Plasmonic - Surface Electromagnetic Wave Communication for subsea asset inspection

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Plasmonic - Surface Electromagnetic Wave Communication for subsea asset inspection

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Abstract— **Underwater wireless communications able to support real-time teleoperated tools and robotics remain a challenging topic and one of great interest for many marine applications. The use of Plasmonic-Surface Electromagnetic Waves (P-SEW) has been assessed for providing low latency, high bandwidth connectivity to Unmanned Underwater Vehicles (UUVs) for inspection of subsea assets. The evaluations show that as the through-water communication distance increases the dominant transmission path will tend toward surfaces where a conductivity mismatch exists, such as the sea surface or a metal structure. Considering this behavior, the team has identified application cases that benefit from the transmission characteristics and utilize this to support low latency, high data rate communication to devices on and around submerged assets. This P-SEW approach is promising for increased penetration ranges through seawater at the lower Radio Frequency (RF) bands, and this paper proposes a stepwise evaluation, considering the opportunities for use of higher frequency P-SEW communications on and around submerged assets and infrastructure, such as toward inspection vehicles and sensors.**

Keywords: Plasmonic Surface Electromagnetic Waves, Underwater Communication, Subsea Infrastructure

I. INTRODUCTION

Underwater wireless communication solutions are typically based on acoustics, RF, magneto-inductive, or optical modulation techniques. These technologies offer a diverse range of capabilities, but as discussed in [1], we find that no one solution is able to provide high data rates, long range, and low latency. As such, wireless communication to support teleoperated tools and robotics in seawater remains a challenge, often resulting in the need for more advanced decision-making capabilities on the robot or the use of an umbilical where real-time control and feedback is required.

In this paper we consider the emergence of an alternative approach, referred to as Plasmonic-Surface Electromagnetic Wave (P-SEW) communication, operating at radio frequencies. Plasmons can be described as surface charge oscillations found at the interface between materials with different dielectric properties, such as along a metal-to-air interface or seawater-to-air interface. The plasmonic antennas are specifically designed to create the right conditions to excite such surface plasmons at defined radio frequencies, which in turn create charge density waves in the electrically charged particles along the surface, at the same frequency as the incident waves. This phenomenon has typically been applied up in the visible frequency band, at 400 - 700 THz [2]. At these higher frequencies it is known that the plasmonic surface waves quickly attenuate and so signal propagation ranges are restrictive (cm range), but at RF frequencies the propagation ranges increase [3].

We describe ongoing evaluation work which is being conducted to determine the suitability of P-SEW for various underwater communication applications, with testing conducted in various environments and applications from 50 MHz up to 2.45 GHz, often referred to as VHF and UHF. The paper focuses on P-SEW communications operating at these frequencies for direct penetration through seawater [3], and considers how underwater infrastructure can act acting as a conduit, extending the communication range when such structures are present [4], hence supporting new use cases and applications.

This study has been built upon work conducted by Saltenna, where through-water communications using P-SEW antennas operating at various radio frequencies in open water conditions were evaluated and tested [5]. As part of this earlier work, Saltenna considered that the transmission paths for the surface electromagnetic waves tend toward the seawater-to-air interface, rather than the direct point-to-point path through the seawater. The conclusions from the theoretical and experimental testing results reported in [5] gave evidence that P-SEW operating at radio frequencies provide communication links over far greater ranges than conventional free-space antennas, based on calculated attenuation associated with the relatively short skin depth for a conductive medium, such as steel or seawater.

For a P-SEW signal, the increased penetration range relative to the skin depth of the medium is only part of the story as the signal also travels along interfaces, such as the dielectric interface of seawater to air, or seawater to steel. The transmission distance along such surfaces is far greater than that of the penetration depth through the seawater alone. This expands the potential coverage of higher frequency transmissions around such structures, rather than being screened or blocked by them, as would be expected for free-space radio waves.

The increase in penetration depth and the propagation along any conductivity interfaces allow P-SEW signals to offer low latency, high bandwidth connectivity from the surface to control a network of unmanned underwater vehicles (UUVs) near an asset, as illustrated in Fig. 1.

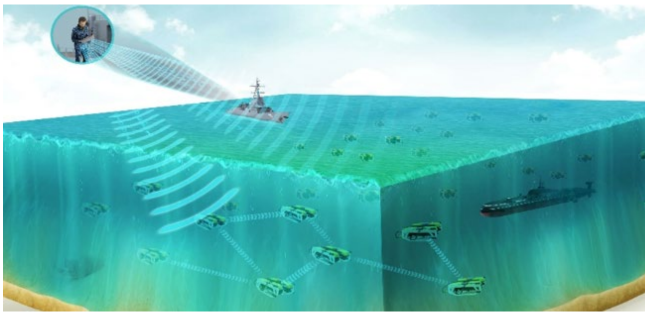

Fig. 1 Unmanned Underwater Vehicle Network Concept

II. P-SEW TECHNOLOGY

The P-SEW antennas developed by Saltenna are designed such that they provide enhanced penetration depth performance compared to conventional state-of-the-art free space antenna configurations. The antenna design enhances the field strength at the tip of the antenna, which in turn is able to excite plasmonic surface electromagnetic waves on structures where a conductivity mismatch exists between two surfaces, such as metal-to-air interfaces. These forced oscillations in the charged particles create the charge density waves [4] which then travel along such surfaces or discontinuities.

Communication along the interface between the seawater and air has been evaluated previously in [3]. The predicted performance over the surface of the sea (propagation length) and through seawater (penetration depth) have been described in Table I, modeled based on a flat sea surface with a transmitter power of 10 Watts [5].

A. Comparison to the state of the art

When comparing the P-SEW to existing free-space RF solutions, we need to consider primarily the penetration depth, as this is the direct through-water path. The surface wave propagation length along an interface, such as the sea surface shown in Table I, is considered in the later sections and future work.

Table II provides details of some of the existing 'state of the art' RF based underwater wireless solutions, allowing for a comparison of the technologies. Evaluation of the two tables shows that P-SEW can provide significant advantages in penetration depth through seawater with lower relative transmit power levels.

In Table II the maximum penetration depth achievable is between 40 m and 100 m, however, these are both at data rates below 100 bps. In comparison, the P-SEW penetration depth at 20 kHz will exceed 72 m with Tx powers of 10 W or greater. A data modem operating with a 20 kHz carrier frequency would be able to support data rates well into the kilobit per second range. As a point of reference, acoustic systems operating at 20 kHz could also achieve data rates up to 6 kbps [10], but acoustics would have a larger latency and reduced performance near structures or the surface.

The ELF and VLF solutions send signals to submarines all around the world, as well as penetrating to 100 m in depth. These low frequency, low data rate systems can penetrate deep underwater, but are only one-way links, due to the large land or air deployed antennas and significant power requirements of up to 1.2 Megawatts [11]. In comparison, the P-SEW waves described in Table I are operating at significantly lower power levels. These will also propagate a significant distance along the sea surface, benefiting from the surface propagation along the seawater-to-air interface. The eventual through-water penetration depth will be determined by the Tx power at the point of insertion.

The advantages of P-SEW over the free-space RF are not only this increased penetration depth, as seen at 20 kHz, but we also see that any infrastructure becomes a low loss conduit increasing the reach of the P-SEW transmission at higher frequencies too. This opens further sensing and control opportunities on and close to such structures. The higher frequency signals can also penetrate the structures, as the surface waves will pass through flanges and couplings. The following experiments and test data sets help us start to evaluate these opportunities with the ambition to run subsea tests on submerged infrastructure in the future.

TABLE I. PROJECTED ENVELOPE FOR P-SEW PROPAGATION AND PENETRATION OF SEAWATER, NO INFRASTRUCTURE

Carrier Frequency	**Tx Power 10 W**	
	Propagation Length	***Penetration Depth***
20 kHz	10 km +	72 m
100 kHz	10 km +	30 m
2 MHz	10 km +	7 m
50 MHz	190 m	1.4 m
2.45 GHz	4 m	0.2 m

TABLE II. EXISTING UNDERWATER RF TECHNOLOGIES

Technology	***Carrier Frequency***	***Penetration Depth***	***Data Rate Tx Power***
Submarine Signaling ELF (Land to sea, simplex) [11]	3 – 300 Hz	100 m	1 bps 1.4 MW
Seatooth S400 [8][1][13]	~ 1 kHz	40 m	10 bps 25 W
Submarine Signaling VLF (Land to Sea, simplex) [11][1]	3 – 30 kHz	20 m	300 bps 2 kW
Seatooth S300 [8][14]	Undeclared	5 m	25 kbps 15 W
CoSA EF Dipole [1]	Undeclared	8 m	200 kbps Undeclared
INESC TEC Dipole [12]	Undeclared	1 m	1 Mbps undeclared
Seatooth S500 [8][14]	Undeclared	0.4 m	10 Mbps undeclared
IFRAMER WiFi [15] / CoSA Wifi [1]	2.4 GHz	0.1 m	20 Mbps 100 mW

B. Underwater Tests conducted

Fig. 2 shows 50 MHz tests conducted in a freshwater lake and a chlorinated swimming pool. The maximum depth and separation distances are marked on the pictures. Results of these tests may be scaled to estimate the performance of P-SEW links in seawater using the known skin depth in freshwater and chlorinated water at the communication frequencies used.

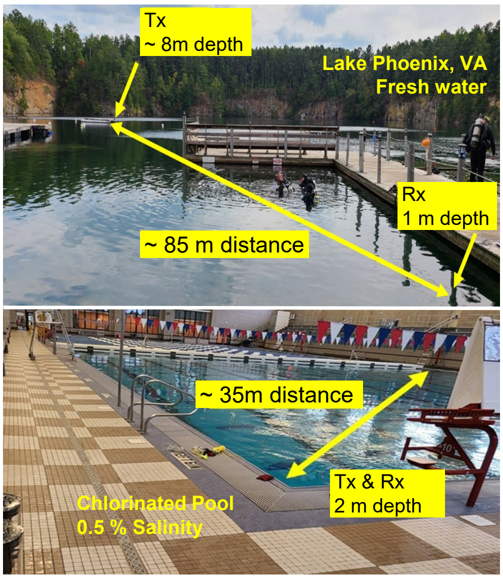

Fig. 2 Testing of 50 MHz, 5W Tx power radios in a freshwater lake and chlorinated pool. Voice communication link (Audio).

The P-SEW antennas were housed in pressure-balanced de-ionized water-filled chambers, for impedance matching and to accommodate pressure changes [3]. This ensured that the antenna resonance frequencies were not altered by the environmental conditions. The communication connection was established using P-SEW antennas attached to 5W Tx power, 50 MHz RF modems (Yaesu VX-8R radios). The communication was established using divers to press the transmit button when submerged.

The skin depth of the fresh water at 50 MHz is estimated to be 40 cm, which would result in an expected communication penetration depth of approximately 10 m. The depth achieved in the freshwater case was limited due to dive equipment, with the diver only able to submerse to 8 m, with the other modem at 1 m depth and 85 m separation between the two.

The salinity in the swimming pool was tested at 0.5%, which related to a skin depth of 10 cm at 50 MHz. This compares to 3.5% in seawater with a 4 cm skin depth and a predicted penetration depth of 1.4 m.

In both cases the measured range of the communication path far exceeds the predicted penetration distance, with the separation between the modems in the freshwater case exceeding 85 m and over 35 m in the chlorinated pool, indicating that propagation along the interface at the water's surface or the seabed influenced the test.

C. *Structucture-borne P-SEW tests*

The testing shown in Fig. 3 was conducted to see how the P-SEW antennas would perform on typical structures and materials found in underwater applications. The figure shows the testing on a decommissioned submarine, with a 10 W Tx power, Wi-Fi video transmitter connected to a 2.45 GHz P-SEW antenna placed outside of the pressure hull, within the submarine's sail (in the vicinity of the Conning Tower). The transmitter can be seen in the top right image of Fig. 3.

The received Wi-Fi video was picked up at various locations throughout the 95 m long submarine pressure hull, using a P-SEW antenna connected to a regular Wi-Fi video receiver which displayed the images on a video screen. The bottom right picture shows the monitor with the images received from the IP camera. If no signal was picked up, then the monitor would display the text 'no signal' on a blue screen.

The test demonstrates the capability to transmit video signals into the compartments within the pressure hull of the submarine which conventional free-space signals were not able to penetrate. Propagation distances were not recorded during this test due to the complex potential paths through the submarine structure.

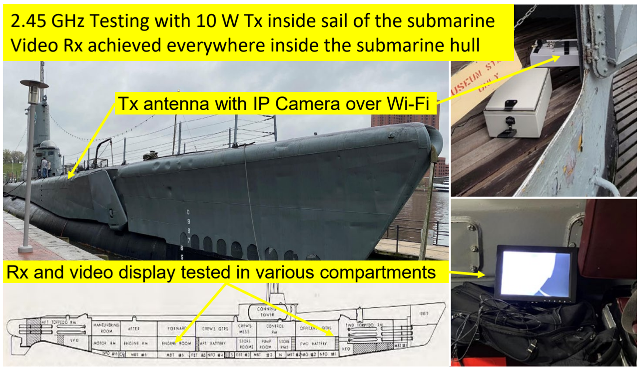

Fig. 3: Transmission throughout a submarine pressure hull

Table III summarizes the results from structure-borne and through-water tests. At the time of writing, the structure-borne testing is only for in-air conditions, with submerged tests planned. The submarine hull data has not been included, again due to the complexity of the paths.

The hyperbaric chamber and flanged pipe tests captured the P-SEW capability to transmit through structures that would block conventional free-space RF signals. The -90 Faraday cage was used to validate systems, and to also support testing

P-SEW antennas and Modems were placed inside a hyperbaric pressure vessel, capable of achieving internal pressures of 690 bar with a wall section of over 7 cm. This test was conducted using the same video Wi-Fi setup as shown in Fig. 3, but with the Tx Power set to 2 W. The effective data rate for the 2.45 GHz modem was between 20 to 54 Mbps. 433 MHz antennas were also tested using serial data modems, with a baud rate of 9.6 kbps and 10 mW Tx power. The 2.45 GHz and 433 MHz antennas, measured less than 1 cm x 3 cm.

The video images from the 2.45 GHz antenna were monitored throughout the closing sequence of the vessel and a laptop was used to communicate with the 433 MHz serial modems.

The serial modems operated using a Master and Slave architecture over Modbus RTU, with commands being sent to establish and confirm a link to the modem and laptop. The slave sent a reply to all messages sent from the master, hence providing a bidirectional communication over the channel, allowing any bit errors and latency to be monitored using Modbus Poll. Latency was not recorded, but the message response timeout was set to 200 milliseconds.

Using the same two modem types, tests were also conducted on two marine pipe sections. These 75 cm diameter steel pipes were flanged together to provide a 32 m length with a 1 cm wall thickness. Both transmitters were placed inside the pipe and incrementally moved up to the midway point, at the location of the central flange, with the external receiver antennas located on the outside of the flange. During this testing with the transmitters inside the pipe the open ends were shielded using metal plates. The antennas were approximately 1 cm offset from the inner wall.

TABLE III. : P-SEW TEST RESULTS

Test Artifact	*Carrier Frequency*	*Tx Power*	*Comment*
-90db faraday cage	433 MHz	0.01 W	9.6 kbps, serial, 10 cm
	2.45 GHz	2W	54 Mbps, video, 10 m
Hyperbaric Chamber	433 MHz	0.01 W	9.6 kbps, serial, 1 cm
	2.45 GHz	2 W	54 Mbps, video, 1 m
Flanged Pipe 1m x 32m, 1 cm wall	433 MHz	0.01 W	9.6 kbps, serial, from inside to receiver 1 cm from internal wall
	2.45 GHz	2 W	54 Mbps, Video a) through pipe from inside b) along 32 m length and 5 cm away from pipe
Freshwater	50 MHz	5 W	85 m range, Audio, 8 m depth
Pool water 0.5% salinity	50 MHz	5 W	35 m range, Audio, 3 m depth
Seawater 3.5%	50 MHz	5 W	1 m range, Audio, 2.7 m depth

In addition to the modem tests reported in Table III, a Keysight Technologies N9926A Microwave Vector Network Analyser was used to show that the 2.45 GHz strength increased near the central riser flange on the riser, relative to the other locations during the through wall test. This is an indication that the P-SEW transmission path from inside the pipe was predominantly through the flange interface.

Signal propagation along the 32 m length of the pipe was also tested using the 2.45 GHz antenna. For this test the P-SEW Tx antenna and Wi-Fi modem were placed in the -90 dB Faraday cage, to remove direct free-space signals radiating from the modem, as both Tx and Rx were on the outside of the pipe, meaning there was no shielding provided by the structure. When tested along the full 32 m length, the video signal could still be received if the antenna was within 5 cm of the pipe surface, demonstrating the structure-borne path.

III. APPLICATION AREAS

When considering wireless communication to sensors or robotic devices for subsea inspection operations there is typically an asset or structure of interest at the location, such as a pipe or equipment foundations. Such structures are not only of interest for the inspection being carried out, but may also influence the communication link. For the case of acoustic or optical links this may be in the form of shadow zones, where the communication signal struggles to reach, or reverberations that can impair the clarity of the link.

In the case of P-SEW these structures are now beneficial and can provide a low loss path for the signals to propagate, acting as a conduit and hence improving the ultimate coverage achievable over and around such infrastructures. The understanding that structures may be considered as part of the communication infrastructure opens up numerous new opportunities for increasing network capabilities.

Systems engineering approaches allowed the team to consider how the novel attributes of P-SEW could enhance the capabilities of existing tools for addressing current stakeholder needs as well as considering new applications and opportunities. This evaluation work has included a deep dive into the technology and experiences of the Saltenna team, working with external parties including both industry players and academia. During this process, the established research and findings associated with the use of P-SEW based underwater radio communication [3-5] were considered against various known customer-driven opportunities within subsea oil and gas [9] and potential future applications for autonomous inspection of subsea assets and infrastructure, such as offshore wind turbines and platforms [7]. These cases were further supported by the testing conducted on and around the structures.

Assets and infrastructure of interest include pipelines, manifolds, Blow Out Preventers (BOPs), or foundations of renewable energy structures. Consideration of these cases leads to numerous applications of P-SEW in both communication and sensing upon, around, and within these structures. Each case presents different challenges and opportunities for communication, with effects such as the flow regime inside an oil and gas pipeline offering different conductivity gradients, depending on the fluid composition.

The seabed itself provides a surface with a gradient of conductivity, also providing a transmission path for plasmonic communication to propagate along. This can be used in applications where the infrastructure is not present, such as seismology and ocean science networks.

IV. CONCLUSION

The predicted and measured penetration depths, and the experimental data obtained so far, strongly indicate that P-SEW communication offers new opportunities within underwater wireless communication areas. The P-SEW antennas offer the possibility to penetrate multiple meters through the seawater at frequencies such as 20 kHz, with Tx powers of 10 W and above, offering over 70 m direct path through seawater. Though this may still not displace acoustics for long-range scenarios where latency or data rate are not key drivers, it is of significant interest for real-time teleoperation of tools around subsea assets. In such situations the P-SEW communication path can benefit from the structures, significantly increase the communication ranges and data rates achievable, enabling low latency operation around the assets of interest.

P-SEW offers value for the underwater wireless network solutions and systems being developed for use with AUVS, resident vehicles, and subsea control and sensing systems. In principle, by adopting the P-SEW approach we begin to consider the structures as part of the communication system. The structures themselves improve the network range and signal strength, offering high data rate, low latency communication links to devices located on or near them.

To date, P-SEW has only been tested at 50 MHz through water. Higher frequency waves such as 2.45 GHz and 433 MHz have been proven to be suited for penetrating through the flanges and similar couplings allowing communication to be established through a pipe or pressure vessel wall. This allows for high data rate signals to be coupled through enclosures, replacing the need for electrical penetrators or access ports for reaching sensors internal to the pipe.

Other benefits of note are the compact size of the P-SEW antennas and low power needs. These facilitate the integration of the antennas into underwater tooling or light-duty vehicles. For most of the cases currently being considered this makes them easy to deploy, such as on small vehicles.

The results are promising with further testing planned to understand the effectiveness of the different frequency antennas in submerged applications, mapping the propagation along the associated submerged structures as well as penetration depths. These tests will help us define the potential range and data rates for networks around these structures, to support applications such as real-time monitoring and control of devices for inspecting pipelines, offshore windfarms, or other such submerged assets.

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REFERENCES

[1] F. Campagnaro, A. Signori and M. Zorzi, “Wireless Remote Control for Underwater Vehicles”, J. Mar. Sci Eng. vol 8, no. 736, 2020,

[2] S. A Maier. “Plasmonics: Fundamentals and Applications”. New York: Springer Publishing. ISBN 978-0-387-33150-8. 2007

[3] I. I. Smolyaninov; Q. Balzano; C. C. Davis; D. Young, "Surface wave based underwater radio communication", IEEE Antennas Wireless Propag. Lett., vol. 17, no. 12, pp. 2503-2507, Dec. 2018.

[4] I. I. Smolyaninov, “Surface Electromagnetic Waves at Gradual Interfaces between Lossy Media”, Progress In Electromagnetics Research, Vol. 170, 177–186, 2021.

[5] I. I. Smolyaninov; Q. Balzano; D. Young, “Development of Broadband Underwater Radio Communication for Application in Unmanned Underwater Vehicles” J. Mar. Sci. Eng. 23 May 2020

[6] K. A. Michalski and J. R. Mosig, “The Sommerfeld half-space problem revisited: From radio frequencies and Zenneck waves to visible light and Fano modes,” J. Electromagn. Waves Appl., vol. 30, pp. 1–42, 2016.

[7] M. Mattioli; T. Bernini; G. Massari; M. Lardeux; A Gower; S. De Baermaker, “Unlocking Resident Underwater Inspection Drones or AUV for Subsea Autonomous Inspection: Value Creation between Technical Requirements and Technological Development”, Offshore Technology Conference, no. OTC-32100-MS, May 2022.

[8] Wireless for Subsea, Seatooth product capabilities. [online]. Available at: https://www.slideshare.net/MikeTheobald3/wfs-summary-presentation-apr16-v1. [Accessed 17 July 2022].

[9] J. J. Mulholland; D. McStay. "Wireless Communication Enhances Subsea Production Monitoring". Offshore. 71: 76 – via Science Direct. 2011.

[10] EvoLogics, "7/17 Devices | EvoLogics", EvoLogics, 2022. [Online]. Available: https://evologics.de/acoustic-modem/7-17. [Accessed: 15-Jul- 2022].

[11] D. L. Jones, “Sending Signals to Submarines” New Scientist, 4 July 1985.

[12] S. I. Inacio, M. R. Pereira, H. M. Santos, L. M. Pessoa, F. B. Teixeira, M. J. Lopes, O. Aboderin, and H. M. Salgado, “Dipole antenna for underwater radio communications,” in Proc. UComms, Lerici, Italy, Aug. 2016.

[13] Wireless for Subsea, “Seatooth S400 Datasheet” [online]. Available: https://www.scribd.com/doc/255859616/seatooth-S400-A4, [Accessed: 16- Jul- 2022].

[14] Wireless for Subsea, “Seatooth product comparison chart” [online]. Available: https://www.environmental-expert.com/downloads/wireless-subsea-controls-seatooth-352746. [Accessed: 16- Jul- 2022].

[15] H.F. Guarnizo Mendez; F. Le Pennec; C. Gac; C. Person. “Deep underwater compatible Wi-Fi antenna development”. 14th International Symposium on Wireless Personal Multimedia Communications, 2011.