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Investigation of Digital Signal Processing Techniques for Compensation of Linear and Nonlinear Impairments in Fiber-Optic Communication Systems



Lehrstuhl für Nachrichten-
und Übertragungstechnik

Investigation of Digital Signal Processing Techniques for Compensation of Linear and Nonlinear Impairments in Fiber-Optic Communication Systems

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Preface

This book is a summary of my achievements during my doctoral studies in the field of fiber-optic communication. In this journey, I was given this great opportunity to combine and further develop my knowledge in mathematics, communication engineering, signal processing, and programming. To me personally, this book represents the end of an important period in my life, a summary of more than 12 years of academic studies, as well as the beginning of a new period with the opportunity to embark upon new and exciting projects.

This book is intended for those who wish to develop further the ideas that I have evolved, especially regarding precoding in fiber-optic communication systems, and for those who wish to have a complete and more profound understanding of my work, which was partly presented in several publications between 2011 and 2017.

This achievement would not have been possible without the support of numerous people I have encountered along my way. First, I would like to thank Prof. Dr.-Ing. Werner Rosenkranz for giving me the opportunity to pursue my doctoral studies as well as for his support and valuable suggestions during my work in his group. I thank Prof. Dr.-Ing. Robert Fischer and Prof. Dr.-Ing. Christian Schäffer for evaluating my thesis and for the fruitful discussions during the SASER-ADVantage-Net project. Many thanks go to Prof. Dr.-Ing. Dipl.-Wirt. Ing. Stephan Pachnicke for his support and for the fruitful discussions during the final stages of my work.

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Kiel, February 2020

Roi Rath

Abstract

Fiber-optic communication systems face various challenges due to the ongoing demand for higher data rates and longer transmission reach. In addition to linear distortions due to chromatic dispersion and bandwidth limitations of devices, the nonlinear fiber impairments, which become more dominant due to transmission with higher launch power, lead to the capacity crunch of the fiber channel.

With the advancement of high-speed electronics, digital signal processing techniques for the compensation of linear and nonlinear impairments in fiber-optic communication systems offer a powerful yet cost-effective solution for the challenges mentioned above. This work investigates potential candidates for pre- and post-compensation of inter-symbol interference (ISI) and nonlinear distortions, separated into three stages.

In the first stage, the compensation of fiber impairments is investigated, with an emphasis on the digital back-propagation (DBP) method as a solution for the capacity-crunch problem. Possible implications of DBP on the future transmission-link design are examined, and its performance in an optical network scenario is evaluated.

In the second stage, the capability of feed-forward and feedback equalizer structures to compensate for ISI is investigated. In particular, the suitability of the Tomlinson-Harashima precoding (THP) method for fiber-optic communications is assessed. It is shown experimentally that THP significantly outperforms decision-feedback equalization in transmission scenarios characterized by spectral zeros.

Apart from compensation techniques, the concept of fitting the decision thresholds to the received signal to allow enhanced symbol detection is introduced and discussed. Clustering-based detection algorithms are compared with selected post-compensation techniques in a case study regarding their performance and computational complexity in order to evaluate the potential of enhanced detection to replace different stages of compensation.

Zusammenfassung

Faseroptische Nachrichtenübertragungssysteme stehen aufgrund der anhaltenden Nachfrage nach höheren Datenraten und längerer Übertragungsreichweite vor verschiedenen Herausforderungen. Neben linearen Verzerrungen durch chromatische Dispersion und Gerätebandbreiteneinschränkungen führen die nichtlinearen Faserbeeinträchtigungen, welche durch Übertragung mit höherer optischer Eingangsleistung dominanter werden, zu einer Kapazitätserschöpfung des Faserkanals.

Mit der Weiterentwicklung der Hochgeschwindigkeitselektronik bieten digitale Signalverarbeitungsverfahren zur Kompensation linearer und nichtlinearer Beeinträchtigungen eine leistungsstarke und dennoch kostengünstige Lösung für die obengenannten Herausforderungen. In dieser Arbeit werden potenzielle Kandidaten, welche in drei Hauptteile gegliedert sind, für die Entzerrung und Vorverzerrung von Intersymbol-Interferenz (ISI) und nichtlinearen Verzerrungen untersucht.

Im ersten Teil wird die Kompensation von Faserbeeinträchtigungen untersucht, wobei ein Schwerpunkt auf das „digital back-propagation“ (DBP) Verfahren als Lösung für die Kapazitätserschöpfung gelegt wird. Des Weiteren werden mögliche Auswirkungen des DBP-Verfahrens auf das zukünftige Übertragungsstreckendesign überprüft, und seine Leistungsfähigkeit in einem optischen Netzwerkszenario bewertet.

Im zweiten Teil wird die ISI-Kompensationsfähigkeit von „Feed-Forward-“ und Rückführungsentzerrerstrukturen untersucht. Insbesondere wird die Eignung des Vorverzerrungsverfahrens „Tomlinson-Harashima Precoding“ (THP) für faseroptische Nachrichtenübertragung bewertet. Es zeigt sich experimentell, dass THP quantisierte Rückführungsentzerrung in Übertragungsszenarien, die durch spektrale Nullen gekennzeichnet sind, leistungsmäßig deutlich übertrifft.

Neben Kompensationsverfahren wird auch das Konzept der Anpassung der Entscheidungsschwellen an das empfangene Signal zur verbesserten Symboldetektion eingeführt und diskutiert. Clusterbasierte Erkennungsalgorithmen werden in einer Fallstudie mit ausgewählten empfängerseitigen Kompensationsverfahren in Bezug auf ihre Leistungsfähigkeit und Berechnungskomplexität verglichen. Hierdurch wird das Potenzial des obengenannten Konzepts, verschiedene Phasen der Kompensation zu ersetzen, bewertet.

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