

**STUDIES ON FEASIBILITY OF VECTOR SENSOR BASED  
UNDERWATER ACOUSTIC COMMUNICATION  
SYSTEMS**

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UNDERWATER ACOUSTIC COMMUNICATION  
SYSTEMS**

by

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Bharti School of Telecommunication Technology and  
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# Certificate

This is to certify that the thesis entitled "**Studies on Feasibility of Vector Sensor based Underwater Acoustic Communication Systems**" being submitted by **Ms. Farheen Fauziya** to the **Bharti School of Telecommunication Technology and Management, Indian Institute of Technology Delhi**, for the award of the degree of **Doctor of Philosophy** is the record of the bona-fide research work carried out by her under our supervision. In our opinion, the thesis has reached the standards fulfilling the requirements of the regulations relating to the degree.

The results contained in this thesis have not been submitted either in part or in full to any other university or institute for the award of any degree or diploma.

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# Abstract

Underwater communications is a very challenging field, because the channel is of very poor quality and extremely difficult to model. Optical, RF and acoustic signals have all been experimented with as means for underwater communications. All have varying challenges and are differently impacted by water as the medium. Because of very high attenuation of the optical and RF signals in water, acoustic signals are the most common means of communications underwater. However, the channel is complex to model even for acoustic signals. The channel for acoustic communications is wide-band, frequency selective and time varying. Spatial diversity has shown to improve the performance of communication systems and the same gains can be exploited in underwater communication systems.

In recent times vector sensors have become popular especially for ranging applications. They have shown some promise in underwater communications. Unlike sensor arrays, vector sensors are compact but can offer diversity gains hence potentially improving the communication system performance. In this work, we explore the impact of the use of vector sensor in underwater communications. Since vector sensors are directional receivers, we first propose an AOA based framework for modeling the underwater acoustic communications system. Multiple paths arrive at the receiver at different time

instances and along different angles. In the framework we introduce an explicit dependence of the channel model on the AOA. This allows us to model the channel based on characteristics of the AOA resulting in a channel model, which is amenable to performance analysis of vector sensor based acoustic communication systems. We use this proposed framework for analyzing performance of different Vector Sensor based underwater acoustic communication systems.

We use the proposed framework for analyzing a vector sensor based SIMO underwater acoustic communications system. The system consists of scalar transducer as a transmitter and a single vector sensor as a receiver. A single vector sensor offers spatial diversity, hence resulting in a SIMO communications system. We obtain the BER performance and a bound on capacity of such a system and compare it against SISO communication systems. The analysis clearly demonstrates the efficacy of the use of a vector sensor as receiver. We then show that vector transducer might not be the best device for providing diversity gains in a MISO communications system. Instead we use directional transmitters and show how performance gains can be achieved by such a MISO underwater acoustic communications system. Here too the BER performance is obtained and upper bound on the channel capacity is computed. The performance is compared against SISO communication systems, and the results clearly demonstrate the superiority of the proposed MISO architecture.

For analyzing a MIMO communications system, we use scalar array at the transmitter and a vector sensor at the receiver. This architecture is used since vector transducers do not provide diversity gains because of its characteristics and the channel geometry. In this analysis too the proposed AOA based framework is used and the performance

of the proposed MIMO architecture is analyzed. The results clearly indicate that use of vector sensors in underwater acoustic communications can provide performance gains, while keeping the size of the receiver compact.

A couple of other findings also resulted from the analysis performed in this work. Since the delay spread is large and the number of multi-paths is relatively smaller, we propose a compressive sensing based method for channel estimation. We apply the proposed estimation method to vector sensor based communication system, and show how it can be used for channel equalization in such communication systems.

In summary, we have proposed an AOA based framework which is apt for analyzing vector sensor based communication systems and have used the framework to analyze different vector sensor based underwater acoustic communication system architectures. The study clearly indicates that vector sensors can offer performance gains, besides the additional benefit of being compact in size.

## सार

अंडरवाटर संचार एक बहुत ही चुनौतीपूर्ण क्षेत्र है, क्योंकि चैनल बहुत खराब गुणवत्ता का है और मॉडल के लिए बेहद मुश्किल है। पानी के भीतर संचार के लिए ऑप्टिकल, आरएफ और ध्वनिक संकेतों का सभी के साथ प्रयोग किया गया है। सभी की चुनौतियां अलग-अलग हैं और पानी के माध्यम के रूप में अलग-अलग तरह से प्रभावित हैं। पानी में ऑप्टिकल और आरएफ संकेतों के बहुत अधिक क्षीणन के कारण, ध्वनिक संकेत संचार पानी के भीतर के सबसे सामान्य साधन हैं। हालांकि, चैनल ध्वनिक संकेतों के लिए भी मॉडल के लिए जटिल है। ध्वनिक संचार के लिए चैनल वाइड-बैंड, फ्रीक्वेंसी चयनात्मक और समय भिन्न होता है। स्थानिक विविधता ने संचार प्रणालियों के प्रदर्शन को बेहतर बनाने के लिए दिखाया है और पानी के भीतर संचार प्रणालियों में समान लाभ का फायदा उठाया जा सकता है।

हाल के दिनों में वेक्टर सेंसर विशेष रूप से अनुप्रयोगों के लिए लोकप्रिय हो गए हैं। उन्होंने पानी के भीतर संचार में कुछ क्षमता दिखाया है। सेंसर सरणियों के विपरीत, वेक्टर सेंसर कॉम्पैक्ट हैं, लेकिन विविधता प्राप्त कर सकते हैं इसलिए संभवतः संचार प्रणाली के प्रदर्शन में सुधार होगा। इस काम में, हम पानी के भीतर संचार में वेक्टर सेंसर के उपयोग के प्रभाव का पता लगाते हैं।

चूंकि वेक्टर सेंसर दिशात्मक रिसीवर हैं, हम पहले पानी के भीतर ध्वनिक संचार प्रणाली के मॉडलिंग के लिए एक एओए आधारित ढांचे का प्रस्ताव देते हैं। कई पथ रिसीवर पर विभिन्न समय उदाहरणों पर और विभिन्न कोणों पर पहुंचते हैं।

इस ढांचे में हम एओए पर चैनल मॉडल की स्पष्ट निर्भरता का परिचय देते हैं। यह हमें चैनल मॉडल के आधार पर एओए की विशेषताओं के आधार पर मॉडल तैयार करने की अनुमति देता है, जो वेक्टर सेंसर आधारित ध्वनिक संचार प्रणालियों के प्रदर्शन विश्लेषण के लिए उत्तरदायी है। हम विभिन्न वेक्टर सेंसर आधारित पानी के भीतर ध्वनिक संचार प्रणालियों के प्रदर्शन के विश्लेषण के लिए इस प्रस्तावित ढांचे का उपयोग करते हैं।

हम एक वेक्टर सेंसर आधारित सिमो पानी के भीतर के विश्लेषण के लिए प्रस्तावित रूपरेखा का उपयोग करते हैं। सिस्टम में एक ट्रांसमीटर के रूप में स्केलर ट्रांसड्यूसर और एक रिसीवर के रूप में एकल वेक्टर सेंसर होते हैं। एकल वेक्टर सेंसर स्थानिक विविधता प्रदान करता है, जिसके परिणामस्वरूप एक सिमो संचार प्रणाली है। हम बी इ आर प्रदर्शन और ऐसी प्रणाली की क्षमता पर एक बाध्यता प्राप्त करते हैं और इसकी तुलना सिमो संचार प्रणालियों से करते हैं। विश्लेषण स्पष्ट रूप से रिसीवर के रूप में एक वेक्टर सेंसर के उपयोग की प्रभावकारिता को दर्शाता है।

हम फिर दिखाते हैं कि वेक्टर ट्रांसड्यूसर सिमो संचार प्रणाली में विविधता प्रदान करने के लिए सबसे अच्छा उपकरण नहीं हो सकता है। इसके बजाय हम दिशात्मक ट्रांसमीटरों का उपयोग करते हैं और दिखाते हैं कि इस तरह के सिमो पानी के भीतर ध्वनिक संचार प्रणाली द्वारा प्रदर्शन लाभ कैसे प्राप्त किया जा सकता है। यहां भी बी इ आर

प्रदर्शन प्राप्त किया जाता है और चैनल क्षमता पर ऊपरी बाध्य गणना की जाती है। प्रदर्शन की तुलना सिसो संचार प्रणालियों से की जाती है, और परिणाम स्पष्ट रूप से प्रस्तावित मिसो वास्तुकला की श्रेष्ठता प्रदर्शित करते हैं।

मीमो संचार प्रणाली का विश्लेषण करने के लिए, हम ट्रांसमीटर पर स्केलर सरणी और रिसीवर में एक वेक्टर सेंसर का उपयोग करते हैं। इस वास्तुकला का उपयोग किया जाता है क्योंकि वेक्टर ट्रांसड्यूसर अपनी विशेषताओं और चैनल ज्यामिति के कारण विविधता लाभ प्रदान नहीं करते हैं। इस विश्लेषण में भी प्रस्तावित एओए आधारित ढांचे का उपयोग किया जाता है और प्रस्तावित एमआईएमओ वास्तुकला के प्रदर्शन का विश्लेषण किया जाता है। परिणाम स्पष्ट रूप से संकेत देते हैं कि पानी के भीतर ध्वनिक संचार में वेक्टर सेंसर का उपयोग रिसीवर के आकार को बनाए रखते हुए, प्रदर्शन लाभ प्रदान कर सकता है।

इस काम में किए गए विश्लेषण के परिणामस्वरूप कुछ अन्य निष्कर्ष भी निकले। चूंकि विलंब फैला हुआ बड़ा है और बहु-पथों की संख्या अपेक्षाकृत कम है, इसलिए हम चैनल आकलन के लिए एक संकुचित संवेदन आधारित विधि का प्रस्ताव करते हैं। हम वेक्टर सेंसर आधारित संचार प्रणाली के लिए प्रस्तावित अनुमान पद्धति को लागू करते हैं, और दिखाते हैं कि इस तरह के संचार प्रणालियों में चैनल के लिए इसका उपयोग कैसे किया जा सकता है।

सारांश में, हमने एक एओए आधारित रूपरेखा का प्रस्ताव किया है जो वेक्टर सेंसर आधारित संचार प्रणालियों के विश्लेषण के लिए उपयुक्त है और विभिन्न वेक्टर सेंसर आधारित पानी के भीतर ध्वनिक संचार प्रणाली आर्किटेक्चर का विश्लेषण करने के लिए फ्रेमवर्क का उपयोग किया है। अध्ययन स्पष्ट रूप से इंगित करता है कि वेक्टर सेंसर प्रदर्शन लाभ की पेशकश कर सकते हैं, इसके अलावा आकार में कॉम्पैक्ट होने का अतिरिक्त लाभ भी है।

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# Abbreviations

AOA	Angle of arrival
AVA	Acoustic Vector Sensor
AZ	Azimuth Spread
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
CRLB	Cramer-Rao Lower Bound
CS	Compressive Sensing
CSI	Channel State Information
DOA	Direction Of Arrival
EZ	Elevation Spread
JADE	Joint Angle and Delay Estimates
LOS	Line-Of-Sight
MIMO	Multiple-Input Multiple-Output
MMV	Multiple Measurement Vector
NLOS	Non-Line-Of-Sight
OFDM	Orthogonal Frequency-Division Multiplexing
OMP	Orthogonal matching pursuit

PAS	Power Angular Spectrum
PDF	Probability Density Function
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
RMSE	Root Mean Square Error
SIMO	Single Input Multiple output
SNR	Signal-to-Noise Ratio
SISO	Single Input Single output
SSE	Sum of Squared Errors
SSP	Sound Speed Profile
UWAC	Underwater Acoustic Communication