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Kalman Filtering for Mitigation of Optical Fiber Transmission Impairments

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Kalman Filtering for Mitigation of Optical Fiber Transmission Impairments

Kalman Filterung zur Unterdrückung von Störeinflüssen bei der faseroptischen Übertragung

Der Technischen Fakultät
der Friedrich-Alexander-Universität
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Abstract

Coherent optical communication systems offer great capability to transmit high data throughput, in order to accommodate the ever increasing data traffic. The advent of coherent detection aided with digital signal processing (DSP) has been one of the major technology breakthroughs that made it possible to multiply the spectral efficiency several times and also to compensate the fiber transmission impairments electronically. However, the nonlinear Kerr effect and its interplay with the amplified spontaneous emission (ASE) noise resulting in the nonlinear phase noise (NLPN), are still a bottleneck restricting the maximum possible transmission reach and capacity. In addition, equalization of the polarization effects as well as the phase and frequency offsets between the transmitter laser and the local oscillator (LO) is also crucial when employing higher order modulation formats and multiplexing techniques. Therefore, efficient DSP algorithms are under active research over the past decade.

In this thesis, the potential of Kalman filtering is exploited for the joint mitigation of several optical transmission impairments including laser phase noise, fiber nonlinearity, amplitude noise, frequency offset as well as polarization effects. A carrier phase and amplitude noise estimation (CPANE) algorithm is proposed and implemented using an extended Kalman filter (EKF) that estimates a complex quantity to track the phase and amplitude noise, simultaneously. Although, various DSP algorithms have been studied in this thesis, more emphasis will be given to the EKF-CPANE algorithm. Its performance is investigated in detail and compared to the conventional DSP algorithms. Approaches to enhance the nonlinear tolerance of the EKF-CPANE algorithm by incorporating with the existing techniques like digital backward propagation (DBP) will be presented. A two stage EKF approach is introduced that exhibits an improved tolerance towards phase and frequency offsets. Furthermore, an adaptive and cascaded Kalman filtering (CKF) is proposed for the joint tracking of polarization state and phase noise. A brief analysis on incorporating forward error correction (FEC) with the EKF-CPANE algorithm is also discussed. Extensive numerical investigations prove that the Kalman filters offer an attractive solution to jointly compensate several optical transmission impairments and thereby, enhance the transmission performance. Moreover, owing to their real-time feasibility and low complexity, Kalman filters seem to be a promising component of future coherent receivers.

Zusammenfassung

Kohärente optische Übertragungsssysteme bieten die Möglichkeit eines hohen Datendurchsatzes und damit auch das Potenzial, dem ständig wachsenden Datenverkehr gerecht zu werden. Das Aufkommen kohärenter Detektion in Verbindung mit der digitalen Signalverarbeitung (DSP) war einer der wichtigsten technologischen Durchbrüche, die es möglich gemacht haben, die spektrale Effizienz zu vervielfachen und auch die Störeinflüsse bei der Faserübertragung elektronisch zu kompensieren. Der nichtlineare Kerr-Effekt und sein Zusammenspiel mit dem Rauschen der verstärkten spontanen Emission (ASE), das zu dem nichtlinearen Phasenrauschen (NLPN) führt, sind jedoch immer noch ein Faktor, der die maximal mögliche Übertragungsreichweite und-kapazität einschränkt. Zusätzlich ist ein Ausgleich der Polarisationseffekte sowie der Phasen- und Frequenzversätze zwischen dem Senderlaser und dem lokalen Oszillator (LO) entscheidend, wenn Modulationsformate höherer Ordnung und Multiplextechniken verwendet werden. Daher wurden effiziente DSP Algorithmen in der letzten Dekade aktiv erforscht.

In dieser Arbeit wird das Potenzial der Kalman Filterung zur gemeinsamen Abschwächung mehrerer Beeinträchtigungen bei der optischen Übertragung, einschliesslich Laserphasenrauschen, Faser Nichtlinearität, Amplitudenrauschen, Frequenzversatz sowie Polarisationseffekte genutzt. Ein Algorithmus zur Trägerphasen und Amplitudenrauschschätzung (CPANE) wird vorgeschlagen und implementiert. Dabei wird ein erweitertes Kalman Filters (EKF) eingesetzt, das eine komplexe Grösse schätzt, um die Phase und Amplitudenrauschen gleichzeitig zu verfolgen. Obwohl in dieser Arbeit verschiedene DSP-Algorithmen untersucht wurden, wird der EKF-CPANE Algorithmus stärker betont. Seine Leistung wird detailliert untersucht und mit den herkömmlichen DSP-Algorithmen verglichen. Ansätze zur Verbesserung der nichtlinearen Toleranz des EKF-CPANE Algorithmus durch Integration in bestehende Techniken wie die digitale Rückwärtspropagation (DBP) werden vorgestellt. Ein zweistufiger EKF-Ansatz wird eingeführt, der eine verbesserte Toleranz gegenüber Phasen- und Frequenzversätzen aufweist. Darüber hinaus wird eine adaptive und kaskadierte Kalman-Filterung (CKF) zur gemeinsamen Verfolgung von Polarisationszustand und Phasenrauschen vorgeschlagen. Eine kurze Analyse zur Integration einer Vorwärtsfehlerkorrektur (FEC) mit dem EKF-CPANE Algorithmus wird ebenfalls diskutiert. Umfangreiche numerische Untersuchungen belegen, dass die Kalman Filter eine attraktive Lösung bieten, um verschiedene störende Effekte bei der optischen Übertragung gemeinsam zu kompensieren und dadurch die Übertragungsleistung zu verbessern. Aufgrund ihrer geringen Komplexität und Umsetzbarkeit in Echtzeit scheinen Kalman Filter eine vielversprechende Komponente zukünftiger kohärente Empfängerkonzepte zu sein.

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Lalitha Pakala, October 2018

Contents

List of Abbreviations

ACF	Auto correlation function
A-CKF	Adaptive cascaded Kalman filtering
ADC	Analog to digital converter
AKF	Adaptive Kalman filtering
AO	Amplitude dependent optimization
AO-CDBP	Amplitude dependent optimization of correlated digital backward propagation
ASE	Amplified spontaneous emission
A-SSFM	Asymmetric split step Fourier method
AWGN	Additive white Gaussian noise
BP	Backward propagation
BTB	Back-to-back
CA	Code aided
CA-EKF	Code aided extended Kalman filtering
CD	Chromatic dispersion
CDBP	Correlated digital backward propagation
CKF	Cascaded Kalman filtering
CMA	Constant modulus algorithm
CPE	Carrier phase estimation
CPANE	Carrier phase and amplitude noise estimation
CW	Continuous wave
DBP	Digital backward propagation
DBPSK	Differential binary phase shift keying
DCF	Dispersion compensating fiber
DD	Decision directed
DD-CPE	Decision directed carrier phase estimation
DD-PLL	Decision directed phase locked loop
DGD	Differential group delay
DQPSK	Differential quadrature phase shift keying
DSP	Digital signal processing

EDFA	Erbium doped fiber amplifier
EKF	Extended Kalman filter
EKF-CPANE	Extended Kalman filter-carrier phase and amplitude noise estimation
FDE	Frequency domain equalization
FEC	Forward error correction
FFT	Fast Fourier transformation
FIR	Finite impulse response
FO	Frequency offset
FOE	Frequency offset estimation
GVD	Group velocity dispersion
IDD-CPE	Ideal decision directed CPE
IDD-PLL	Ideal decision directed PLL
IEKF-CPANE	Ideal extended Kalman filtering CPANE
IFFT	Inverse fast Fourier transformation
IIR	Infinite impulse response
IMP-DD-CPE	Improved decision directed carrier phase estimation
KMC	K-means clustering
LKF	Linear Kalman Filter
LO	Local oscillator
LPF	Low pass filter
MIMO	Multiple input multiple output
ML	Maximum likelihood
MLSE	Maximum likelihood sequence estimation
MMA	Multi modulus algorithm
MMSE	Minimum mean squared error
MW	Measurement weight
MZM	Machzehnder modulator
NDD	Non decision directed
NLPN	Nonlinear phase noise
NLSE	Nonlinear Schroedinger equation
NZ-DSF	Nonzero dispersion shifted fiber
OBPF	Optical band pass filter
ODBP	Optimized digital backward propagation
OOK	On off keying

OSNR	Optical signal to noise ratio
OSPS	One step per span
PBC	Polarization beam combiner
PBS	Polarization beam splitter
PDM / PM	polarization division multiplexing / Polarization multiplexing
PLL	Phase locked loop
PMD	Polarization mode dispersion
PSK	Phase shift keying
QAM	Quadrature amplitude modulation
QPSK	Quadrature phase shift keying
SD-FEC	Soft decision forward error correction
SPM	Self phase modulation
SMF	Single mode fiber
SSMF	Standard single mode fiber
SSFM	Split step Fourier method
SSM	State space model
SSNL	Single step nonlinear
S-SSFM	Symmetric split step Fourier method
U-CPE	Universal CPE
UKF	Unscented Kalman filter
VV	Viterbi-Viterbi
VV-CPE	Viterbi-Viterbi carrier phase estimation
WDM	Wavelength division multiplexing
WIA	Weighted innovation approach
XPM	cross phase modulation

List of Figures

List of Tables