Lehrstuhl für Netzwerktheorie
und Signalverarbeitung

Forschungsberichte
Herausgeber: Prof. Dr. techn. Josef A. Nossek

Andreas Winterstein

Design, analysis and demonstration of a hybrid analog/digital retro-directive antenna system for satellite communications

Shaker Verlag

Berichte aus dem Lehrstuhl für Netzwerktheorie und Signalverarbeitung der Technischen Universität München

Andreas Winterstein

Design, analysis and demonstration of a hybrid analog/digital retro-directive antenna system for satellite communications

Shaker Verlag
Düren 2019

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.: München, Techn. Univ., Diss., 2019

Printed in Germany.

ISBN 978-3-8440-6642-5
ISSN 1433-1446

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

Abstract

The goal of this thesis is to propose and validate a retro-directive antenna (RDA) system which is applicable for satellite communications. RDAs have been suggested at the end of the 1950s and their usage in satellite communications was proposed shortly thereafter. Inherent properties of RDAs are automatic self-tracking of mobile terminals, low complexity and power consumption, good scalability and the lack of complex digital signal processing (DSP). Although these are appealing features, there are no commercial RDAs in use up to the present time. This is due to the additional requirements imposed on antenna systems for satellite communications. We begin this thesis by introducing the retro-directive principle, the so-called phase conjugation, and its advantages. We contrast these properties with the demands in satellite communications. These are the need for different frequency bands for transmit and receive, the use of the antenna gain which plays a crucial role in the link budget, and the ability to operate in full duplex, i.e. to simultaneously receive and transmit. By an extensive literature review, we show that conventional RDAs are not able to fulfill these requirements.

From the demands of satellite communications, we deduce requirements for an ideal retro-directive transceiver for such applications. Using these requirements, we design an analog/digital hybrid system architecture. In contrast to conventional RDAs, the key idea is the separation of analog receiver (Rx) and transmitter (Tx) paths. Information between these paths is exchanged solely via a low-cost DSP unit. This unit processes slowly varying phase information and thus realizes the desired retro-directive behavior of the system. The data carrying signals with high bandwidths are processed exclusively by analog components. Thus we omit the necessity of high speed DSP which is a vital feature of RDAs. Using digital hardware to perform phase conjugation between the Rx and Tx paths, we enable the retro-directive principle for full-duplex, dual frequency operation.

In the following, we focus our analysis on the receiver path which performs the crucial task of extracting the necessary geometric phase information. The proposed receiver system is thereby described by phase transfer functions in the Laplace domain. We propose an optimization technique for the dynamic behavior which aims at improving the location of the slowest system pole. The receiver performance and the effect of the optimization are analyzed by continuous time domain simulations of a C-band example system using Simulink. We find that the receiver is suitable for phase detection down to a signal-to-noise ratio (SNR) of 3 dB. Additionally, we show the capability for phase modulation where we predict a data rate of up to 700 kbit/s.

In order to validate the proposed system architecture, we implement it in digital hardware. For this, we transfer the analytic continuous time system model to the discrete time domain. We show similarity between the continuous and discrete time models both analytically and by simulations. Additionally, we realize the discrete time system on a field-programmable gate array (FPGA) and validate the predicted phase detection performance with errors lower than $\pi/32$ rad. The digital hardware implementation is then used in combination with analog Rx and Tx front-ends as well as an eight element uniform linear array (ULA) to form a complete RDA demonstrator. We characterize this system with antenna measurements in an anechoic chamber where we show direction-of-arrival (DoA) estimation capability with errors smaller than 2.0° over a field-of-view (FoV) of 135°. Finally, we prove the retro-directive capability of our demonstrator system by monostatic and bistatic measurements. We achieve monostatic behavior using 5.8 GHz Rx and 7.0 GHz Tx frequencies. The variations in the returned Tx power are smaller than 5 dB over a FoV of 113°.