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博　士　学　位　论　文

无线自组织网络中 IEEE 802.11 协议的性能分析与优化

Performance Analysis and Optimization of IEEE 802.11 Protocol in Wireless Ad Hoc Networks

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摘 要

作为新一代无线通信网络的核心技术之一，无线自组织网络技术已成为当前信息技术领域的一大研究热点。作为无线自组织网络的关键技术，媒体接入控制（Medium Access Control，MAC）协议决定着无线信道的使用方式，并负责为节点分配无线通信资源，其性能的优劣直接影响无线信道的利用率和网络的整体性能。其中，IEEE 802.11 的 MAC 协议是目前无线自组织网络的测试系统和实际应用中使用最多的 MAC 协议之一，也是许多无线自组织网络 MAC 协议的研究基础。因此，系统研究 IEEE 802.11 的性能并加以针对性的改进，具有极为重要的理论意义和广泛的应用价值。

IEEE 802.11 MAC 协议以分布式协调功能（Distributed Coordination Function，DCF）为最基本的信道接入机制。本文围绕无线自组织网络 DCF 协议性能分析与性能优化这两个关键问题展开了深入研究，分析了影响 DCF 协议性能的本质原因。论文的主要内容和研究成果表现在以下几个方面：

1. 以 Markov 链分析模型为基础，针对理想信道，提出了一种改进的非饱和 IEEE 802.11 DCF 分析模型

Markov 链分析模型以其简单性与准确性被广泛用为 IEEE 802.11 DCF 性能分析的参考模型。本文以理想信道为应用背景，在现有模型的基础上，针对现有模型并没有完全满足 IEEE 802.11 协议规定以及实际应用情况，提出了一种改进的非饱和条件下 IEEE 802.11 DCF 分析模型。同时本文考虑有限的 MAC 缓冲队列的实际情况，将 Markov 模型稳定状态的求解结合 M/G/1/K 排队分析模型，进一步推导出不同负载下吞吐量和时延性能的模型。仿真结果表明，该理论模型能够精确地预测广义 IEEE 802.11 DCF 协议的系统性能。

2. 针对衰落信道，建立了一种基于 PHY/MAC 跨层的 DCF 性能分析模型

考虑到实际无线自组织网络信道中存在误码和捕获效应，本文研究了在高斯白噪声（Additive White Gaussian Noise，AWGN）信道、瑞利（Rayleigh）衰落信道和莱斯（Rician）衰落信道下对应的三种不同调制方式（DBPSK、DQPSK 和 CCK）的误码率模型，并在误码率模型和捕获效应模型的基础上建立了一种基于 PHY/MAC 跨层的 IEEE 802.11 DCF 性能分析模型。数值结果和

仿真结果验证分析了不同误码率和不同捕获阈值下吞吐量的性能，两种结果具有较好的一致性。

3. 在理想信道和衰落信道的分析模型基础上，推导出了一种针对最大吞吐量的饱和点性能分析模型

通过理想信道中吞吐量性能模型的推导，得出了非饱和吞吐量的值与网内节点数、数据业务量和数据帧长三者线性相关的结论，但当网络负载达到饱和吞吐量的上界时，吞吐量不再是线性增长。基于理想信道中性能分析模型，进一步推导出了业务量和节点数目的饱和点模型。针对衰落信道环境中，数据帧过长导致误帧率偏大的缺点，在基于 PHY/MAC 跨层的 DCF 性能分析模型基础上得出了在衰落环境中最优帧长模型。在一定的网络负载下，通过饱和点模型可以获得最优网内节点数或者最优数据到达率的值，从而指导网络达到最优状态。

4. 在理想信道的性能分析模型基础上，提出了一种基于网络竞争度的自适应退避算法

自适应算法需要根据网络状况来动态调整自身的参数以达到最优的网络性能，而网络最优的性能可以根据协议的性能分析模型得到。本文根据 IEEE 802.11 DCF 的性能分析模型提出了一种网络竞争度的估计，并基于该估计提出了一种自适应退避算法（Adaptive Backoff algorithm，ABA）。该算法能够有效地根据网络当前状况调整数据包的发送，同时根据当前网络负载情况调整竞争窗口，从而充分利用网络资源使协议性能得到提高。仿真结果表明，ABA 算法能够较大地提高 DCF 的吞吐量和时延性能，并且在节点密集度高的网络中具有更好的适应性。

本文提出的 IEEE 802.11 DCF 协议性能分析与优化算法，在福建省重大专项“自组织应急通信系统设计”和英国工程和自然科学研究委员会（EPSRC）项目“Wireless Sensor Networks for Industrial Processes（WSN4IP）”中，为衰落应用环境中 MAC 协议参数的设置和调节提供了理论依据和实际指导。

关键词：无线自组织网络；媒体接入控制；IEEE 802.11；性能分析；退避算法

ABSTRACT

As one of the essential technologies of next generation mobile communication system, wireless Ad Hoc network has become the focus in the field of current information technologies. As the key component of wireless Ad Hoc networks, Media Access Control (MAC) protocols determine the usage mode of wireless channels and allocate radio resource for nodes, which can directly influence the efficiency of wireless channels and overall performance of the network. IEEE 802.11 protocol is one of most popular contention-based MAC protocols in the test systems and practical applications of Ad Hoc networks at present, which is also the research basis of MAC protocols in wireless Ad Hoc networks. Therefore, it is meaningfulness to study and improve the performance of IEEE 802.11 protocol systematically, which is of important theoretical significance and extensive application value.

The most basic channel access mechanism in IEEE 802.11 MAC protocol is Distributed Coordination Function (DCF). In this dissertation, the performance analysis and optimization of DCF protocol in wireless Ad Hoc networks were thoroughly investigated, and the main factors which affect the performance of DCF protocol were analyzed. The main contents and research results of the dissertation are presented as follows:

1. An improved IEEE 802.11 DCF analysis model under an ideal channel was proposed based on the Markov chain analysis model

The Markov chain analysis model is widely quoted as the basic model of IEEE 802.11 DCF performance analysis due to its simplicity and accuracy. Under the ideal channel scenario, based on the existed performance analysis model, according to the situation the IEEE 802.11 standard and practical application, an improved performance analysis model of IEEE 802.11 DCF under unsaturated conditions was proposed. Moreover, considering the finite MAC queue in reality, the model of throughput and delay performance was further derived by the combination of the solution of stationary state of the Markov model and an M/G/1/K queuing model. The simulation result indicates that the proposed model can accurately predict the performance of generalized IEEE 802.11 DCF protocol.

2. A performance analysis model based on PHY/MAC layer was presented according to the fading channel in reality

Considering the transmission error and capture effect in real implementations of wireless Ad Hoc network channels, the bit error rate models of three different physical modulations (DBPSK, DQPSK and CCK) of IEEE 802.11 used in Additive White Gaussian Noise (AWGN) channel, Rayleigh fading channel and Rician fading channel separately were studied. A performance analysis model based on PHY/MAC layer of IEEE 802.11 was built based on the bit error rate model and capture effect model. The simulation results validated the accuracy of throughput performance model under different bit error rates and capture thresholds.

3. A saturated performance analysis model about the maximum throughput was introduced based on the performance analysis models in ideal channel and fading channel

By deducing the throughput of the performance analysis model in ideal channel condition, the conclusion can be drawn that there existed a linear relation between the unsaturated throughput and three parameters, including the number of network nodes, the traffic load and the data frame length. However, the relation would be nonlinear when the network payload reaches the upper bound of saturation throughput. Based on the performance analysis model in ideal channel, a saturated point model of traffic load and the number of network nodes was further derived. Taking into account the fading channel environment, for the bigger frame error rate caused by the longer data frame, an optimal frame length model in fading environment was derived based on the PHY/MAC performance analysis model. The optimal number of network nodes, the optimal traffic load or date frame length can be obtained by the saturated point model and the optimal frame length model, which are helpful to predict and optimize the system performance of the networks.

4. An adaptive backoff algorithm about network competition degree was proposed based on the performance analysis model in ideal channel

Adaptive algorithm can adjust its own parameters to achieve the optimal network performance according to the network status. The optimal network performance can be predicted by the performance analysis model of the protocols. Based on the performance analysis model, an estimation of network competition degree was presented, and an adaptive backoff algorithm based on network competition degree (ABA) was proposed. The proposed backoff algorithm can effectively adjust the packet transmission probability and contention window according to the current network status and the current traffic load, which improves the performance of

protocols by making full use of network resources. The simulation validated that ABA algorithm can enhance the throughput and delay performance of DCF protocol, especially in the networks of high density nodes.

The proposed performance analysis model and optimization algorithm of IEEE 802.11 DCF protocol are provided as a theoretical and practical guidance for the setting and adjusting of MAC parameters in fading environment at “Design of Wireless Ad Hoc Emergency Communications System” under the Major Science and Technology Special Project of Fujian Province, and “Wireless Sensor Networks for Industrial Processes (WSN4IP)” under the Engineering and Physical Sciences Research Council (EPSRC) of UK.

Key words: Wireless Ad Hoc Network; Medium Access Control; IEEE 802.11; Performance Analysis; Backoff algorithm

目 录