GEOMETRY AND STATISTICS BASED GENERALIZED SYSTEM MODEL FOR UNDERWATER ACOUSTIC CHANNEL

MANISHIKA RAWAT

Department of Electrical Engineering
Indian Institute of Technology Delhi

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by

MANISHIKA RAWAT

Department of Electrical Engineering

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I dedicate my thesis to my parents for their undying support and love, putting me through the best education possible, for all their sacrifices and prayers, and for making me the person I am today. I am forever indebted.

Certificate

This is to certify that the dissertation entitled '**Geometry and Statistics based Generalized System Model for Underwater Acoustic Channel**', being submitted by **Ms. Manishika Rawat** for the award of the degree of **Doctor of Philosophy** is a record of bonafide research work carried out by her in the Department of Electrical Engineering at Indian Institute of Technology Delhi, New Delhi.

Ms. Manishika Rawat has worked under our supervision and has fulfilled the requirements for the submission of this dissertation, which to our knowledge has reached the requisite standard. The results obtained here have not been submitted to any other University or Institute for the award of any degree.

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Prof. Brejesh Lall
Professor
Department of Electrical Engineering
Indian Institute of Technology Delhi
Hauz Khas, New Delhi 110016, India

. . . .

Dr. Seshan Srirangarajan
Assistant Professor
Department of Electrical Engineering
Indian Institute of Technology Delhi
Hauz Khas, New Delhi 110016, India

Date:

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Date:

Place: New Delhi   Manishika Rawat

Abstract

The research work presented in this dissertation focuses on geometry and statistics-based generalized system modeling for underwater acoustic communication channel. It has been observed that statistical modeling of underwater channel is inadequate and still a matter of ongoing research. Thus, in this dissertation, a geometry-based statistical model for the path gain and angle of arrival (AoA) is proposed.

As the demand for data rate and capacity increases, there is growing attention on employing cooperative communication techniques to mitigate this problem. Besides, it has been proved that vector sensor enhances the performance of underwater acoustic communication over a long range by measuring particle motion along with pressure changes associated with a sound wave. Thus, in this dissertation, an AoA based statistical model for the path gain in an underwater channel is proposed. The proposed model is used to obtain a novel characterization of a multi-hop multi-branch cooperative framework for a frequency-selective underwater channel. The above analysis was carried out assuming amplify and forward (AF) and decode and forward (DF) relaying in successive nodes. Numerical integration expressions for the average bit error rate and ergodic capacity for a multi-hop multi-branch framework of a log-normal distributed frequency-selective channel has been derived. Results are obtained for hydrophone and vector sensor receiver. A trade-off is observed between the size of the architecture, the performance, and computational complexity, which can be of interest in designing an optimized system.

AoA analysis is essential for the statistical characterization of the underwater channel. In underwater channels, the acoustic signal reaches the receiver either through the line of sight or after scattering from the sea surface and bottom. At relatively higher frequencies (above 10 kHz), the acoustic signal undergoes incoherent scattering from the surface and bottom, resulting in an omnidirectional scattering pattern at each point of interaction with the sea surface. In this dissertation, we have derived analytical expressions for the AoA distribution for paths that undergoes incoherent scattering from the surface/bottom in an underwater channel.

Further, we have evaluated the statistical characterization of the AoA at the receiver due to scattering from a random sea surface. The distribution of AoA is evaluated for coherent and incoherent scattering. The overall scattering for any given channel state

would be an appropriate combination of coherent and incoherent components. A similar effect manifests itself in the distribution of the overall AoA. The impact of factors such as acoustic signal frequency, wind speed, and the underwater channel geometry on the parameters of the overall AoA has been studied.

Finally, we have derived the analytical expressions for the Doppler spectrum and Doppler shift at the receiver for the signal reflected from a moving undulating surface. The spectrum for each reflected path is observed to be a function of the slope of the sea surface around the scattering point and scatterer location. The derived expression for the Doppler shift is general and can be used to enable Doppler compensation at the receiver.

सार

इस शोध प्रबंध में प्रस्तुत शोध कार्य अंतर्जलीय ध्वनिक संचार (यूएसी) चैनल के लिए ज्यामिति और सांख्यिकी आधारित सामान्यीकृत प्रणाली प्रतिरूप पर केंद्रित है। यह देखा गया है कि अंतर्जलीय (यूडब्ल्यू) चैनल का सांख्यिकीय प्रतिरूप अपर्याप्त है और अभी भी प्रासंगिक अनुसंधान का एक क्षेत्र है। इस शोध प्रबंध में पथ लाभ तथा आगमन के कोण (एओए) के लिए एक ज्यामिति आधारित सांख्यिकीय प्रतिरूप प्रस्तावित है।

जैसे-जैसे डेटा दर और क्षमता की मांग बढ़ रही है, इस समस्या को कम करने के लिए सहकारी संचार तकनीकों को नियोजित करने पर ध्यान दिया जा रहा है। साहित्य में यह साबित हो गया है कि वेक्टर सेंसर (वीएस) ध्वनि तरंग से जुड़े दबाव परिवर्तनों के साथ कण गति को मापकर लंबी दूरी पर यूएसी के प्रदर्शन को बढ़ाता है। इसलिए, इस शोध प्रबंध में एलओएस और परावर्तित पथों की यादृच्छिकता पर विचार करते हुए, यूडब्ल्यू चैनल में पथ लाभ के लिए एओए आधारित सांख्यिकीय मॉडल प्रस्तावित किया गया है। उपरोक्त विश्लेषण क्रमिक पद में एम्प्लीफाई और फॉरवर्ड (एएफ) तथा डिकोड और फॉरवर्ड (डीएफ) प्रसार मानकर किया गया था। इस प्रकार, इस शोध प्रबंध में, हमने लघु गणक प्रसामान्य आवृत्ति-चयनात्मक चैनल के एमएचएमबी ढांचे के लिए औसत बीईआर और ईसी के लिए संख्यात्मक एकीकरण (एनआई) अभिव्यक्ति प्राप्त की है। पद और शाखाओं की चर संख्याओं के लिए परिणाम प्राप्त किए गए हैं। प्राप्त परिणामों में एमसी सिमुलेशन और एनआई अभिव्यक्तियों के बीच उत्कृष्ट मिलान व्युत्पन्न अभिव्यक्तियों की सटीकता को मान्य करता है। वास्तुकला के आकार, प्रदर्शन और कम्प्यूटेशनल जटिलता के बीच एक दुविधा देखी गई है, जिसका उपयोग एक अनुकूलित प्रणाली को डिजाइन करने में किया जा सकता है।

यूडब्ल्यू चैनल के सांख्यिकीय लक्षण वर्णन के लिए एओए विश्लेषण आवश्यक है क्योंकि ध्वनिक संकेत प्रसार एक प्रतिबंधित ज्यामिति तक ही सीमित है। यूडब्ल्यू चैनलों में ध्वनिक संकेत या तो एलओएस के माध्यम से या समुद्र की सतह और नीचे से बिखरने के बाद रिसीवर तक पहुंचता है। उच्च आवृत्ति वाले ध्वनिक संकेत (10 किलो हर्ट्ज़ से ऊपर) पर असंगत प्रकीर्णन होता है, जिसके परिणामस्वरूप समुद्र की सतह के साथ अंतःक्रिया के प्रत्येक बिंदु पर एक सर्वदिशात्मक प्रकीर्णन स्वरूप होता है। इस शोध प्रबंध में, हमने पथ के लिए एओए वितरण के लिए एक संवृत-रूप अभिव्यक्ति प्राप्त की है जो एक यूडब्ल्यू चैनल में सतह/नीचे से असंगत रूप से बिखरती है।

इसके अलावा, हमने यादृच्छिक समुद्री सतह से प्रकीर्णन के कारण रिसीवर पर एओए के सांख्यिकीय लक्षण वर्णन का मूल्यांकन किया है। समुद्र के किनारे संभावित बिखरावों का यादृच्छिक व्यवहार सुसंगत और असंगत प्रकीर्णन, सतह तरंग की ऊँचाई और एओए के वितरण पर उनके प्रभाव का मूल्यांकन किया गया है। किसी भी चैनल स्थिति के लिए समग्र बिखराव सुसंगत और असंगत घटकों का एक उपयुक्त संयोजन होगा। एक समान प्रभाव समग्र एओए के वितरण में प्रकट होता है। इसके अलावा, समग्र एओए के मापदंडों पर ध्वनिक संकेत आवृत्ति, हवा की गति और यूडब्ल्यू चैनल ज्यामिति जैसे कारकों के प्रभाव का अध्ययन किया गया है।

अंत में, इस शोध प्रबंध में हमने रिसीवर पर एक चलती लहरदार सतह से परावर्तित संकेत के लिए डॉपलर स्पेक्ट्रम (डीएस) और डॉपलर शिफ्ट के लिए विश्लेषणात्मक अभिव्यक्ति प्राप्त की है। प्रत्येक परावर्तित पथ के स्पेक्ट्रम को प्रकीर्णन बिंदु और प्रकीर्णक स्थान के आसपास समुद्र की सतह के ढलान के एक फलन के रूप में देखा जाता है। डॉपलर शिफ्ट के लिए व्युत्पन्न अभिव्यक्ति सामान्य है और इसका उपयोग रिसीवर पर डॉपलर मुआवजे को सक्षम करने के लिए किया जा सकता है।

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Nomenclature

The symbols are given in this nomenclature. Some symbols are defined as and when required in the text.

$\mathcal{M}_x(x)$	moment generating function of a random variable x
$\mathcal{U}(.)$	Unit Step Function
$\|\mathbf{X}\|$	Frobenius Norm of a matrix $\mathbf{X}$
$\mathbf{X}$	Bold uppercase letter represents a matrix
$\mathbf{x}$	Bold lowercase letter represents a vector
$\mathbf{X}^{\dagger}$	Hermitian of a matrix $\mathbf{X}$
$\mathbf{X}^{T}$	Transpose of a matrix $\mathbf{X}$
$E[.]$	Expectation operator
$F_x(x)$	cumulative distribution function of a random variable x
$f_x(x)$	probability density function of a random variable x
$Q(.)$	Gaussian q-function
$tr\{\mathbf{X}\}$	trace of a matrix $\mathbf{X}$
$x \sim \mathrm{LN}(\zeta, \eta)$	x is log-normal distributed random variable with mean ζ and standard deviation η

$x \sim \mathcal{N}(\zeta, \eta)$	x is log-normal distributed random variable with mean ζ and standard deviation η
α_s, α_b	rate of change of probability of successive bounces along the surface or bottom as the previous point of interaction moves closer to the Rx
χ	Rayleigh parameter
κ_s, κ_b	normalization parameters for the surface uniform depth exponential distribution along the surface and bottom
θ_g	grazing angle associated with the nominal specular path from the mean sea level (radians)
θ_s, θ_b	AoA at the Rx for a path undergoing single bounce from the sea surface and bottom
$\theta^n_{s_1}$, $\theta^n_{b_1}$	AoA at the Rx for a path undergoing n bounces with the last interaction from the sea surface or bottom
c	speed of sound in an underwater channel (m/s)
f_c	acoustic signal frequency (Hz)
h	root mean square wave height of the sea surface (m)
K_{Ns}, K_{Nb}	normalization parameter of the joint PDF of all the scatterer locations for a multiple bounce path with last scattering from the surface or bottom
n_s, n_b	number of interactions of the path with the sea surface and bottom
v_r	relative speed of Rx with respect to source (m/s)
Λ	acoustic wavenumber $(\mathrm{m})^{-1}$
Λ_n	wavenumber of the n^{th} realization of the sea surface

$\theta_c, \theta_{in}, \theta$	AoA at the receiver for coherent, incoherent, and overall scattering
a_n, ω_n, ϕ_n	amplitude (m), angular frequency (radians/sec), and phase (radians) of the n^{th} realization of the sea surface
F	fetch limit range (km)
N	number of frequencies that constitute the sea wave
U	speed of wind blowing above the sea surface (m/s)
v_s	velocity at which the sea surface drifts or moves (m/s)
X_c, Y_c	randomness in scatterer location and surface wave height for ensemble-averaged sum of sinusoids surface assuming coherent scattering
X_{ic}, Y_{ic}	randomness in scatterer location and surface wave height for ensemble-averaged sum of sinusoids surface assuming incoherent scattering
τ	time delay w.r.t. LoS path (sec)
f_d	Doppler shift (Hz)
v_v	vertical velocity of the sea surface (m/s)
v_{sp}	projection of the velocity along the p^{th} path