Computer Networks 55 (2011) 2545–2557

Contents lists available at ScienceDirect

Computer Networks

journal homepage: www.elsevier.com/locate/comnet

Modeling and analysis of TXOP differentiation in infrastructure-based WLANs

Geyong Min, Jia Hu *, Mike E. Woodward

Department of Computing, School of Informatics, University of Bradford, Bradford BD7 1DP, United Kingdom

ARTICLE INFO

Article history:
Received 29 September 2010
Received in revised form 1 March 2011
Accepted 27 April 2011
Available online 6 May 2011
Respondible Editor: Y.-D. Lin

Keywords:
Medium access control
Unbalanced traffic
Access point
TXOP
Queueing analysis

ABSTRACT

The Access Point (AP) is the bottleneck of infrastructure-based Wireless Local Area Networks (WLANs) due to its responsibility for forwarding all the incoming and outgoing frames. As a result, the network performance is significantly deteriorated by the unbalanced traffic loads at AP and other mobile stations. A potential solution to the bottleneck problem is to assign different Transmission Opportunity (TXOP) limits to the AP and mobile stations, respectively. This study develops a new analytical model to investigate the Quality-of-Service (QoS) performance metrics including throughput, total frame delay, and frame loss probability in infrastructure-based WLANs with TXOP differentiation under the unbalanced traffic loads. To this end, the transmission queue is modeled as a bulk service queueing system in order to address the challenge of queueing analysis arising from the TXOP burst transmission mechanism. The accuracy of this model is validated through extensive NS2 simulation experiments. The analytical results demonstrate that the implementation of TXOP differentiation can substantially alleviate the bottleneck effects of unbalanced traffic loads, increase the aggregate throughput and decrease the frame delay and loss probability. Moreover, the developed model can be adopted as a cost-efficient tool to evaluate the impact of TXOP limits on the network performance and to investigate the optimal setting of TXOP limits under different working conditions.

1. Introduction

The IEEE 802.11-based Wireless Local Area Networks (WLANs) [16] have been widely deployed at campuses, enterprises, homes, and hotspots to provide ubiquitous wireless access. The fundamental Media Access Control (MAC) scheme in the IEEE 802.11 standard is called Distributed Coordination Function (DCF) [16], which is a random access scheme based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol. Practical WLANs are primarily configured to operate in the infrastructure mode, where a cluster of Mobile Stations (MSs) associated with an Access Point (AP) construct a Basic Service Set (BSS). All MSs in a BSS communicate with each other through the AP which provides access to the Internet and other associated BSSs. WLANs can also operate in the ad hoc mode where MSs communicate with each other directly in a peer-to-peer manner if they are within the transmission range of each other.

Analytical modeling of MAC protocols in WLANs has been extensively reported [1–7,9–13,18,20,22–25,27–29,31–33,35,36,38–44]. Most of the existing models have been limited to the scenario of homogeneous stations with the unrealistic assumption that all stations have identical traffic loads. However, it is insufficient to confine performance analysis to such a scenario due to the unbalanced traffic loads caused by the AP for forwarding the incoming and outgoing frames in infrastructure-based

* Corresponding author. Tel.: +44 7701084588.
E-mail addresses: g.min@brad.ac.uk (G. Min), jiahu9@gmail.com (J. Hu), m.e.woodward@brad.ac.uk (M.E. Woodward).

1389-1286/$ - see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.comnet.2011.04.015

WLANs. The unbalanced traffic loads make the AP a bottleneck of WLANs and can severely degrade network performance, which needs to be further investigated.

This study differs from prior work in two major aspects. Firstly, we incorporate the Transmission Opportunity (TXOP) scheme [17] into the infrastructure-based WLANs with unbalanced traffic loads in order to solve the bottleneck problem and improve the network performance. TXOP scheme has been specified in the IEEE 802.11e Enhanced Distributed Channel Access (EDCA) protocol [17]. This scheme can reduce the contention overhead and also provide service differentiation between various traffic classes. To combat the bottleneck problem caused by the unbalanced traffic loads, the AP with the higher traffic loads is assigned with a larger TXOP limit and thus can send more frames after winning the channel. Secondly, an analytical performance model is developed for the TXOP scheme in infrastructure-based WLANs. Most existing analytical models of DCF under unsaturated conditions cannot be directly applied to analyze TXOP under unbalanced traffic loads due to its burst transmission mechanism. Therefore, we develop a new model for TXOP using a bulk-service queueing system which can properly overcome the difficulties arising from the burst transmission mechanism. The key contributions of this paper can be summarized as follows:

(1) A new analytical model is developed to study the performance of the infrastructure-based WLANs with TXOP differentiation and unbalanced traffic loads. This model is able to quantitatively analyze the Quality-of-Service (QoS) performance metrics including throughput, total frame delay and loss probability. The accuracy of this model is validated by comparing the analytical results against those obtained from extensive NS2 simulation experiments.
(2) The analytical model is adopted to investigate the efficiency of using the differentiated TXOP limits to solve the bottleneck problem arising from unbalanced traffic loads in WLANs. The numerical results demonstrate that the use of the larger TXOP limit at the AP than those at other mobile stations can substantially increase the aggregate throughput and decrease the total frame delay and loss probability, and thus significantly enhance the network performance.
(3) Moreover, this model can be adopted as a cost-efficient tool to evaluate the impact of TXOP limits on the network performance with the varying number of mobile stations and to investigate the optimum setting of TXOP limits under different working conditions.

The rest of this paper is organized as follows: In Section 2, we present an overview of the DCF protocol and the TXOP scheme. Section 3 reviews the related work in the literature. The analytical model is presented in Section 4. We validate the accuracy of the model and conduct the performance analysis in Section 5. The conclusions follow in Section 6.

2. Medium access control

2.1. Overview of the DCF protocol

The fundamental MAC protocol in the IEEE 802.11 standard is DCF [16], a random access scheme based on the CSMA/CA protocol. In DCF, a station senses the channel before attempting transmission. If the channel is detected idle for a Distributed Inter-frame Space (DIFS), the station transmits the frame. Otherwise, if the channel is sensed busy (either initially or during the DIFS), the station defers until the channel is detected idle for a DIFS and then generates a random backoff counter before the transmission starts. In addition, a station must separate two consecutive frame transmissions by a random backoff interval, even if the channel is sensed idle for a DIFS after the successful transmission of the first frame.

The value of the backoff counter is uniformly chosen in the range $[0, W_i - 1]$, where $W_i = 2^i W$ is the current contention window and i is the backoff stage. W_i is initially set to $CW_{\min} = W$ and doubled after each unsuccessful transmission until it reaches a maximum value $CW_{\max} = 2^m W$ where m represents the maximum number of backoff stages. It remains at the value $CW_{\max}$ until it is reset to $CW_{\min}$ upon the successful frame transmission or if the number of unsuccessful transmission attempts reaches a retry limit. The backoff counter is decreased by one for each time slot (*i.e.*, an interval of a fixed duration specified in the protocol [16]) when the channel is idle, halted when the channel becomes busy and resumed when the channel is idle again for a DIFS. A station transmits a frame when its backoff counter reaches zero. Other stations that hear the transmission of the frame set their Network Allocation Vector (NAV) to the expected period of time when the channel is busy, as indicated in the duration identity field of the frame. This is called the virtual carrier sensing mechanism. If either the virtual carrier sensing or physical carrier sensing [16] indicates that the channel is busy, the station commences the back-off procedure. Upon the successful reception of the frame, the destination station sends an ACK frame back immediately after a Short Inter-frame Space (SIFS) interval. If the source station does not receive the ACK within a specified ACK timeout interval, the frame is retransmitted according to the given backoff rules. Each station maintains a retry counter that increases by one after each retransmission. The frame is discarded after an unsuccessful transmission if the retry counter reaches the retry limit.

2.2. The principle of the TXOP scheme

In DCF, the system efficiency is considerably affected by various overheads referred to as Physical (PHY) layer headers, control frames, backoff, and inter-frame space. The overhead problem becomes more serious as the data rate increases [36]. To mitigate the impact of the overheads and improve the system efficiency, the TXOP scheme has been proposed in the IEEE 802.11e protocol [17].

Different from DCF where a station can transmit only one frame after winning the channel, the TXOP scheme