Samsung S9 mobile phone

The simulations were performed by simulating the transmission response of a mobile phone/integrated antenna in time domain in CST Studio Suite® (2018). The simulations parameters are presented in Table 2.1.

Table 2.1: (a) Parameters used for simulation

Water type	Temp. (^{0}C)	ε	Mu	σ (S/m)
Fresh	25	78	1	1.59
Seawater	25	74	1	3.53

Table 2.1: (b) Parameters for simulation (contd.)

Water type	Rho	Thermal Cond. (W/K/m)	Heat capacity (kJ/K/kg)	Diffusivity (m^2/s)
Fresh	1000	0.6	4.2	1.429x10^{-7}
Seawater	1025	0.6	4.2	1.394x10^{-7}

3. Results and Discussion

The practical experiments were conducted using a Samsung Galaxy S9 smartphone running a commercial 4G/LTE SIM card at 2100 MHz and a Wi-Fi router operating at 2437 MHz. In the swimming pool, the mobile phone was connected to a mobile Wi-Fi hotspot to test Wi-Fi reception. For the computer simulations, we analysed the propagation loss in freshwater and seawater from 100 MHz to 2600 MHz. The results for both experiments are presented and discussed below.

3.1 Experimental Results

As Equation (4) shows, the propagation loss in water is a function of depth and absorption losses. The received signal strength for LTE is shown in Fig. 3.1, as captured by the network analyser software. Tables 3.1 and 3.2 show the received signal strength at different penetration depths in water for both the LTE and Wi-Fi signals. The tables show at a glance that the received signal strength is lower in water compared to air and that it decreases with increasing depth. Due to the dimensions of the mobile phone used relative to the container size, the recorded depths are approximate. It was also observed that the mobile phone takes about five seconds longer to ring in water than in air. This is due to the slower speed of electromagnetic waves in water compared to freespace. Radio waves are slowed by about a factor of 9 compared to the speed of light in freespace [1]. The values of the signal strength in air have also been provided in the tables for reference.

Table 3.1. Mobile (LTE) signal strength for various penetration depths at 2100 MHz

Water type	Approximate Depth (cm)	Signal Strength (dBm)
Freshwater	5	-90
	10	-97
	15	-108
	20	-111
	30	-131
	In freespace	-85
Seawater	15	Signal lost
Swimming pool	15	Signal lost

Table 3.2. Wi-Fi signal strength for various penetration depths at 2437 MHz

Water type	Approximate Depth (cm)	Signal Strength (dBm)
Freshwater	5	-74
	10	-80
	15	-84
	20	-88
	In freespace	-41
Seawater	10	Signal lost
Swimming pool	10	Signal lost

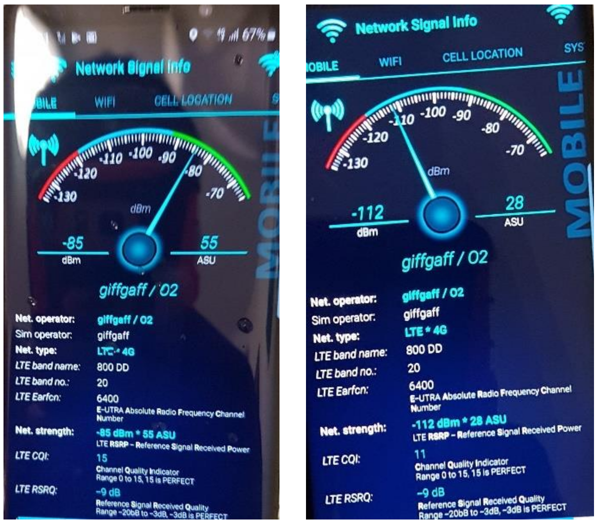
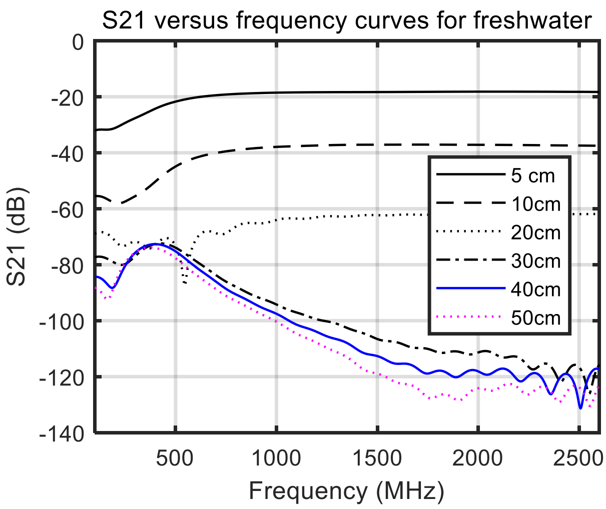


Fig. 3.1: LTE signal strength in (a) air and (b) freshwater

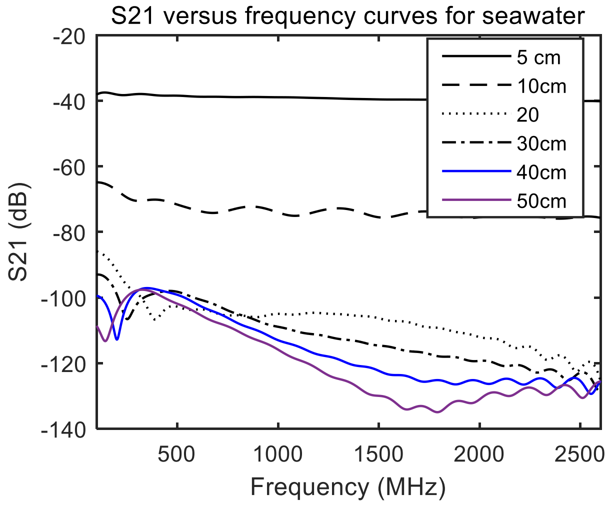
3.2 Simulation Results

As highlighted in Section 2, path loss increases with separation between the transmitter and receiver and with increasing frequency. Fig. 3.2 shows frequency-dependent attenuation for freshwater and seawater. As can be seen from both figures, the propagation loss increases exponentially even for small increases in the separation between the transmitter and receiver (it increases with depth for transmissions from air to water). This result indicates that RF signals are highly attenuated in water at higher frequencies. The curves show that at close ranges, there is no significant change in the received signal strength with increasing frequency. This may be attributed to the antennas being in the near field region at such close ranges. However, the losses rise sharply after 500 MHz, and keeps rising as the separation between the transmitter and receiver increases.

As expected, attenuation is more severe in seawater than in freshwater. Fig. 3.2 (b) evidences the difficulty of microwave propagation in seawater, where the losses are highly compounded, and signals can be received above the noise floor only at very close ranges. The high attenuation of radio energy in seawater has been well investigated and documented [10-14]. Radio absorption in seawater is aggravated because the dissolved salts in seawater increase its conductivity. Hence, at microwave frequencies, seawater behaves as a conductor [15]. The conductivity of seawater is about 4.0 S/m [16]. Our simulation results show that signals can be received above the noise floor for distances over 20 cm in freshwater whereas in seawater, microwave signals cannot be reliably received for distances above 10 cm for all frequencies. Our results also indicate that it is possible to receive signals at wider transmitter-receiver gaps at lower frequencies below 500 MHz, even in seawater (Fig. 3.2).



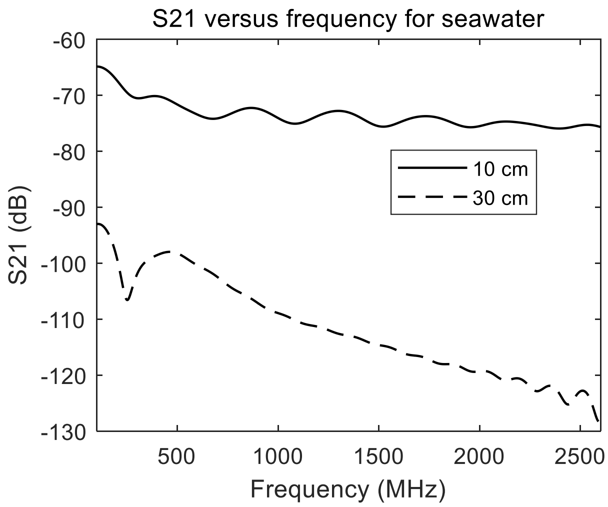
(a) Freshwater



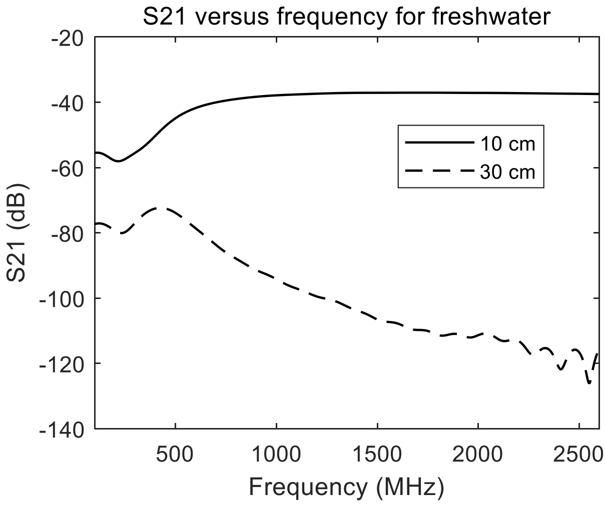
(b) Seawater

Fig. 3.2. Curves showing decrease in the magnitude of S21 response versus frequency from 100 MHz to 2600 MHz at different transmitter-receiver separations for (a) freshwater and (b) seawater.

To clearly demonstrate the severity of signal attenuation in seawater compared to freshwater, we evaluated the path loss at two reference transmitter-receiver distances in freshwater and in seawater. The results are shown in Fig. 3.3 below. As seen from the figures, there is several orders of magnitude drop in signal strength for propagation at the same frequency for seawater compared to freshwater.



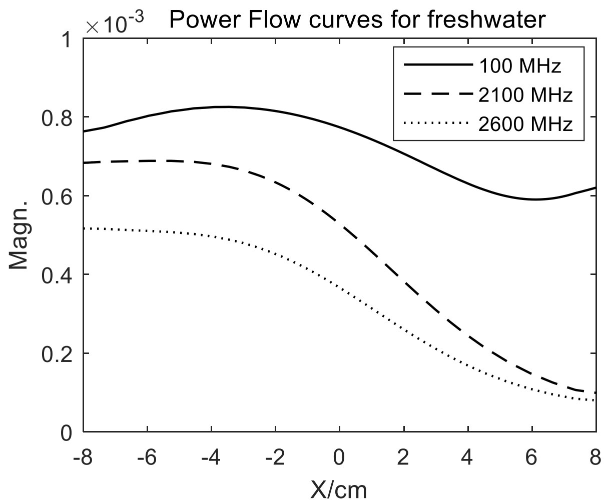
(a) Seawater



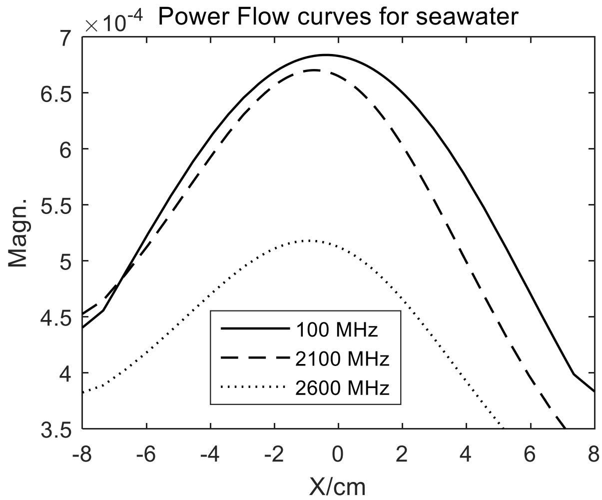
(b) Freshwater

Fig. 3.3. Example curves showing that (a) seawater has higher losses than (b) freshwater for the same transmitter-receiver distances.

As highlighted earlier, the ease of signal propagation in water is a function of frequency in addition to the separation between the transceivers. Fig. 3.3 shows power flow curves for microwave signals at different frequencies for a separation of 10 cm between the transmitter and receiver. The aggravation of power losses at higher frequencies is due to the frequency-dependency of the relative complex dielectric permittivity, as shown in Equation (1). This result is consistent with the classical theory of microwave propagation in water and with results obtained in [8] and [9].



(a) Freshwater



(b) Seawater

Fig. 3.3 Power Flow curves indicating frequency-dependent power losses for a reference transmitter-receiver separation of 10 cm for (a) freshwater and (b) seawater.

It should be noted that longer transmission ranges were achieved in the experiments than in the simulations. This can be attributed to the gain of the antennas used in the mobile phone and the transmitting base station. In addition, the antennas used in the practical experiments were highly tuned and contained other gains due to directivity and diversity-combining schemes.

4. Conclusion

In this work, we practically demonstrated microwave propagation through different types of water at different frequencies. Our results show that the propagation is affected by the separation between the underwater transmitter and receiver, as well as by the frequency of propagation. We also conducted computer simulations to validate the experiments. The simulation results are consistent with the experimental results and follow the trend of the results obtained by previous researchers. In future work, we will investigate appropriate networking schemes for underwater sensors in the licensed mobile frequencies, especially in frequencies that have been approved for use in 5G.

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