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博　士　学　位　论　文

无线中继系统干扰抑制算法研究

The Research of Interferences Mitigation Algorithms for Wireless Repeaters

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摘 要

随着通信技术的发展，无线中继在现有系统以及未来的分布式协同通信系统与网络中起着重要的作用。在同频同时收发的情况下，覆盖天线信号容易反馈至施主天线，造成系统的自激振荡。而且中继系统一般输出功率较大，因而容易受到功率放大器等设备非线性效应的影响，产生带内失真和带外频谱扩展，对邻近信道产生干扰。因此，中继技术在获得覆盖和容量增益的同时，往往也产生了新的干扰源，导致了更复杂的干扰结构。其中反馈自激和带外泄漏是两种主要的干扰源，论文采取的抑制方法是自适应噪声抵消和基于数字预失真的功放线性化技术。

本文包含反馈干扰抵消和带外抑制算法研究两大部分。其中的反馈干扰抵消部分主要针对最小均方(LMS)算法收敛速度和精度之间的矛盾，结合无线信道和信号的特点，提出了若干新的改进算法。带外抑制部分针对目前幂级数记忆多项式预失真算法的问题，着重研究了基于单形规范线性分段(SCPWL)函数的分段预失真算法，以及粒子群优化等智能算法在预失真领域的应用。

在 LMS 算法研究方面，论文首先对几种最优变步长算法进行了比较研究，澄清了最优变步长的表达式，总结出了一类实用的最优变步长算法。通过步长分配策略的改进，得到了快速而均匀收敛的比例归一化 LMS(PNLMS)算法。同时将最优步长和改进的比例算法相结合，提出了一种实用的最优变步长 PNLMS 算法，大幅提高了算法的收敛速度。随后对复数凸组合与仿射组合 LMS 算法进行了全面的研究并给出了性能解析式，证明了组合滤波器的性能将接近（对凸组合）或优于（对仿射组合）个体滤波器；提出了可工作于任意步长的仿射组合参数计算方法；证明了 PNLMS 与 NLMS 凸组合算法的性能优势。最后导出了复数最小均四次方(LMF)算法的收敛域与稳态误差解析式，比较结果表明 LMF 在非高斯分布输入信号的条件下稳态误差优于 LMS 算法。将反馈抵消问题纳入独立分量分析(ICA)的框架中，根据极小化互信息的准则，导出了一种基于复数 ICA 的自适应算法，该算法在二项等双峰型分布信号输入的条件下稳态误差优于 LMF 与 LMS 算法。

在数字预失真算法方面，基于幂级数记忆多项式的间接学习结构已经实现了工程应用。然而存在着对强非线性和特殊功放的补偿效果不佳，非线性数据矩阵的条件数较大，稳定性差，高阶多项式不易硬件实现等问题。论文针对这些问题，采用 SCPWL 函数分段线性化的方法实现预失真。论文首先给出了 SCPWL 函数预失真器的结构和参数辨识方法。理论推导和仿真结果表明该函数的抗干扰性优于幂级数多项式。提出了一种 SCPWL 基函数的扩展方法，得到了完备的 SCPWL 函数以及新的预失真器结构。提出了一种基于加权曲率-弦长积的断点优化方法，提高了 SCPWL 函数的非线性拟合精度。SCPWL 函数与幂级数记忆多项式级联应用以及系数的分批求取方法有效地减少了计算量。随后推导了复数可分离最小二乘和两步 LS 辨识算法，为 Hammerstein 和 Wiener 预失真器的参数辨识提供了统一的快速收敛算法。包络跟踪(ET)功放具有独特的“S”型特性曲线，仿真结果表明，SCPWL 函数预失真算法针对该类功放可获得 35dB 以上的带外抑制。最后将粒子群算法引入到预失真领域。提出了一种分裂粒子群辨识功放参数，随后运用坐标反变换法求取 SCPWL 函数预失真器系数的算法，避免了复杂的矩阵求逆运算。同时提出一种粒子群优化分阶段辨识的频域预失真算法，避免了反向通道的高速采样和环路时延估计。

论文还对转置重定时延时 LMS(TF-RDLMS)算法的高速硬件实现结构进行了剖析。在 FPGA 上实现了该算法并在硬件平台上初步测试了反馈干扰抵消器，获得了 30dB 的自激消除度。最后对全文的工作进行了总结，并展望了下一步的研究工作。

关键词：自适应滤波；带外抑制；LMS 算法；数字预失真；SCPWL 函数；粒子群优化

Abstract

With the development of communication technology, wireless relay systems play an important role in existing and future distributed cooperative communication systems and networks. Signals from service antenna are apt to feed back to donor antenna in the case of working on the same frequency and same time, which causes the system into self-oscillation. Furthermore, due to their large output power, wireless relays are vulnerable to the power amplifiers and other equipments' nonlinear effects, which results in inband distortion, outband spectrum expansion and adjacent channel interference. Therefore, while obtaining coverage and capacity gain, relay technoloty also creats new sources of interference and leads to more complex interference structures. Wherein the feedback self-oscillation and outband leakage are the two main sources, and the suppression methods taken in this dissertation are adaptive noise cancellation and digital predistortion based power amplifier linearization technology.

This dissertation includes two parts: feedback interference cancellation and outband suppression. On the one hand, feedback interference cancellation aims at the contradictions of convergence speed and accuracy of the Least Mean Square (LMS) algorithm and combines with radio channel and signal characteristics, hense some new improved algorithms are presented. And on the other hand, outband suppression aims at the defects of power series based memory polynomial, and takes research into piecewise predistortion algorithms based on Simplicial Canonical Piecewise Linear Function (SCPWL) and the applications of intelligent algorithms such as Particle Swarm Optimization (PSO) in the predistortion field.

In the aspect of LMS algorithm research, first, several optimal variable step size algorithms are compared to clarify the optimal variable step size expression, and a kind of practical optimal variable step size algorithm is summed up. Through step allocation strategy improvements, rapid and uniform convergence Proportionate

Normalized LMS (PNLMS) algorithms are obtained. And at the same time, combining two algorithms of optimal step size and improved proportionate, a practical algorithm of optimal variable step size PNLMS algorithm is presented, which can improve the convergence speed greatly. Second, on the basis of the comprehensive study of complex convex combination and affine combination of LMS algorithms, the performance analytic expressions are obtained, which proves that the performances of combination filter will be close (for convex combination) or superior (for affine combination) to that of component filters. An affine mixing parameter calculating method which can work in arbitary step combination is presented. And the performance superiority of the convex combination algorithm of PNLMS and NLMS is proved. Finally, the analytic expressions of convergence domain and steady-state error of the complex least mean fourth (LMF) algorithm are presented, and the comparison results demonstrate that steady-state error of LMF is superior to that of LMS algorithm in case of non-gaussian distribution signals input. The feedback interference cancellation problem is brought into Independent Component Analysis (ICA) demix framework, and according to mutual information minimization criteria, an adaptive algorithm is derived based on complex ICA, whose steady-state error is superior to that of LMF and LMS algorithm in case of bimodal type such as binomial distribution signals input.

In the aspect of digital predistortion algorithm, engineering application of the indirect learning structure based on power series memory polynomial has been achieved. However there exist various problems as follows: poor compensation to strong nonlinear and special amplifiers, large condition number of non-linear data matrix, poor stability and difficult hardware implementation of high order polynomials. Focusing on these problems, this dissertation exploits SCPWL function piecewise linearization to achieve predistortion. First, structure of predistorter based on SCPWL function and its' parameter identification method are presented. theoretical derivation and simulation results demonstrate that anti-interference

performance of SCPWL function is superior to that of power serious polynomials. A base function expansion method is proposed and thus a complete SCPWL function and a new predistorter structure are obtained. A breakpoint optimization method based on weighted curvature-chord products is presented as well, which improves the accuracy of nonlinear fitting. Application of SCPWL function cascaded with power series memory polynomials and coefficients acquisition in batches effectively reduce the amount of calculation. Second, complex separable Least Square (CSLS) and two-step LS identification algorithm are derived, which provide a unified rapid convergence parameter identification algorithm for Hammerstein and Wiener predistorters. Envelope tracking (ET) power amplifiers have unique “S” type characteristics curve. Simulation results demonstrate that over 35dB outband suppression can be obtained via SCPWL function predistortion acted on ET power amplifers. Finally, the particle swarm optimization algorithm is introduced into the field of predistortion. An algorithm of identifying amplifier parameters via split PSO, and then acquiring SCPWL function predistorter’s coefficients by inverse coordinate mapping method is presented, which avoids complicate matrix inversion operations. And at the same time, an in phase particle swarm optimization identification frequency domain predistortion algorithm is presented, which avoids reverse channel high-speed sampling and loop delay estimation.

Structure of transposed form fine grained retimed delayed LMS (TF-RDLMS) algorithm for high speed hardware implementation is dissected as well. The algorithm is implemented in FPGA and a preliminary feedback interference canceller is tested on the hardware platform, which obtains 30dB self-oscillation suppression. In the end, the dissertation summarizes the work and looks forward to the next step of the research work.

Key Words: Adaptive Filters; Outband Suppression; LMS Algorithm; Digital Predistortion; SCPWL Function; Particle Swarm Optimization

目录