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厦门大学

博 士 学 位 论 文

稀疏水声信道的近似范数估计

Approximation Norm Estimations of Sparse Underwater Acoustic Channel

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摘　要

声波是目前水下无线通信方式中广泛采用的信号传输媒介, 且水下声传播面临着与陆地无线电通信中不曾有的困难和挑战, 如: 随载波频率增加而衰减严重; 传播路径的多变性; 以及速度约为1500m/s 的传播速度。这些约束使得水声信道具有较为明显的时延多普勒双扩展等现象。

论文以水声通信系统为应用背景, 针对稀疏水声信道下的可靠通信问题, 以水声信道稀疏特性-信道建模- 信道估计-均衡器输出结果验证为主线, 着重研究水声信道估计算法。在算法理论研究的基础上, 结合多次数值仿真和海试实验; 进而通过数据处理分析, 验证论文方案的有效性。

本文结合稀疏水声信道估计的实际应用场景以及压缩感知领域中出现的稀疏信号恢复方法, 对近似范数相关知识结构进行梳理, 本文以近似范数约束为算法设计的切入点, 贯穿后续各章节中提出的稀疏水声信道估计算法。

信道特性的研究是分析和设计水声通信系统的基础。论文针对水声信道的稀疏特性对信道进行稀疏建模。首先利用水声信道的稀疏特性, 结合水声信道冲激响应函数中抽头的大小变化和位置变化分别拟合各到达路径的幅度时变和时延时变, 并以这些参数数字化为基础, 给出描述水声信道输入输出关系的数学模型。本论文采用近似范数约束下的多径参数化模型考虑了信道稀疏度变化等问题, 因此能够更好地估计出稀疏度变化的实际水声信道。

论文主要工作集中在以下方面:

分别采用逐符号和逐块信道估计策略, 结合分析水声信道所具有的稀疏结构特点。论文提出了引入梯度导引p范数约束、可适应稀疏度变化的非均匀范数、简化调整似p范数约束的逐符号自适应稀疏水声信道估计方法。这些算法针对水声信道的稀疏度变化, 算法参数能自适应地调整以便得到更精确的信道估计结果, 并结合仿真和实验进行了有效性验证。

此外, 利用Toeplitz卷积矩阵框架对水声信道冲激响应进行周期性估计。考虑到水声信道的稀疏性或簇稀疏性, 在此基础上分析几种范数约束项, 结合压缩

感知方法, 提出适应水声信道稀疏或簇稀疏特性的似零范数算法及其簇稀疏条件下的版本, 并对所提出的这两种算法性能进行分析, 结合仿真和实验进行了有效性验证。

水声信道中多普勒扩展导致时间选择性衰落, 多径扩展引起频率选择性衰落。这些因素严重限制了水声通信性能。考虑到双重扩展水声信道模型能更加精细地刻画水声信道变化特征以及降低水声双扩展信道模型计算复杂度的实际需要, 本文以时延多普勒双扩展模型- 水声信道估计算法设计-基于双扩展模型均衡器处理为主线, 引入非均匀范数约束到最小均方误差的代价函数中。基于时延多普勒双扩展模型提出非均匀范数约束下的水声信道估计算法。结合仿真和海试与传统算法进行对比, 给出相关讨论和结论。

本文在分析水声信道稀疏结构特征的基础上, 结合近似范数稀疏约束特性, 导出水声信道的逐符号估计方法以及逐块估计方法, 以及基于时延多普勒双扩展信道模型下的水声信道估计方法设计, 针对这些不同的近似范数约束水声信道估计算法, 采用基于信道估计的均衡器对其进行评估, 验证了本文所提算法的有效性。

关键词： 稀疏; 簇稀疏; 范数约束; 水声信道; 信道估计; 压缩感知; 信道冲激响应

ABSTRACT

Sound is a commonly adopted medium in underwater wireless communication, in addition, underwater acoustic communication faces the difficulties and challenges which haven't been encountered in the terrestrial wireless communication, e.g. signal strength falls off with carrier frequency; the variability of the propagation paths; and the transmitted speed is limited to round of 1500 m/s. All these constraints lead to the obvious delay Doppler (DD) doubly spread in underwater acoustic channel (UAC).

With the background of the underwater acoustic communication, this thesis focuses from UAC sparsity and UAC modeling, to UAC estimator designing and evaluation of results of channel based equalizer. Especially focuses on the research of the UAC estimators. Based on the basis of algorithm theory, we test their performance with simulations and at-sea experiments, to verify the validity of the proposed methods by the data analysis.

The thesis combines the applications of the estimation of sparse UAC and sparse recovery methods in compressed sensing area, provides the related introduction of the conceptions of approximation norms. The thesis begins at the designing of the approximated norm method, which will be throughout the subsequent chapters.

The research of the characteristics of the UAC is the basis of underwater acoustic communication. The thesis builds models for UAC with its sparsity. Firstly, we utilize the sparsity of UAC, the variability of the taps value and locations of the channel impulse response (CIR) are used to denote the the time varying of the amplitude or the time-delay of the separated paths. Based on the digital model, this thesis provides the input-output relationship. It simulates the real UAC better than those of traditional methods without sparse constraints, because the variability of sparsity of the UAC is considered in approximated norm constraint based multi-path modeling.

The main work of this thesis is listed as following:

Adopting the symbol-wise and block-wise channel estimation strategies separa-

tively, and combining the analysis of the sparse structure of the UWC, the thesis proposes a gradient guiding p norm constraint based, a non-uniform norm sparsity based, and simplified adjustment by p norm-like constraint based adaptive sparse UAC estimation methods. These algorithms can adaptively adjust the parameters in order to obtain a more accurate channel estimation results for sparse UAC according to the variability of the sparsity of UAC. Simulations and at-sea experiments are provided to verify the performance of the proposed methods.

In addition, this thesis uses Toeplitz convolution matrix to estimate the UAC periodically. Considering the sparsity or group sparsity of UAC and the analysis of several nom constraints, combining the compressed sensing methods, the thesis proposes approximated l_0 (AL0) norm method or its group sparse version for sparse or group sparse UAC. We provide the analysis of the proposed two methods. Simulations and at-sea experiments are provided to verify the performance of the proposed methods.

The Doppler spread in UAC leads to the time selective fading, delay spread causes the frequency selective fading, both of the factors severely limit the performance of underwater acoustic communication. Considering the DD model can be used to describe the variability characteristic of UAC and the necessity of reducing the complexity of the model, the thesis focuses the main ideas from DD model and UAC estimator design, to DD based equalizer, introduces the non-uniform norm constraint (NNC) to a cost function, the thesis provides the NNC based method for UAC estimation based on DD model. The proposed method is compared with traditional methods in simulations and at-sea experiments. Discussions and conclusions are given in the thesis.

Based on the analysis of the sparse structure of the UAC, this thesis combines the characteristic of the approximation norm, derives the symbol-wise and block-wise estimations of UAC, and DD based estimator in UAC. The channel based equalizers are used to test and verify the performance of the different estimators.

Key Words: Sparse; clustered sparse; norm constraint; underwater acoustic chan-

nel (UAC); channel estimation; compressed sensing (CS); channel impulse response (CIR)