Enhanced Channel Capacity Underwater Multi-Diver Communication with Dual-Resonant Magnetoquasistatic Coupling

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***Abstract*— In underwater group missions, where effective communication among divers is crucial, delays in information exchange present significant challenges. Such delays can compromise mission success and pose serious risks to diver safety. Existing communication technologies, including RF, optical, magnetic-induction, and acoustic-based systems, suffer from low data rates due to limitations imposed by underwater medium properties (conductivity, permeability, visibility). Among these, magnetically coupled systems exhibit reduced signal attenuation in highly conductive media but are constrained by their limited data transmission rates. This work introduces a novel wideband communication system utilizing dual-resonant MQS coupling, employing human-sized coils for multi-diver communication. The proposed system demonstrates a data rate of $\sim 30\ Mbps$ over a 70 cm range using single-turn 10 cm coils in seawater. Additionally, a larger 40 cm single-turn coil achieves a data rate of 10 $Mbps$ over a 1-$meter$ distance, showcasing the system's potential to overcome the limitations of existing near-field magnetically coupled systems.**

***Keywords*— Dual resonance, diver-diver underwater wideband communication, magnetoquasistatic (MQS) resonant coupling, near-field magnetic induction.**

I. Introduction

Underwater communication among divers on a mission to study ocean beds or perform defense operations becomes challenging due to the need for high-speed data transfer, handling bulky devices, or the high costs involved in installing new systems 300 feet underwater. The existing solutions as discussed in [1], [2], [3], include acoustic-based, which has a low data rate due to the speed of sound; optical-based, which is prone to interference due to the underwater ecosystem; RF-based suffers from a high signal attenuation due to the conductivity of seawater; and magnetic induction (MI) based systems have a limited bandwidth and data rate [4], [5]. However, magnetic field coupled systems experience lesser signal attenuation in highly conductive mediums, are more energy efficient, and are independent of the medium property as the relative permeability(μ_r) of seawater $\simeq 1$ [6]. Near Field MI (NFMI) based communication is a promising technique implemented by [7] and [8] but is limited by lower data rates.

This work proposes a wideband channel with human-sized dual resonant coils for multi-diver communication within 2 meters using MQS coupling [9] as shown in Fig. 1a. Contrary to the usage of narrowband resonance for WPTs, dual resonance enhances the system's bandwidth, leading to over tens of $Mbps$ data rate at a distance of over 60 cm. It is ensured that the system is MQS coupled as the decay in channel capacity reduces as a function of $1/r^3$ to $1/r^2$.

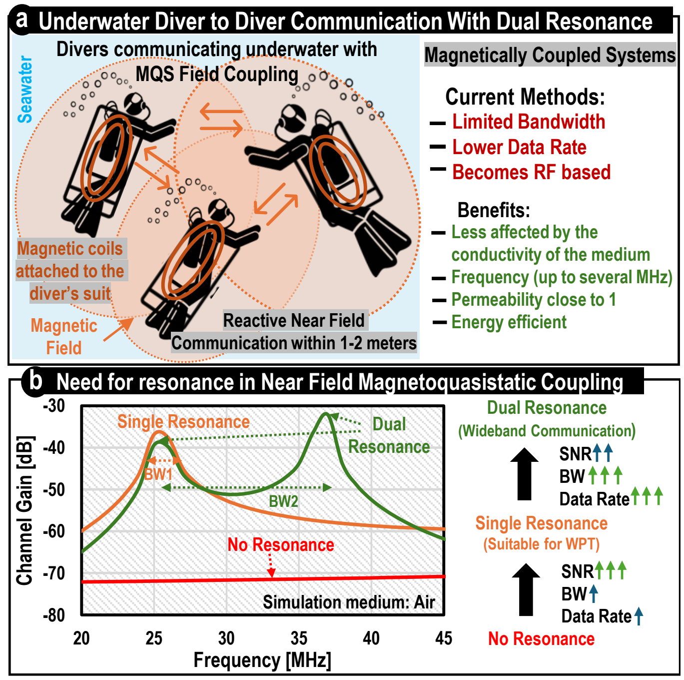

Fig. 1. (a) Multi-diver underwater wideband communication channel (b) Dual resonance in near-field MQS coupling.

A two-coiled system is simulated to observe the channel characteristics without resonance (no tuning capacitor), with single resonance (tuning capacitor at Tx), and with dual resonance (different tuning capacitors at Tx and Rx but closer resonant frequencies). Fig. 1b shows an increase of over 30 dB with resonance, while dual resonance increases the bandwidth by over five times, increasing the channel capacity. Using this benefit of dual resonance, a wideband communication channel is achieved to facilitate diver-diver communication under seawater. Fig. 2 compares this work against other MI-based underwater communication methodologies. Near-field coupling techniques for underwater communication have been widely used and have achieved promising results, but the focus of this work is to enhance the bandwidth and data rate of the near-field MQS coupled systems for short-range underwater communications.

II. Design Considerations

A. Device Size and Operation Frequency

For magnetically coupled coil systems, the transmitting and receiving coils should be in the near-field reactive region,

Comparison against the State-of-the-Art Underwater Communication Works

	[4]	[6]	[5]	[7]	[8]	This Work
Maximum Device Size	15 cm	10 cm with 20 turns	120 cm	-	0.375 cm	10 cm (Exp.) 40 cm (Sim.)
Application Scenario	Underwater Vehicles/ Robots	Underwater Vehicles/ Robots	Underwater Vehicles	NFMI	NFMI	Multi-diver comm.
Range	15 mm	< 1 m in seawater	1.5 m	2.7 m	1-2 m	Exp. 70cm; Sim. 110cm
Data Rate	-	-	9.6-115.2 kbps	600 kbps	600 kbps	30 Mbps (Exp.)
Frequency	150 KHz	10 MHz	600 kHz	13MHz	10.6MHz	1-45 MHz
Exp./ Sim./ Implementation	Exp.	Sim.	Exp.	ASIC	ASIC	Exp. (70 cm); Sim. (110cm)

Fig. 2. State of the art underwater communication works

which is determined by the frequency of operation. The near-field region is defined by $\lambda/2\pi$. To avoid the effects of radiation and for a system to be entirely magnetically coupled, the maximum length of the coils should be less than $\lambda/10$ while the intrinsic wave impedance E/H should be less than 377 $ohms$ [10]. Since the proposed system involves large human-sized coils, the frequency of operation should be lower for the devices, thereby increasing the near-field distance. Despite lowering the frequency to sustain near-field magnetic coupling, the channel's bandwidth, as shown in Fig. 3, is over 10 MHz. As the near-field distance increases with wavelength, the channel remains MQS coupled up to several meters while maintaining a high data rate.

Seawater's high conductivity increases eddy currents at higher frequencies, creating an opposite magnetic field that reduces the coupling efficiency between the coils [11]. Eddy current is a function of the penetration depth, $\delta = \eta(\mu, \sigma, f)$ [3] leading to signal attenuation in magnetically coupled systems in high conductivity mediums. For a few tens of MHz, the effect of eddy currents is negligible as seawater's $\mu_r \simeq 1$.

B. Coil Design for Dual Resonance

Simple wire loop inductor coils are designed with an inductance of L and tuned with a series capacitor C_x to form a series LC resonant circuit. Series LC resonance is chosen for maximum voltage transfer. To take advantage of dual resonance, the transmitter and receiver coils are tuned with different capacitors, C_{Tx} and C_{Rx}, but at a closer frequency, as shown in Fig. 3b. In the following sections, it is observed that the quality factors of the coils are reduced in conductive mediums such as seawater compared to when in air due to the eddy current losses. However, the dual-resonant peaks are still present, showing that the near-field coupling is still prominent. The coils have been designed to demonstrate the possibility of the proposed method and are not considered the most efficient, but good enough to be used as a proof of concept.

C. Simulation Setup and Analysis

Fig. 3 depicts the simulation model used for the analysis and feasibility of the dual-resonant MQS systems in Ansys' HFSS. The simulations are performed with air and seawater

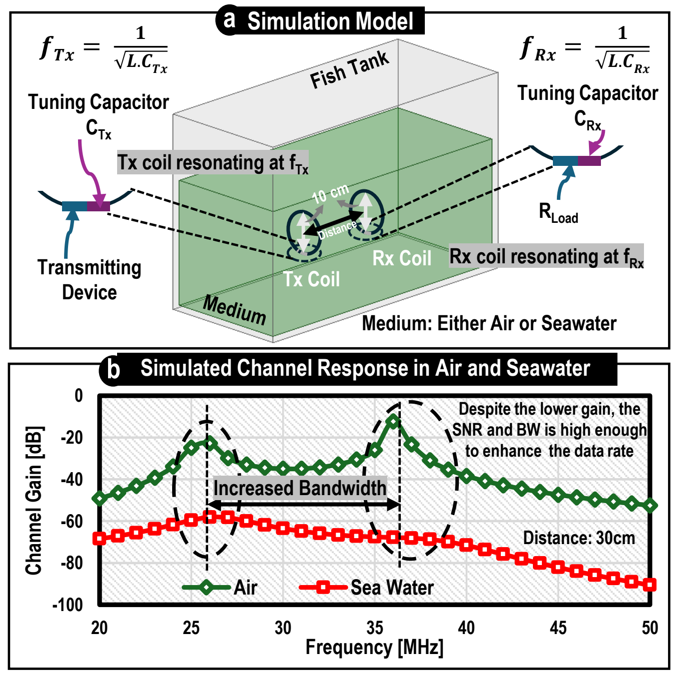

Fig. 3. (a) Simulation model to study the near field coupling between the coils in air and seawater (b) Channel response in air and seawater.

as the medium and large enough to accommodate the coils and demonstrate the near-field region. The Tx coil is excited by a sinusoid with a peak voltage of $1V$. Based on the chosen resonant frequency of f_{Tx}, a tuning capacitor, C_{Tx} is connected in series with the coil. Similarly, on the Rx coil, a capacitor C_{Rx} tuned at f_{Rx} is connected in series with a load resistor across which the received voltage is measured by calculating the line integral of the electric field. The design parameters are calculated and listed in Table 1. The coils in the simulations are considered to be fully aligned to demonstrate maximum coupling in the near field. However, misalignments are acceptable if the coils are placed in the near field [12].

Table 1. Design Parameters for Experiments

Parameter	Values
Tx, Rx Coil Diameter	10 cm
Coil Wire Length	30 cm
L_{Tx}, L_{Rx}	250 nH
C_{Tx}	150 pF
C_{Rx}	82 pF
f_{Tx}	35 MHz
f_{Rx}	26 MHz
λ	6-10 m
$\lambda/2\pi$	1-1.5 m
$\lambda/10$	60-100 cm

Fig. 3b shows the channel characteristics of the simulation setup with the medium as air and seawater. Strong coupling in the air with a peak channel gain of around $-20\ dB$ and reduced coupling in seawater with a channel gain of around

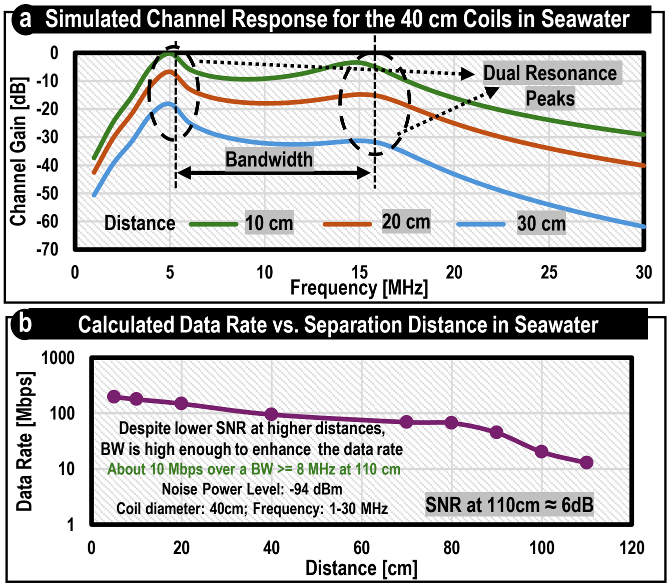

Fig. 4. Simulation Results (a) Channel characteristics (b) Channel capacity.

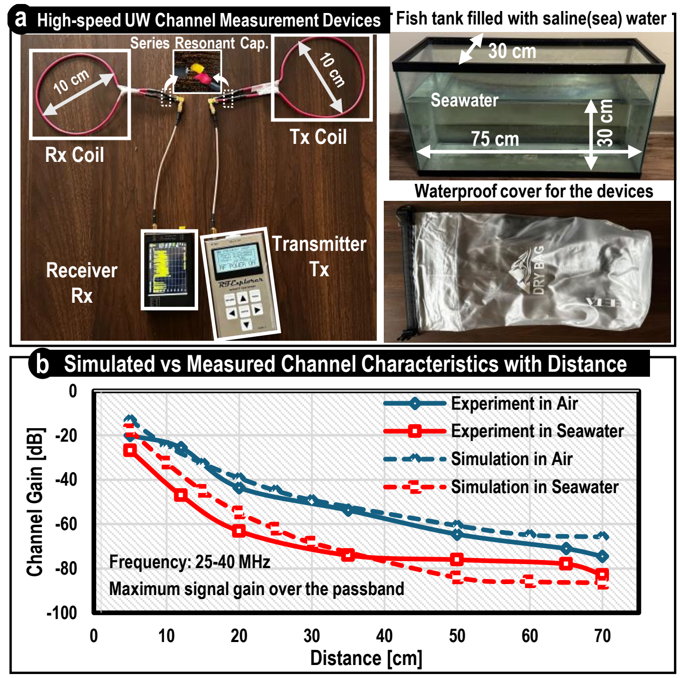

Fig. 5. (a) Test Setup to demonstrate MQS-based underwater communication (b) Simulated versus measured channel characteristics with distance.

$-60\ dB$ are observed with clear resonant peaks, indicating magnetic field coupling rather than far-field radiation. The increased eddy currents induced in the conductive medium at the optimal operating frequency exist as a tradeoff between enhanced MI coupling at higher frequencies and increased eddy current losses at higher frequencies.

D. Channel Capacity Achieved with a Larger Coil

To test for larger coils, the coil diameter in the model shown in Fig. 3a is increased to 40 cm, and the fish tank's dimensions are increased to facilitate the near-field region communication. The operation frequency is lowered to 30 MHz to ensure that the maximum dimension (coil wire length) is less than $\lambda/10$ for the system to be magnetically coupled. Fig. 4a shows the simulated channel response with distance. It is seen that the bandwidth of the system remains unaffected as the distance increases. The channel loss from the simulations has been calculated using the Shannon-Hartley theorem to calculate the theoretical data rate. Fig. 4b shows the data rate up to a distance of about 1 m. The SNR falls rapidly beyond 90 cm, decreasing the overall bandwidth. Dual resonance plays an essential role in maintaining the increased bandwidth of the system, improving the overall data rate. The coupling coefficient can be enhanced for a longer communication range with an increased coil size and number of turns.

III. Experiment Results

A. Experimental Setup

The proposed system to enhance the bandwidth of the underwater communication channel is demonstrated with single-turn small coils as a proof of concept, which would apply to large human-sized multi-turn coils for implementation. The coils are designed according to the dimensions used in the simulations, as shown in Fig. 5 with the design parameters mentioned in Table 1. Due to the addition of parasitics, the design parameters have been adjusted to achieve the desired resonant frequency. The designed coils are characterized and tested with the help of Vector Network Analyzer and found to have a parasitic capacitance of about 10 μF, ensuring the coil's self-resonance does not lie under the operating frequency band. The quality factors of the coils are measured to be over 10.

The seawater is prepared to achieve a salinity of 37 g/l to replicate the conductivity of seawater and is filled in a fish tank, as shown in Fig. 5a. To protect the devices (transmitter and receiver) and avoid electric field coupling, each coil and its respective device are separately placed in dry waterproof bags, which are then immersed in the fish tank for seawater measurements. The transmitter is held on one side of the tank while the receiver is moved away at distances, as shown in the plot in Fig. 5a. At every position, the receiver is held for a few minutes to capture the channel response for the continuous transmission of the signals over a frequency band $25-55$ MHz. Due to the upthrust of the water, the coils are not perfectly aligned with each other. For measurement in air, the coils have mostly been aligned perfectly, with the coils and the device well-insulated and fixed on a wooden table.

A handheld RF Explorer Signal Generator is used as the transmitting device while the receiver is a tinySA Spectrum Analyzer, as shown in Fig. 5a. The coils are connected with the help of SMA cables. The SMA connector on the coil's end is not perfectly matched and may cause reflections. Hence, the resonant capacitors are adjusted to lower the reflections at the expected resonant frequency. The observed trend aligns closely

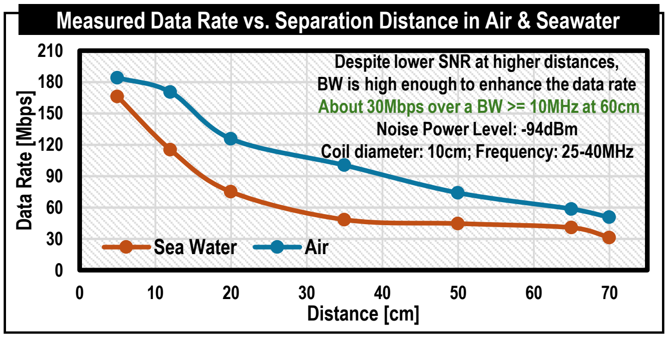

Fig. 6. Measured channel capacity versus distance in seawater and air.

with the simulation results.

B. Measured Channel Gain with Distance

The plot in Fig. 5b shows the measured variation of channel gain in air and seawater over distance and is seen to decay as a function of $1/r^3$ to $1/r^2$. It can be concluded that the system is magnetically coupled in the near-field region. The channel gain is reduced by $\sim 12\ dB$ due to the attenuation of the seawater and the limited quality factor of the coils. The measured results follow a similar trend in air and seawater. However, some variations in the experiment are observed as the coils are not perfectly aligned, reducing the coupling coefficient.

C. Communication Channel Capacity in Near Field Region

Fig. 6 shows the achieved data rate based on the measured loss in seawater. The data rate is calculated over a bandwidth of $10\ MHz$ with a receiver noise floor of $-94\ dBm$. A channel capacity of over $30\ Mbps$ is achieved at a distance of $70\ cm$ in seawater. The data rate in air is $\sim 15\ Mbps$ higher than in water due to signal attenuation in seawater and varied misalignments during experiments. Dual resonance enhances the system bandwidth in near field, leading to a high data rate communication channel with MQS field coupling.

IV. Conclusion

This work demonstrates a dual-resonant MQS coupled system for underwater multi-diver communication utilizing a compact, single-turn coil with a diameter of $10\ cm$. Through Finite Element Method (FEM) simulations in Ansys HFSS and experimental validation, it is shown that a data rate exceeding $30\ Mbps$ is achieved over a bandwidth of more than $10\ MHz$ at a distance of $70\ cm$ in seawater, which is within the near-field region of the coils. For implementation with larger, human-sized multi-turn coils, the coupling coefficient between the coils increases along with the increase in the near-field region. Within this near-field region, similar data rates can be maintained over greater distances, facilitating underwater diver-to-diver communication at ranges of 1 to 2 meters. While the design and analysis of larger multi-turn coils are beyond the scope of this study, theoretical evaluations and simulations of single-turn coils with a $40\ cm$ diameter indicate a data rate of approximately $40\ Mbps$ over a $10\ MHz$ bandwidth at a distance of $90\ cm$ under dual-resonant conditions.

Acknowledgement

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References

[1] Y. Li, S. Wang, C. Jin, Y. Zhang, and T. Jiang, "A survey of underwater magnetic induction communications: Fundamental issues, recent advances, and challenges," *IEEE Communications Surveys Tutorials*, vol. 21, no. 3, pp. 2466–2487, 2019.

[2] M. Muzzammil, N. Ahmed, G. Qiao, I. Ullah, and L. Wan, "Fundamentals and advancements of magnetic-field communication for underwater wireless sensor networks," *IEEE Transactions on Antennas and Propagation*, vol. 68, no. 11, pp. 7555–7570, 2020.

[3] A. M. Bamhdi, "Underwater magnetic induction communication range enhancement survey and comprehensive evaluation.," *International Journal of Advances in Soft Computing & Its Applications*, vol. 16, no. 2, 2024.

[4] T. Luo and S. Zhang, "Design of underwater wireless power transmission system based on inductive coupling," *Journal of Marine Science and Engineering*, vol. 11, no. 9, p. 1699, 2023.

[5] G. Canales-Gómez, G. León-Gónzalez, N. Jorge-Muñoz, J. H. Arroyo-Núñez, E. D. Antonio-Yañez, and R. S. Núñez-Cruz, "Communication system based on magnetic coils for underwater vehicles," *Sensors*, vol. 22, no. 21, p. 8183, 2022.

[6] I. F. Akyildiz, P. Wang, and Z. Sun, "Realizing underwater communication through magnetic induction," *IEEE Communications Magazine*, vol. 53, no. 11, pp. 42–48, 2015.

[7] AudioXpress, "Near-field magnetic induction (nfmi): Dreams of wireless hearables." Accessed: 2024-12-04.

[8] F. Electronics, "Near-field magnetic induction (nfmi)," 2017. Accessed: 2024-12-04.

[9] M. Nath, A. K. Ulvog, S. Weigand, and S. Sen, "Understanding the role of magnetic and magneto-quasistatic fields in human body communication," *IEEE Transactions on Biomedical Engineering*, vol. 69, no. 12, pp. 3635–3644, 2022.

[10] C. A. Balanis, *Antenna theory: analysis and design*. John wiley & sons, 2015.

[11] T. S. Pham, T. D. Nguyen, B. S. Tung, B. X. Khuyen, T. T. Hoang, Q. M. Ngo, L. T. H. Hiep, and V. D. Lam, "Optimal frequency for magnetic resonant wireless power transfer in conducting medium," *Scientific Reports*, vol. 11, no. 1, p. 18690, 2021.

[12] N. Golestani and M. Moghaddam, "Theoretical modeling and analysis of magnetic induction communication in wireless body area networks (wbans)," *IEEE Journal of Electromagnetics, RF and Microwaves in Medicine and Biology*, vol. 2, no. 1, pp. 48–55, 2018.