Chapter 22

Queuing Delay Analysis of Multi-Radio Multi-Channel Wireless Mesh Networks

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ABSTRACT

Wireless mesh networking is becoming an economical means to provide ubiquitous Internet connectivity. In this chapter, we study wireless communications over multi-radio and multi-channel wireless mesh networks with IEEE 802.11e based ingress access points for local clients and point-to-point wireless links over non-overlapping channels for wireless mesh network backbones. We provide a set of algorithms to analyze the performance of such wireless mesh networks with wideband fading channels in various office building and open space environments and commonly-used Regulated and Markov On-Off traffic sources. Our goal is to establish a theoretical framework to predict the probabilistic end-to-end delay bounds for real-time applications over such wireless mesh networks.

I. INTRODUCTION

Wireless mesh networking is a new technology that complements infrastructure-based wired networks to provide ubiquitous Internet connectivity. Generally, wireless mesh networks (WMNs) are composed of wireless mesh routers and clients. The mesh routers with gateway/routing functions form wireless mesh backbones and provide multi-hop connectivity between clients and the Internet or between clients. Unlike nodes in traditional wireless networks such as mobile ad hoc networks (MANETs), mesh routers are static and have no power constraint and their locations can be carefully selected. The unique features and characteristics of WMNs, which distinguish WMNs from wired networks, include

a. Low initial investment
b. Extensive coverage areas
c. Ease of deployment and expansion
d. Fault tolerance

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With extensive research efforts on wireless mesh networking by academic and industrial communities (Akyildiz, Wang, & Wang, 2005; Bruno, Conti, Gregori, Wijting, Kneckt, & Damle, 2005; Faccin, Wijting, Kneckt, & Damle, 2006; Kyasanur, So, Chereddi, & Vaidya, 2006; Lee, Zheng, Ko, & Shrestha, 2006) as well as the commercial deployments of wireless mesh networks (WMNs) around the world, wireless mesh networking technology is becoming a vital component of our daily life.

In wireless communications, wireless channels are error-prone and their capacities are physically limited. There are many factors that affect the performance of wireless channels, e.g., signal power attenuation, inter-channel and co-channel interference, thermal noise, Doppler frequency, shadowing, and multipath channel fading. Therefore, QoS provisioning for many applications, which have diverse performance requirements in terms of minimum data rate, delay/delay jitter bound, and packet loss rate over wireless networks, poses a very difficult challenge. Moreover, it has been revealed (Gupta & Kumar, 2000) that the throughput of per source-destination pair in a multihop wireless network with a single shared channel scales with the number of network nodes n as $O(1/n^{0.5})$. It has also been demonstrated (Ganguly, Navda, Kim, Kashyap, Niculescu, Izmailov, Hong, & Das, 2006; Niculescu, Ganguly, Kim, & Izmailov, 2006) that the performance of VoIP applications over single channel WMNs degrades quickly as the lengths of VoIP traffic routes increase. Thus, the QoS capability of multihop wireless networks with a single shared channel is very limited.

With the rapid evolution of radio technologies, commercial multi-radio products have emerged in the market, e.g., BelAir Networks` BelAir200 mesh router with up to four radios and Motorola`s Motomesh node with up to four radios and Strix`s OWS mesh router with up to six radios. Moreover, there are 27 non-overlapping channels for IEEE 802.11 based wireless networks, i.e., 3 non-overlapping channels for IEEE 802.11b/g standards in 2.4 GHz frequency band and 24 non-overlapping channels with IEEE 802.11a standard in 5 GHz frequency band. These factors make it natural to consider WMNs with multi-radio and multi-channel mesh routers as a feasible solution to mitigate the inherent capacity limitation of conventional single channel wireless networks for QoS provisioning. It is worth noting that the asymptotic capacity of multi-channel and multi-radio wireless mesh networks has been theoretically characterized (Kyasanur & Vaidya, 2005) and experimentally verified (Kodialam & Nandagopal, 2005).

Generally, one of crucial performance metrics for QoS provisioning over multihop wireless networks is the end-to-end delay experienced by traffic flows. Following the seminal work (Gupta & Kumar, 2000), the wireless communication and networking research community has made extensive efforts to understand the throughput-delay scaling law. The results provided in (Bansal & Liu, 2003; Gamal, Mammen, Prabhakar, & Shah, 2004; Needly & Modiano, 2005; Moraes, Sadjadpour, & Garcia-Luna-Aceves, 2004; Moraes, Sadjadpour, & Garcia-Luna-Aceves, 2004; Lin, Sharma, Mazumdar, & Shroff, 2006; Perevalov & Blum, 2003; Perevalov & Blum, 2006) have established the asymptotic relationship between the average delay and maximum feasible throughput of per source-destination pair in wireless networks with network nodes extending to infinity. While these elegant results shed light on the deployment of wireless networks as well as the design of protocols and algorithms from a high level perspective, the asymptotic features may not match real wireless networks that usually have finite nodes. Therefore, they may not be suitable for practical WMNs. There exist two papers (Chen & Yang, 2006; Bisnik & Abouzeid, 2006) that address the multihop delay analysis for WMNs with finite nodes. In (Bisnik & Abouzeid, 2006), WMNs are modeled as G/G/1 queuing networks. Based on the diffusion approximation approach