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Achieving weighted fairness in WLAN mesh networks: An analytical model

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ABSTRACT

Multi-hop WLAN mesh networks employing the enhanced distributed channel access (EDCA) scheme as the medium access control protocol have been shown to suffer from serious throughput unfairness among competing flows. Indeed, some flows can even capture the whole channel bandwidth while other flows get starved. In this paper, we focus on achieving weighted fairness for differential services in WLAN mesh networks. We first introduce the concepts of the instantaneous collision zone and the persistent collision zone of receivers in multi-hop networks. Then we suggest that collisions induced by the hidden jammers located in the persistent collision zone of receivers are the primary causes for the throughput unfairness. We further develop a three-dimensional Markov chain model to determine how to precisely tune the backoff persistence factors to achieve the weighted fairness for flows with diverse quality of service (QoS) demands. In this model, we put forward the pseudo states to distinguish the different backoff procedures induced by the RTS collisions and the data collisions. Through analytical modeling, we get the proper backoff persistence factors to achieve a predefined weighted fairness goal. Finally, we validate the accuracy of our model by comparing the analytical results with that obtained by means of simulations.

1. Introduction

Wireless local area network (WLAN) mesh networking has recently gained significant attentions [1–4], as it is a promising technology to provide ubiquitous wireless connectivity and broadband Internet access. The IEEE 802.11 Task Group "s" (TGs) initiated the standardization process for WLAN mesh networks in May 2004, and formally issued 802.11s as a mesh amendment for the IEEE 802.11 standard in September 2011 [5]. A typical WLAN mesh network comprises of a set of stationary wireless mesh points (MPs) which construct the multi-hop backbone with wireless links and forward the traffic to or from the Internet in a multi-hop fashion. Some of the MPs have also equipped with a WLAN access point function, which are referred to as mesh access points (MAP). MAPs offer Internet accesses for wireless stations that are legacy WLAN stations and can be implemented in consumer electronic devices as well as laptop computers. One or several MPs act as mesh portals points (MPP) connected to the Internet via high-speed wires.

IEEE 802.11s continues to adopt the enhanced distributed channel access (EDCA) [6] scheme defined in the base standard to provide medium access control (MAC) for MPs [7,8]. EDCA relies on the physical and virtual carrier sense that does not require synchronization among MPs. It employs the four-way handshake technique (RTS/CTS/data/ACK) to resolve the hidden terminal

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problem in multi-hop environments. Meanwhile, it differentiates packets from the upper layer into four different access categories (AC) based on their quality of service (QoS) priorities, and provides differentiated services for each AC via adjusting contention parameters. These parameters include the arbitration inter frame space (AIFS), the minimum and the maximum contention window sizes (CW_{min}, CW_{max}), the backoff persistence factor (BPF), and the continuous transmission opportunity (TXOP) limit.

EDCA continues to adopt the exponential backoff scheme. A MP that wants to transmit a packet waits until the channel is sensed idle for an AIFS period, and then continues to wait for a random backoff time. The random backoff time is uniformly chosen in the interval [0, $CW-1$], where CW denotes the current contention window size of the MP and is initially set to CW_{min}. When an unsuccessful transmission occurs, the CW is expanded by BPF until the CW_{max} is reached, i.e.,

$$CW = \begin{cases} BPF^i CW_{min} & BPF^i CW_{min} < CW_{max} \\ CW_{max} & BPF^i CW_{min} \geqslant CW_{max} \end{cases}, \tag{1}$$

where i denotes the consecutive transmission failure times. The value of BPF of each node can be tuned individually. Contrarily, the CW should be reset to CW_{min} after any successful transmission or the retransmission counter reaches a specific retry limit. During the random backoff period, the backoff time counter of the MP is decremented at the beginning of each time slot if the channel is sensed idle, suspended as long as the channel is sensed busy, and resumed only when the channel is sensed idle for an AIFS period again.

Since the EDCA scheme was originally designed for the purely single-hop independent basic service set (IBSS) of WLAN, where the nodes are inter-connected via a direct wireless link, it exhibits a poor performance in multi-hop environments [9–11]. As we will show in Section 2, WLAN mesh networks suffer from serious throughput unfairness among competing flows. That is, some flows may yield larger throughput than the other flows with the same or higher QoS priorities. In some cases, low priority flows can even monopolize the channel bandwidth while high priority flows get starved [12]. This problem is often referred to as the weighted fairness problem of multi-hop WLAN mesh networks. Here, "weighted fairness" means that the adjacent multimedia flows should share the channel bandwidth according to their different QoS priorities.

Recently, a number of studies have shown that the weighted fairness problem can be addressed by appropriately tuning the contention parameters of flows. Among them, most of the attentions have been focused on developing distributed weighted fairness guarantee schemes within the framework of EDCA, and thus designing fair medium access control protocols for WLAN mesh networks [13–19]. Simulation results show that these schemes can achieve the predefined weighted fairness goal under the given network conditions. However, these schemes are tend to be opportunistic in nature as they fail to provide a universal analytical model to address the foundations of the weighted fairness problem by means of qualitative methods.

There have been considerable attempts to model the MAC-layer saturation throughput performance of the IEEE 802.11 WLAN. Here, the saturation throughput is defined as the maximum throughput that the network can achieve in saturation conditions. The "saturation" means that the network layer queue of each node is always nonempty. Bianchi [20] uses a discrete Markov chain to model the backoff procedure performed by a tagged node, and derives the saturation throughput through the stationary probability that the node transmits a packet in a generic slot time. This pioneering work motivates substantial subsequent analysis. Robinson and Randhawa [21] proposed an analytical model to analysis the saturation throughput of the EDCA protocol. Yang [22] also presented a Markov model to validate the effectiveness of the service differentiation in EDCA by differentiating CW_{min}, BPF and maximum backoff stage. In addition, Gas et al. [23], Ho Young et al. [24] and Ching-Ling and Wanjiun [25] proposed analytical models which considered the impact of virtual collisions among different ACs within a node.

These saturation throughput models and the analytical results obtained have also motivated and guided research efforts on analyzing the throughput allocation ratio among multimedia flows in WLAN. Cheng et al. [26] have proposed a Markov model to derive the relationship between the throughput allocation ratio and the value of CW_{min}. Afterwards, CW_{min} was adjusted to achieve a predefined weighted fairness goal based on the relationship. Liu [27] also presented an analytical model to find the optimal configuration of contention parameters to achieve the weighted fairness among multimedia flows. Ge et al. [28] and Banchs and Vollero [29] put forward analytical models to address the issue of finding the optimal configuration of the contention parameters to maximize the total saturation throughput and achieve the weighted fairness among multimedia flows.

Although various modeling techniques and viewpoints of the weighted fairness performance are observed in these works, they have a lot in common with regards to the model assumptions. The most common assumption taken by the existed work is that the collisions may only occur at the start instant of the RTS frame transmission. Since all the nodes are within the transmission range of each other and the carrier of a node can be detected by all other nodes, this assumption is true in single-hop network scenarios [20]. After a transmitter starts to send an RTS frame to its receiver, the other nodes in the network sense the channel busy and defer their transmissions by the physical carrier sense. Meanwhile, nodes can set their network allocation vector (NAV) by overhearing the reservation information in the RTS/CTS frames and defer access to the channel during the reservation period. Hence, the data/ACK handshake should not be interfered by the jammers as long as the RTS/CTS handshake is performed successfully. However, the situation is quite different in multi-hop network scenarios [30], as the carrier of a node may not be detected by some of the nodes [10]. We will discuss in the following section, collisions induced by the jammers within the physical carrier sense range of the