Numerical Analysis of Orbital Angular Momentum Waves Regarding Wave Propagation and Communication



Numerical Analysis of Orbital Angular Momentum Waves Regarding Wave Propagation and Communication

Vom Promotionsausschuss der Technischen Universität Hamburg zur Erlangung des akademischen Grades

Doktor-Ingenieur (Dr.-Ing.)

genehmigte Dissertation

von Michael Wulff

> aus Eutin

2024

1. Gutachter: Prof. Dr. sc. techn. Christian Schuster

2. Gutachter: Prof. Dr.-Ing. Thomas Eibert

3. Gutachter: Prof. Dr. Lei Wang

Vorsitzender des Prüfungsausschusses: Prof. Dr.-Ing. Gerhard Bauch

Tag der mündlichen Prüfung: 05.04.2024

Berichte aus der Elektrotechnik

Michael Wulff

Numerical Analysis of Orbital Angular Momentum Waves Regarding Wave Propagation and Communication

> Shaker Verlag Düren 2024

Bibliographic information published by the Deutsche Nationalbibliothek

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at http://dnb.d-nb.de.

Zugl.: Hamburg, Techn. Univ., Diss., 2024

Copyright Shaker Verlag 2024 All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior permission of the publishers.

Printed in Germany.

ISBN 978-3-8440-9506-7 ISSN 0945-0718

Shaker Verlag GmbH • Am Langen Graben 15a • 52353 Düren Phone: 0049/2421/99011-0 • Telefax: 0049/2421/99011-9 Internet: www.shaker.de • e-mail: info@shaker.de

Summary

In this work, the propagation behavior of orbital angular momentum (OAM) waves is numerically studied in scenarios commonly encountered in radio frequency (RF) communication links.

In the RF domain, OAM waves comprise an orthogonal mode system, where the different OAM modes distinguish themselves in their spacial phase pattern. One method to excite OAM waves in free space is using a uniform circular array (UCA). Currently, two main applications of OAM waves are being discussed. First, they can be used in future communication systems as a type of multi-input multi-output (MIMO) system, where the orthogonality of the mode system allows the OAM modes to be used as independent communication channels. One challenge here is that the orthogonality of the modes is disrupted by some environments. Second, OAM waves can be used in the sensing domain, improving the resolution of the target by evaluating the reflection of different OAM modes.

To improve the fundamental understanding about the behavior and interactions of OAM waves, this thesis numerically evaluates the wave behavior in different scenarios. To that aim, the OAM mode system is introduced generally for N-ports and the symmetry requirements for the network parameters to retain mode orthogonality are derived. In addition, the numerical challenges in the simulation are discussed. The behavior of the OAM modes is subsequently investigated in scenarios encountered along a communication link in terms of mode transmission and mode orthogonality. After utilizing a matching and mode excitation network, the OAM modes can be guided along a transmission line, for which multiple types and geometries are investigated for their ability to retain the mode orthogonality. The UCAs that translate the guided OAM modes into radiated OAM modes can vary widely, e.g., in terms of the array elements used or their orientation. The impact of these variations on the radiated OAM modes is explored. While the radiated OAM modes propagate, they can encounter different scenarios. This work evaluates simple environments, such as free space and communication over ground and more complex scenarios, such as aperture penetration, shielding, and interference from other antennas.

Acknowledgments

This thesis is the result of my research at the Institut für Theoretische Elektrotechnik at the Hamburg University of Technology (TUHH) in the years 2019 to 2023 and was only possible due to the support and guidance of many individuals.

First of all, I would like to thank my supervisor Prof. Dr. sc. techn. Christian Schuster for his guidance, insightful discussions, and general support. Without him, many aspects of this thesis would not have been explored and interesting questions would not have been raised. I would also like to acknowledge the contribution of Prof. Dr. Lei Wang, Prof. Dr-Ing, Thomas Eibert, and Prof. Dr. Andrew F. Peterson, which provided helpful insight into various topics addressed in this thesis. I would like to thank my coauthors Dr. Cheng Yang, Dr. Heinz -D. Brüns, Prof. Dr. Alexander Kölpin, Til Hillebrecht, Woocheon Park, and Tong Zhang for their contribution to the research discussed in this thesis.

I want to thank the former and current scientific staff of the institute Morten Schierholz, Hamideh Esmaeili, Lennart Bohl, Youcef Hassab, Jose Enrique Hernandez Bonilla, Torben Wendt, Ömer Faruk Yildiz, and Katharina Scharff for the numerous interesting discussions held over the years, for the great support in technical and non-technical fields and for generally creating a relaxed working environment. Furthermore, I would like to thank the former and current non-scientific staff of the institute Pelin Usta, Stefan Conradi, Volker Paulsen, and Angela Freiberg for the support provided for the many problems that occurred over the years.

Lastly, I want to thank my family. I thank my parents Torsten Wulff and Waltraut Wulff for their constant support in everything I set out to do and their time taken for my many visits over many weekends, providing me with a place to separate me and my thoughts from the city and the university. I want to thank my brothers Sascha Wulff and Kai Niklas Wulff and my sister Tanja Wulff for their support in difficult situations and the good relationships we share.

Contents

Summary				
Ac	know	ledgments	iii	
Lis	st of	Figures	ix	
Lis	st of	Tables >	v	
Ac	crony	ns xv	/ii	
Sy	mbol	s, and Notation x	ix	
1.	Intro	duction and Motivation	1	
	1.1.	State of the Art	2	
		1.1.1. Historic Development	2	
		1.1.2. OAM Wave Excitation and Detection	4	
		1.1.3. Applications	8	
	1.2.	Organization of this Work	8	
	1.3.	Conference and Journal Contributions	9	
2.	The	OAM Mode System: Definition, Symmetry and Simulation 1	.1	
	2.1.	Definition and Excitation of OAM Modes	.1	
	2.2.	Modal Network Parameter	.3	
	2.3.	Orthogonality and Symmetry	.6	
		2.3.1. Orthogonality of the OAM Modes	.7	
		2.3.2. Symmetry Requirement for the Network Parameters	.7	
	0.4	2.3.3. Mode Conversion Resulting from Asymmetries I	.9 .9	
	2.4.	Numerical loois	:3 52	
		2.4.1. MOM Dased Full-wave Simulations	20 24	
		2.4.2. FEW Dased Full-Wave Simulations	24)5	
		2.4.0. Multiconductor transmission line simulations \dots 2.2.4. Simulation Accuracy	.0)5	
		2.4.5 Meshing for OAM Wave Simulation	20	
	2.5	Summary	.0 ₹∆	
	2.0.	Summery	, т	

3.	Transmission Lines Carrying OAM Modes	35
	3.1. Symmetry of the Cross-Section	35
	3.2. Mode Properties	39
	3.3. Mode Excitation and Matching	42
	3.4. Mode Performance on Different Conductor Types	46
	3.5. Summary	55
4.	Free Space OAM Wave Communication and OAM Antenna Properties	57
	4.1 Free Space OAM Wave Communication	57
	4.1.1. Excitation using a Uniform Circular Array	58
	4.1.2 Wave Properties	58
	4.1.3. Communication Properties	60
	4.2. Influence of Array Element Orientation	64
	4.2.1. Uniform Circular Array with Normal Elements	66
	4.2.2. Uniform Circular Array with Tangential Elements	67
	4.2.3. Communication Between Arrays with Different Element	
	Orientations	73
	4.3. Influence of Array Element Type	75
	4.4. Perturbation of Array Geometry	76
	4.5. Summary	83
5.	Complex Environments and Interference	85
	5.1. OAM Communication over Ground	85
	5.2. Influence of Symmetry of the Environment	86
	5.3. Aperture Penetration of OAM Waves	93
	5.3.1. Effect of Aperture Shape and Size	95
	5.3.2. Effect of Distance	101
	5.3.3. Effect of Arrival Position and Angle	103
	5.4. Shielding of OAM Waves	105
	5.5. Interference between UCAs and Other Antennas	112
	5.6. Summary	118
6.	Conclusion and Outlook	119
Α.	The OAM Density	121
в.	OAM Modes on Circular Waveguides	127
с.	Correction to Published Paper [1]	133

D. Derivation of the Electric Far Field of Different UCAs	135		
D.1. Electric Far-Field of a UCA with Normally Oriented Array El-	105		
D 2 Electric Far-Field of a UCA with Tangentially Oriented Array	. 135		
Elements	. 136		
E. Simulation of Apertures in an Infinite PEC Plane	143		
Bibliography			