LOW LATENCY UNDERWATER COMMUNICATIONS USING MAGNETIC INDUCTION

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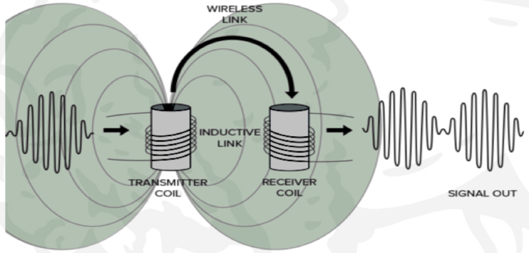
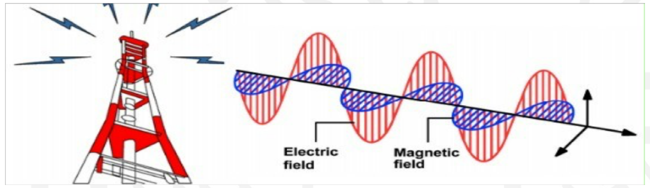
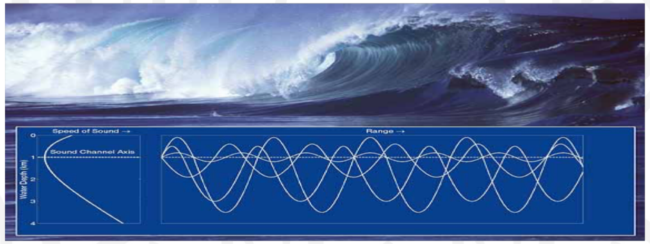
Comparison of Underwater Communication Paradigms

Communication Paradigm	Propagation Speed	Coverage Ranges	Channel Dependency	Stealth Operation
Magnetic Induction (MI)	3.33 x 10^7 m/s	~10^0 m	conductivity	yes
Electromagnetic (EM) Waves	3.33 x 10^7 m/s	~10^0 m	conductivity, multipath	yes
Acoustic Waves	1500 m/s	~10^3 m	multipath, Doppler, temperature, pressure, salinity, ambient sound noise	audible
Optical Rays	3.33 x 10^7 m/s	~10^1 m	light scattering, line of sight, ambient light noise	visible

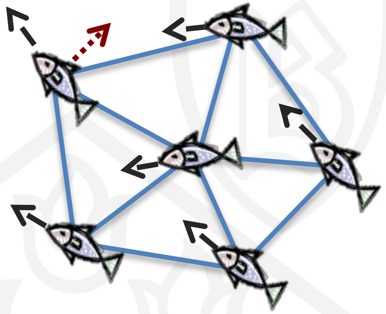






MI-based Underwater Communications

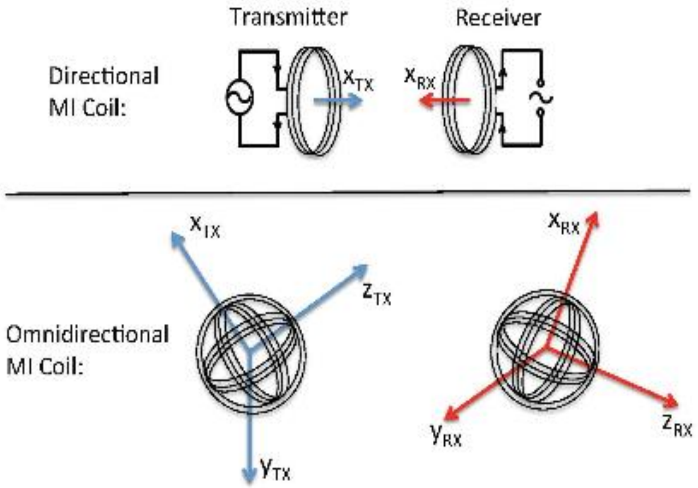
- We have been using MI technique to establish low latency and reliable communication among robots in underwater robotic swarm. (NSF CNS-1446484, targeting at river and lake water environments)
- Pros:
  - **Negligible propagation delay** – Favorable for real time control
    - PHY layer synchronization is simple and reliable due to the negligible delay and the stable channel
  - Predictable and stable channel conditions
    - No multipath fading, no scattering, no Doppler effect
  - Low power consumption, stealth underwater operations
- Cons:
  - **Directional coverage**
    - The axial direction of TX and RX coils gets strongest signal
    - No induced signal if RX coil is perpendicular to TX coil
  - **Limited communication range** due to inefficient transmitting and receiving
    - Large wavelength (tens of meters) vs Small underwater devices (tens of centimeter)

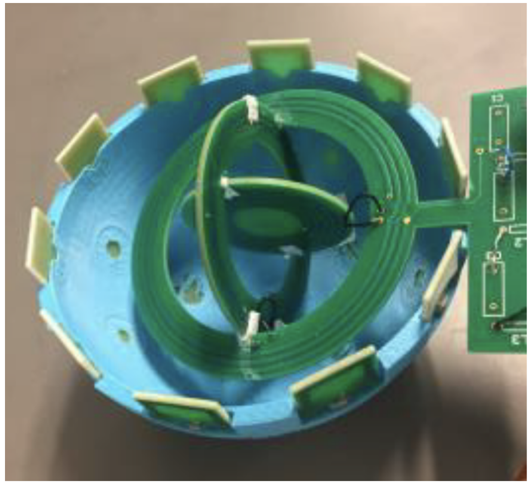


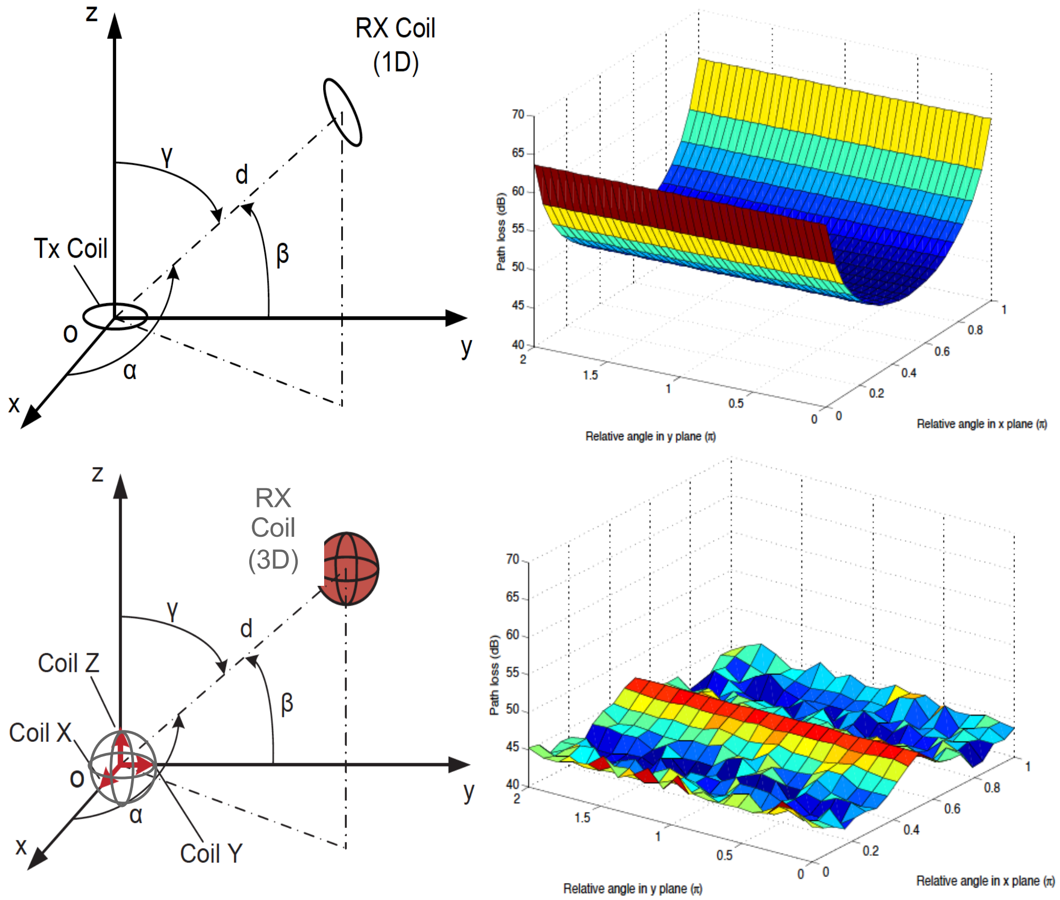
Z. Sun and I. F. Akyildiz, "Magnetic Induction Communications for Wireless Underground Sensor Networks," IEEE Transactions on Antenna and Propagation, 2010.

I. F. Akyildiz, P. Wang, and Z. Sun, "Realizing Underwater Communication through Magnetic Induction", IEEE Communications Magazine, 2015.

Addressing the Directional Issue







- MI antenna with 3 orthogonal coils
  - Omni-directional communications
  - Enhanced received signal strength
  - Can be used for 3D localization

Pathloss independent of relative locations between underwater nodes

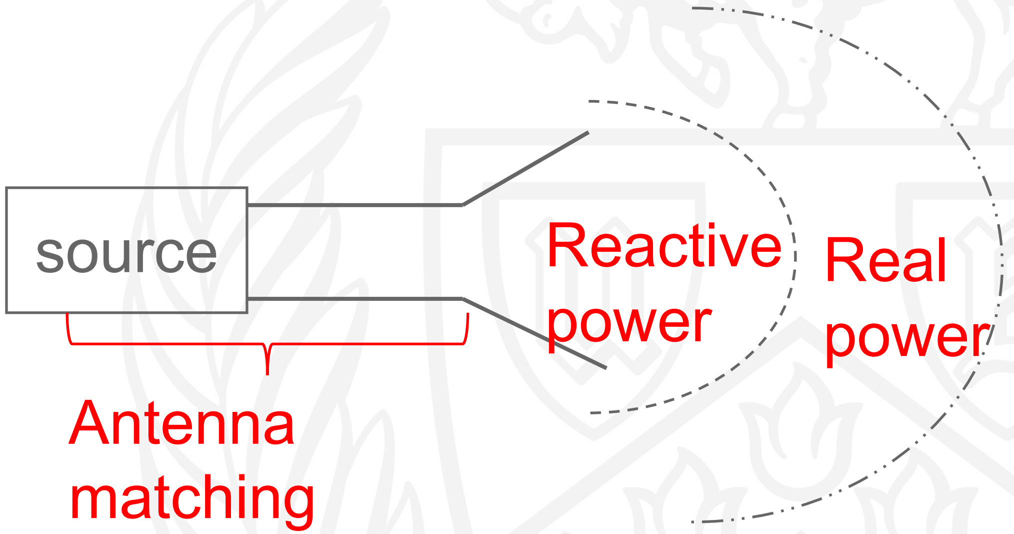
Addressing the Short Communication Range Issue

- MI signal penetrates lossy medium (e.g., water) more efficiently.
- The power of the Magnetic field in the near field attenuates much faster than the propagating EM waves ($1/r^2$ vs $1/r^6$).
- Hence, existing MI techniques utilize very large coil antennas (6 m in diameter) to mitigate the high attenuation rate problem.

Why Current MI Coil Antenna is not Efficient?

- Most of the power radiated by the antenna is reactive which cannot propagate.
- For an electrically small antenna

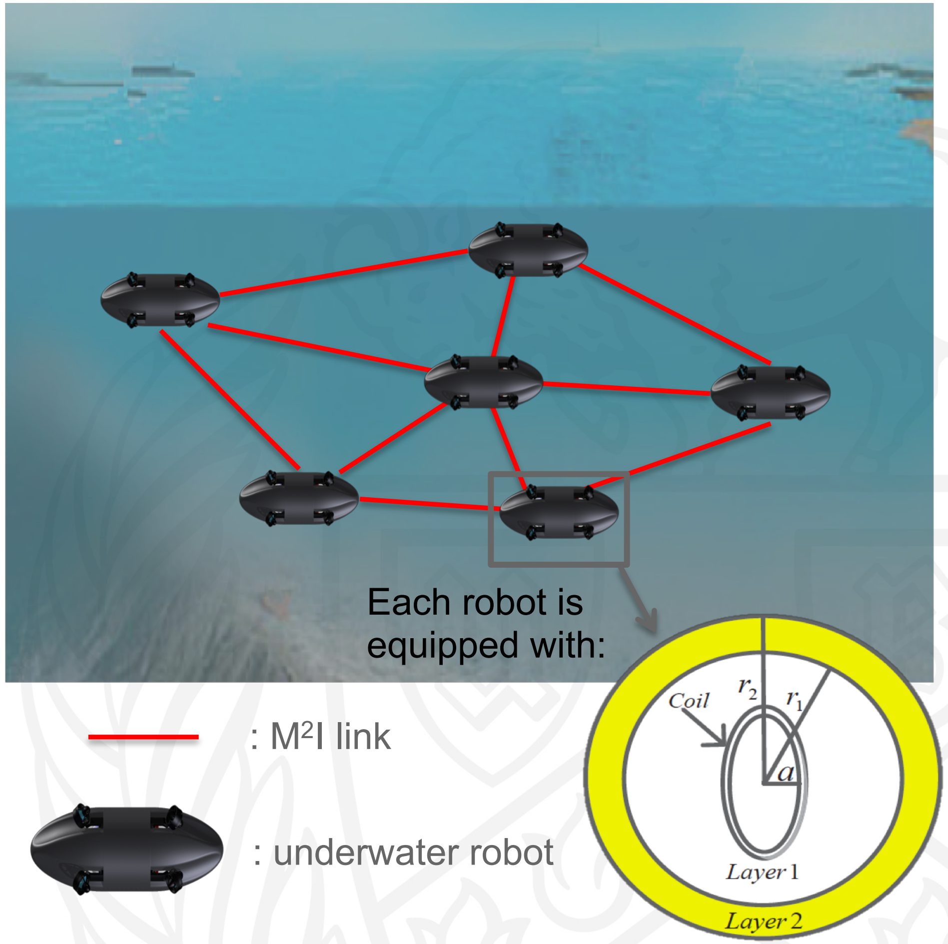
$$\frac{\textit{reactive power}}{\textit{real power}} \approx \frac{1}{(ka)^3}$$



Objective: reduce reactive power and increase radiated power.

Our Solution: Metamaterial-enhanced MI

- We need to design and fabricate the ultra-compact metamaterial enhanced antennas.
- We propose to use a metamaterial sphere to enclose the coil antenna to create an omnidirectional structure:
  - The 1st layer is a sphere with radius r_1.
  - The 2nd layer is metamaterial with radius r_2.
  - The underwater environment outside the sphere is regarded as 3rd layer.
  - The TX coil with radius a is located at the center.



Metamaterial-enhanced magnetic induction (M2I) transceiver

H. Guo, Z. Sun, J. Sun, and N. M. Litchinitser, "M2I: Channel Modeling for Metamaterial-Enhanced Magnetic Induction Communications", IEEE Transactions on Antennas and Propagation, Vol. 63, No. 11, pp. 5072-5087, November 2015.

Zhi Sun, “Low Latency Underwater Communications using Magnetic Induction”, 2018 NSF Workshop on Underwater Wireless Infrastructure (UWI), 11/5/2018.

Theoretical Foundation of M²I

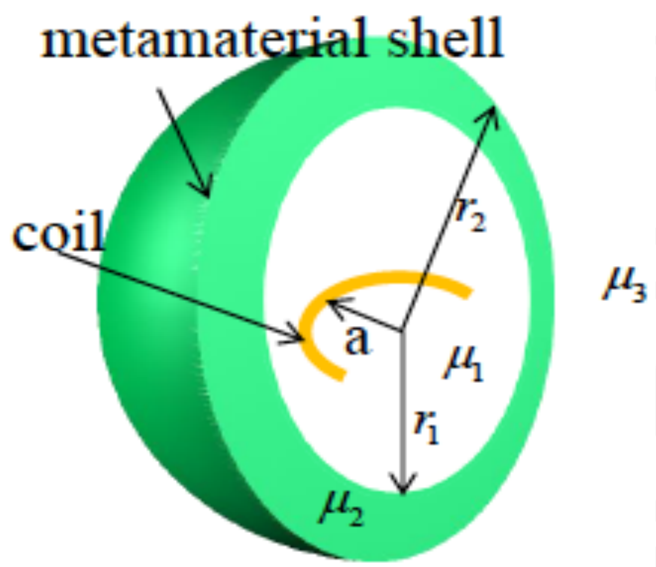
- A spherical shell with ideally isotropic and homogeneous negative-permeability metamaterial is utilized to surround a coil antenna.

- Mutual inductance $M_0 = \frac{\mathcal{F}_1}{\bar{S}_m}$, where

$$\bar{S}_m = \mathcal{F}_2 \left[2r_1^3(\mu_1 - \mu_2)(\mu_3 - \mu_2) - r_2^3(2\mu_2 + \mu_1)(2\mu_3 + \mu_2) \right]$$

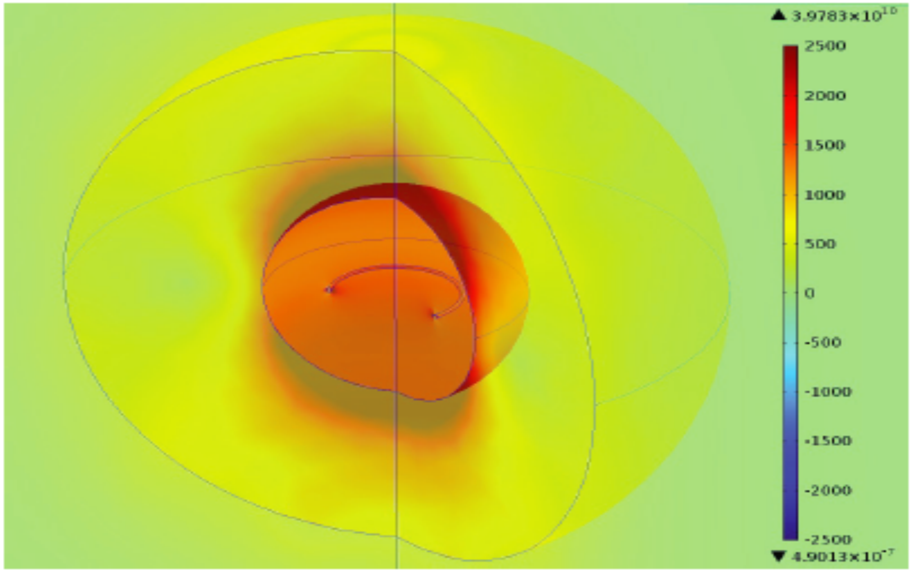
- The second item of $\bar{S}_m$ can be designed to be 0, then, the mutual inductance can be maximized.

- $\mu_3 = 1, \mu_1 \geq 1.$ Only if $\mu_2 < 0,$ $\bar{S}_m$ can be minimized.

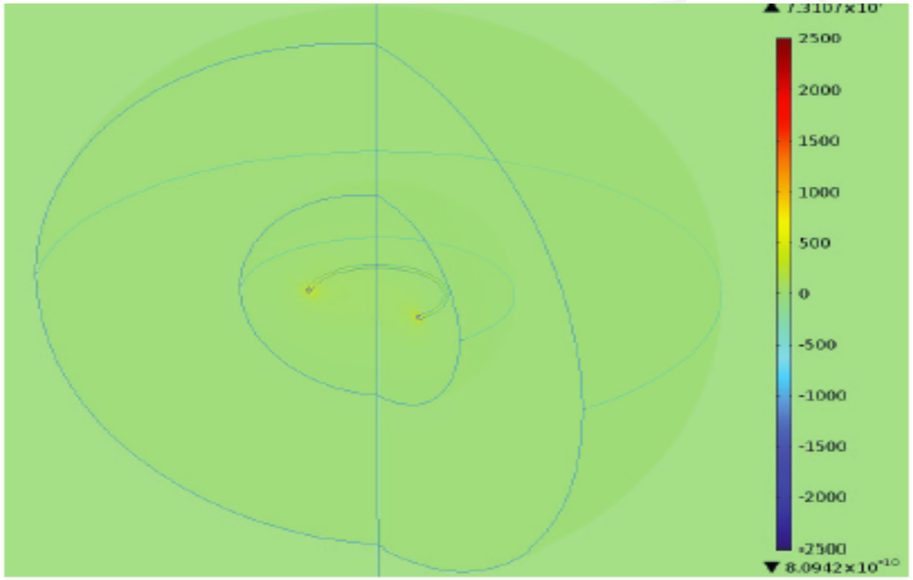


Theoretical and Simulation Results

TX end simulations



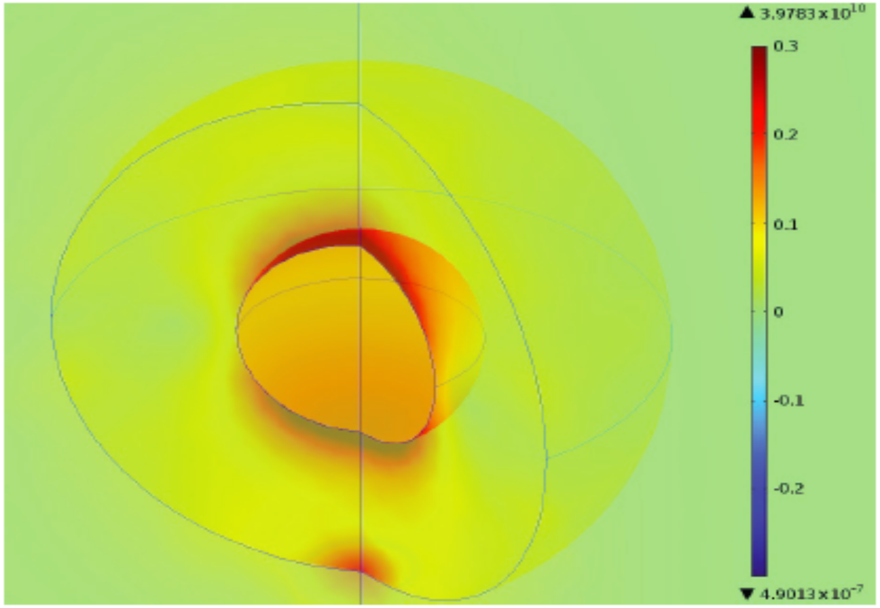
(a) Magnetic field with metamaterial ($\mu = -1, \epsilon = -1$).



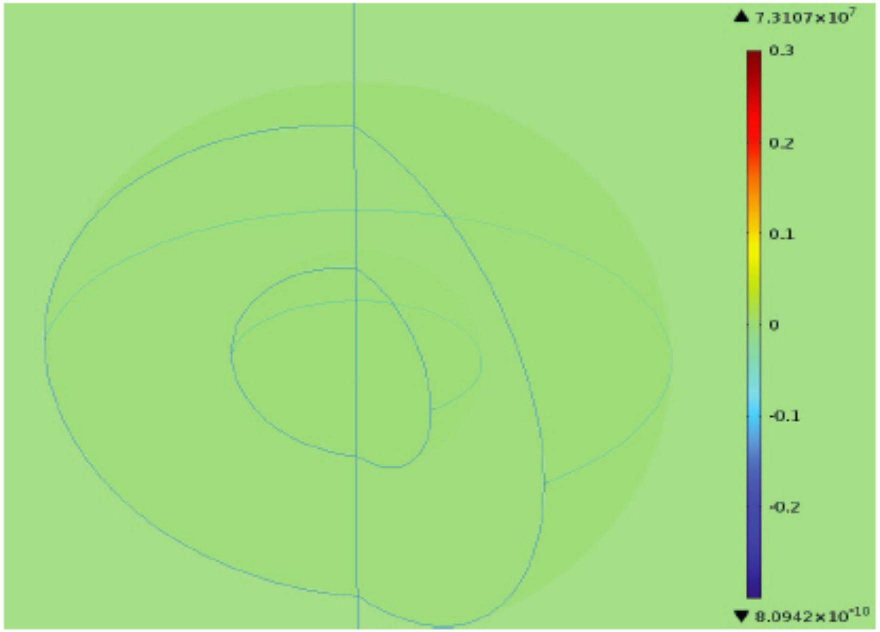
(b) Magnetic field without metamaterial ($\mu = 1, \epsilon = 1$).

Theoretical and Simulation Results

RX end simulations



(a) Magnetic field with metamaterial ($\mu = -1, \epsilon = -1$).



(b) Magnetic field without metamaterial ($\mu = 1, \epsilon = 1$).

M^2I: From Theoretical Modeling to Practical Design

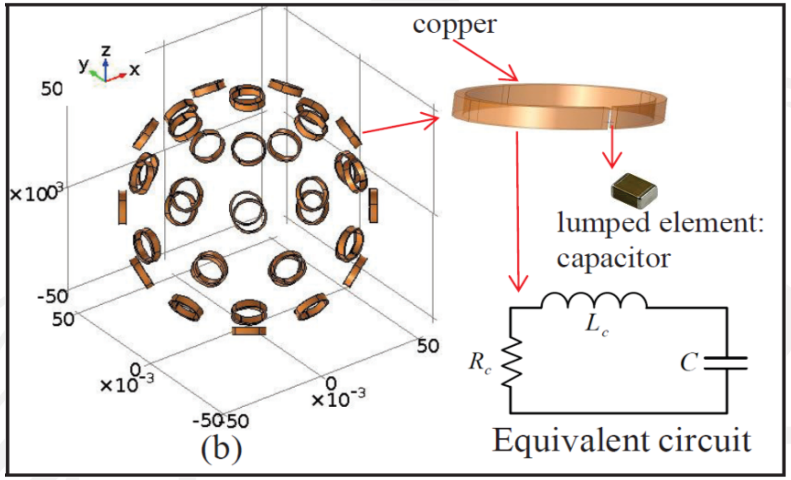
- Theoretical modeling
  - Ideal metamaterial: homogeneous, isotropic, negative permeability, no loss;
  - Not exist in nature
- Practical design
  - Use existing antenna structure
  - Design negative permeability material in spherical shape
  - Find optimal configurations: antenna size, frequency, etc
  - Compare practical design with ideal theoretical M^2I

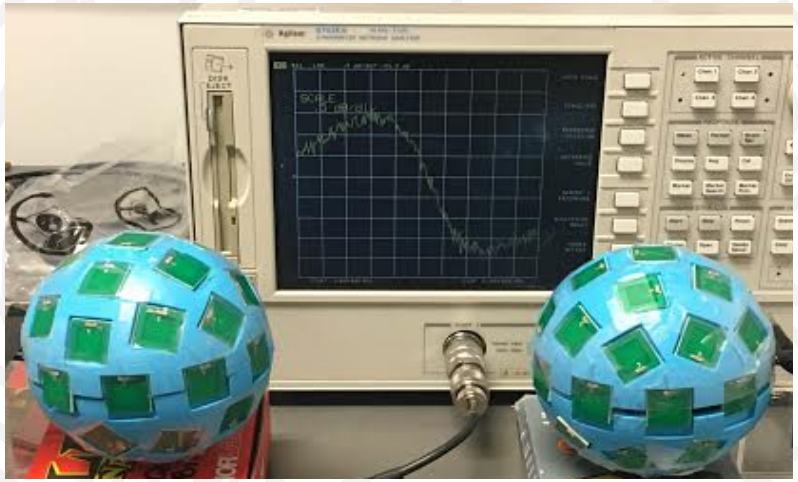
H. Guo and Z. Sun, "M^2I Communication: From Theoretical Modeling to Practical Design", IEEE ICC 2016, Kuala Lumpur, Malaysia, May 2016.

H. Guo, Z. Sun, and C. Zhou, "Practical Design and Implementation of Metamaterial-Enhanced Magnetic Induction Communication", IEEE Access 2017.

Spherical Shell

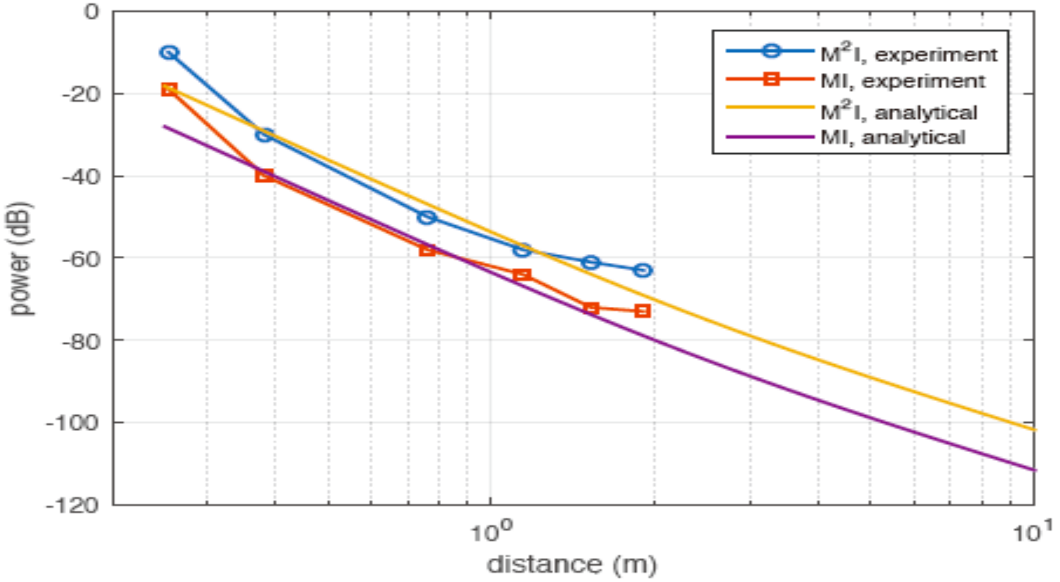
- Pentakis icosidodecahedron: divide a sphere into 42 vertices uniformly; each vertex is the center of a coil.
- A lumped capacitor is used to adjust the coils’ frequency.
- Recent work: 3D printed sphere & printed coil on PCB.

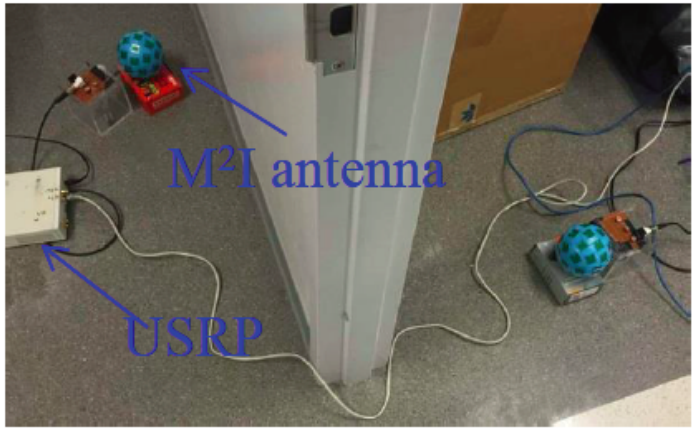




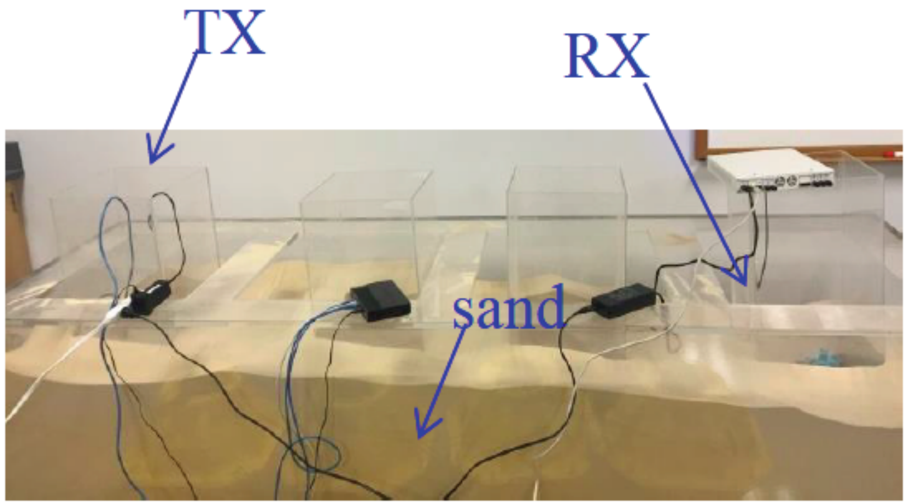
In-lab Experiments

- Test through-the-wall and wet sand environments.
  - Not in underwater yet
- Achieves tens of meters communication range with 10 cm spherical antenna.





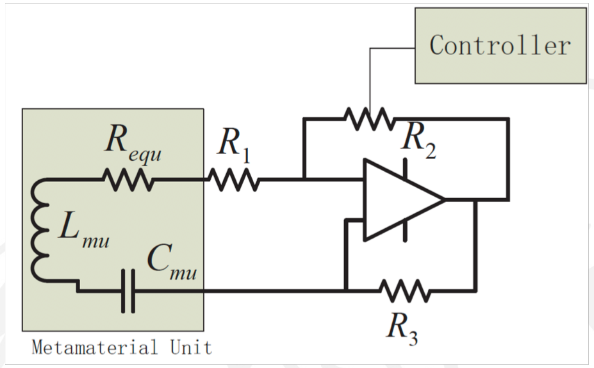
(a) Indoor

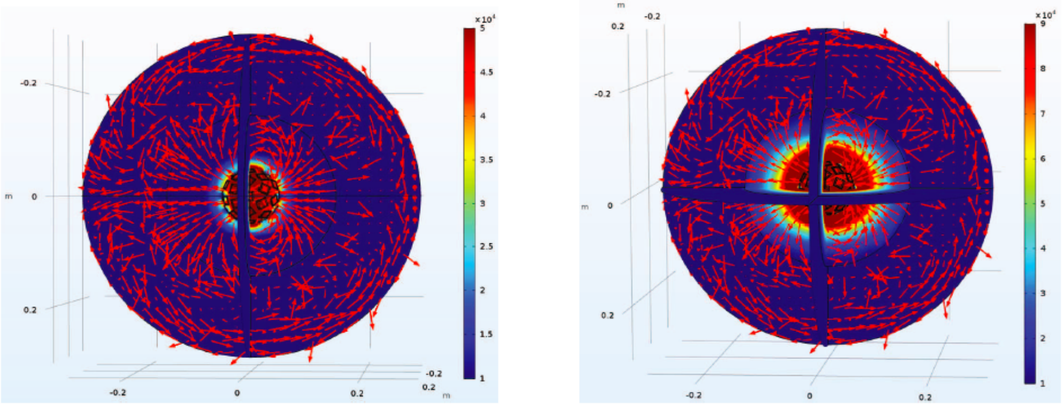


(b) Underground

Active M2I Transceiver Design

- Instead of the 30 dB theoretical prediction, the current practical M^2I implementation only achieves 8 dB enhancement.
  - The key reason of the gap is the metamaterial loss.
  - Caused by the resistance of the meta-unit, i.e., the coil on the spherical array.
- We introduce the active metamaterials and optimally design the coil array structure to realize the predicted performance.
- Use negative resistance to compensate metamaterial loss.
  - Negative impedance converter (NIC) creates negative resistance.





(a) Passive practical M^2I system (b) Proposed active M^2I system

H. Guo and Z. Sun, "Full-duplex Metamaterial-enabled Magnetic Induction Networks in Extreme Environments", IEEE Infocom 2018.

Z. Li and Z. Sun, "Optimal Transceiver Design for Active Metamaterial-enhanced Magnetic Induction Communications", submitted for conference publication, 2018.

Conclusion

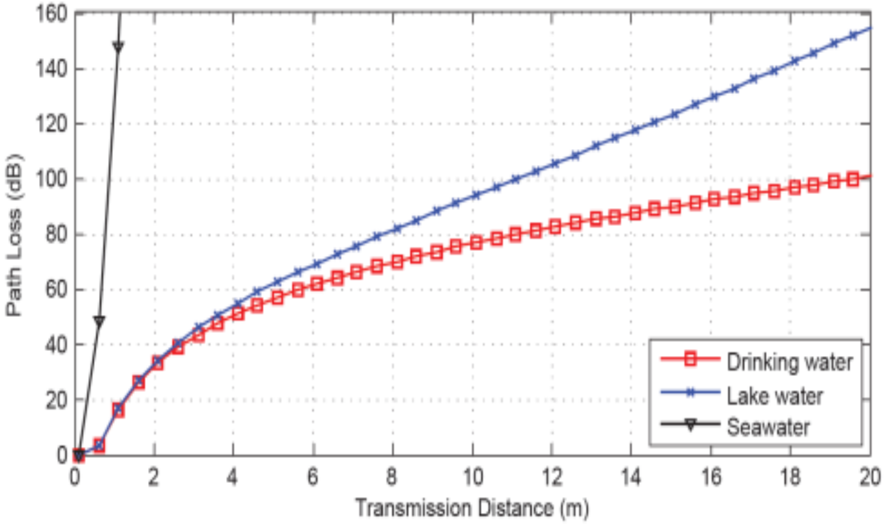
- We discuss feasibility to use MI technique to establish low latency and reliable communications among underwater robotic swarm in lakes and rivers.
- We introduce the metamaterial enhanced magnetic induction (M^2I) communication.
  - Increase the data throughput and communication range while keeping the device size small.
  - Theoretical modeling and understanding.
  - Design a spherical coil array to realize the theoretical M^2I

THANK YOU

Path Loss in Different Underwater Environments

Antenna configuration	Operating Frequency	Operating environments
10 cm radius 20 turns of AWG26 wire	10 MHz	(1) Seawater with conductivity 4 S/m
		(2) Lake water with conductivity 0.005 S/m,
		(3) Drinking water with conductivity 0.0005 S/m.

- Small node can achieve 20 m and 10 m range in Case 3 and 2, but less than 1m range in Case 1.
- High conductive seawater induces significant Eddy current incurring very high path loss.



H. Guo, Z. Sun, and P. Wang, "Broadband Channel Modeling and Analysis for Magnetic Induction Communication in Practical Underwater Environments", IEEE Transactions on Vehicular Technology, Vol. 66, No. 8, pp. 6619-6632, August 2017.