



Emerging Technologies in Wireless LANs

Theory, Design, and Deployment

Edited by Benny Bing

CAMBRIDGE

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Emerging Technologies in Wireless LANs

Wireless LANs have become mainstream over the last few years. What started out as cable replacement for static desktops in indoor networks has been extended to fully mobile broadband applications involving moving vehicles, high-speed trains, and even airplanes. An increasing number of municipal governments around the world and virtually every major city in the United States are financing the deployment of 802.11 mesh networks, with the overall aim of providing ubiquitous Internet access and enhanced public services. This book is designed for a broad audience with different levels of technical background and can be used in a variety of ways: as a first course on wireless LANs, as a graduate-level textbook, or simply as a professional reference guide. It describes the key practical considerations when deploying wireless LANs and equips the reader with a solid understanding of the emerging technologies. The book comprises 38 high-quality contributions from prominent practitioners and scientists, and covers a broad range of important topics related to 802.11 networks, including quality of service, security, high-throughput systems, mesh networking, 802.11/cellular interworking, coexistence, cognitive radio resource management, range and capacity evaluation, hardware and antenna design, hotspots, new applications, ultra-wideband, and public wireless broadband.

“Benny Bing has created a masterful, horizon-to-horizon compendium covering the foundations, functionality, implementation, and potential-for-the-future of IEEE 802.11 wireless LAN communications. Whether your interests are in QoS, security, performance and throughput, meshing and internetworking, management and design, or just the latest in Wi-Fi applications, you will find an in-depth discussion inside these covers. *Emerging Technologies in Wireless LANs: Theory, Design, and Deployment* is an excellent resource for anyone who wants to understand the underpinnings and possibilities of the Wi-Fi offerings we see evolving in the marketplace today.”

– Robert J. Zach, Director, Next Generation Broadband, EarthLink, Inc., USA

“Over the past 20 years, wireless LANs have grown from technical curiosity to a mainstream technology widely installed across residential, enterprise, and even municipal networks. The mobility and convenience of wireless has been augmented by the advanced throughput and range performance available in today’s products, extending the reach of wireless LANs to a broad array of applications. This book explores all aspects of contemporary wireless LANs, from the basics through wireless security, meshes, QoS, high throughput, and interworking with external networks. The broad range of topics and perspective make this the ideal reference for experienced practitioners, as well as those new to the field.”

– Craig J. Mathias, Principal, Farpoint Group, USA

“This book is a wonderful resource for anyone who works with Wi-Fi wireless technologies. It provides an excellent overview for the newcomer and an extensive and up-to-date reference for the expert. This book is a crucial tool for everyone involved in this exciting, fast-paced field. Everyone will learn from it!”

– Professor David F. Kotz, Director, Center for Mobile Computing, Dartmouth College, USA

“The ability of Wi-Fi technology to expand in so many directions while maintaining backwards compatibility has been one key to its success and the technology will certainly continue to evolve. This book has hopefully given you some insights into where we have been and where we may be headed.”

– Greg Ennis, Technical Director, Wi-Fi Alliance

Benny Bing is a research faculty member with the School of Electrical and Computer Engineering, Georgia Institute of Technology. He is an IEEE Communications Society Distinguished Lecturer, IEEE Senior Member, and Editor of the *IEEE Wireless Communications* magazine.

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Foreword

Every now and then, a technology comes along which changes everything. Wi-Fi is one of those technologies.

Although wireless LAN technology has been around for close to 20 years, what we think of today as Wi-Fi has really existed for less than a decade. The IEEE 802.11b standard was ratified in 1999, enabling the then unheard of speed of 11Mbps. Shortly thereafter, the Wi-Fi Alliance was formed to focus on product interoperability certification and the development of the ecosystem and market. The combination of the right industry standard, unprecedented industry cooperation, and the novel utilization of unlicensed spectrum, created a new paradigm in terms of how people could connect to the Internet without wires.

Today, with the advent of draft 802.11n technology, we are able to deliver data rates in the multi-hundred Mbps range. We can now reliably cover most homes with a single access point using sophisticated MIMO techniques. We can connect large cities using advanced mesh architectures. With these developments, Wi-Fi is no longer confined to just the PC and networking application segments. Rather, Wi-Fi is now becoming a must-have feature in the latest consumer electronics products and handsets, ushering in new applications like voice and video. In a short period of time, Wi-Fi has moved from a cool, niche technology to one that is a mainstream, global phenomena.

I hope this book gives you a better appreciation for the power of Wi-Fi and stimulates your thoughts on where it can go in the future. Enjoy!

Frank D. Hanzlik
Managing Director
Wi-Fi Alliance

Preface

Wireless Fidelity (Wi-Fi) networks have become mainstream over the last few years. What started out as cable replacement for static desktops in indoor networks has been extended to fully mobile broadband applications involving moving vehicles, high-speed trains, and even airplanes. Perhaps lesser known is the proliferation of unique Wi-Fi applications, from Wi-Fi mosquito nets (for controlling malaria outbreaks) to Wi-Fi electric utility and parking meters to Wi-Fi control of garden hose sprinklers. The global revenue for Wi-Fi was nearly \$3 billion at the end of 2006 and will continue its upward trend in the coming years.

When Wi-Fi wireless LANs were first deployed, they give laptop and PDA users the same freedom with data that cellphones provide for voice. However, such networks need not transfer purely data traffic. It can also support packetized voice and video transmission. People today are spending huge amounts of money, even from office to office, calling by cellphones. With a Wi-Fi infrastructure, it costs them a fraction of what it will cost them using cellphones or any other equipment. Thus, voice telephony products based on 802.11 have recently emerged. A more compelling use of Wi-Fi is in overcoming the inherent limitations of wireless WANs. An increasing number of municipal governments around the world and virtually every major city in the U.S. are financing the deployment of Wi-Fi mesh networks with the overall aim of providing ubiquitous Internet access and enhanced public services. Cheap phone calls using voice over IP may turn out to be one of the biggest benefits of a citywide Wi-Fi network, benefiting residents, businesses, tourists, and government agencies. This has led some technologists to predict that eventually we are more likely to see meshed Wi-Fi cells that are linked together into one network rather than widespread use of high-powered WAN handsets cramming many bits into expensive and narrow slices of radio spectrum.

I first edited a Wi-Fi book, *Wireless LANs*, in 2002. The book was well received by both academia and industry and was extensively reviewed by the *IEEE Network*, the *ACM Networker*, and the *IEEE Communications Magazine*, the first time a book has been featured by all 3 journals. This edited book comprises 38 new chapters covering a wide range of interesting Wi-Fi developments, including mesh networking, sensors, real-time tracking, cellular interworking, coexistence, hotspots, high-throughput multiple antenna systems, cognitive radio resource management, hardware and antenna design, ultra-wideband, and new 802.11 initiatives focusing on some of the areas mentioned above.

Organization of the Book

This book is designed to be accessible to a broad audience with different levels of technical background. It is not a collection of research papers that only specialists can understand nor is it collection of articles from trade magazines that give general overviews. Rather, it

aims to strike a balance between technical depth and accessibility. To achieve this goal, the book is organized into a mix of chapters that cover fundamental tutorials, standards and case studies, mathematical analysis and modeling, and emerging technologies. Many chapters are written by prominent research scientists and industry leaders.

Part I: Introduction to 802.11

The original 802.11 standard is celebrating its 10th birthday this year and has progressed with a number of amendments since 1997. However, understanding the family of 802.11 amendments, including the acronyms, can be a daunting process. To this end, the first two chapters attempt to equip the reader with the necessary background for the rest of the book. The first chapter gives an overview of the emerging 802.11 amendments while the second chapter provides a detailed guide to 802.11 functionality and deployment issues. Chapter 2 also contains a list of basic 802.11 acronyms used throughout the book and it is highly recommended that these terms be familiarized before proceeding to other chapters.

Part II: 802.11 Quality of Service

The ratified IEEE 802.11e amendment will serve as a benchmark for servicing time-sensitive traffic such as voice and video and will become a major component of many home entertainment systems and set-tops, including Slingboxes that now come equipped with Wi-Fi connectivity. In the future, 802.11e may assume a more important role in mobile entertainment with the growing trend of Wi-Fi enabled portable devices such as iPod@s and smartphones. Chapter 3 covers the fundamental aspects of 802.11e namely, channel access, admission control, and power management mechanisms, with an emphasis on voice transmission. This is followed by a chapter on 802.11/802.11e modeling, written by a lead author (G. Bianchi) who developed the first analytical model for the 802.11 MAC protocol. The final chapter in this section presents an analytical framework for video transmission over multi-hop 802.11 networks. I am confident these three chapters will provide a solid foundation for engineers and researchers to evaluate the performance of voice, video, and data transmission over single-hop and multi-hop 802.11 networks.

Part III: 802.11 Security

Mobile client devices are becoming increasingly smarter and can easily act as an authorized Wi-Fi station. They can also move to different locations and shut off at any time. As such, soft access points involving client devices are becoming harder to detect, identify, and locate than hard-wired rogue access points. More recently, “evil twin” hotspots are becoming a rising danger for users who rely on public hotspots for Internet access. A hacker simply creates a hotspot with the same or similar name to a legitimate hotspot nearby. There are powerful features in 802.11i/WPA2 that can effectively counter security breaches related to intentional and accidental association. Thus, there has been a gradual migration from captive portals (often employed by Wi-Fi hotspot service providers) and VPNs to security architectures built around these standards. Unfortunately, Wi-Fi devices conforming to these standards can potentially add latencies in the order of hundreds of milliseconds and this can be very disruptive to voice connections as mobile

users roam between networks. New methods such as key caching may be needed to support real-time traffic and the emerging 802.11r amendment is addressing secure mobility (and mobile QoS) with reduced handoff delays between 802.11i (and 802.11e) access points. Since different levels of Wi-Fi security lead to different levels of convenience for the end-user, the Wi-Fi Alliance's Wi-Fi Protected Setup (WPS) standard was designed to ease the set-up process of Wi-Fi networks. The first chapter in this section equips the reader with a clear understanding of Wi-Fi security basics while the second chapter focuses on a more in-depth coverage of Wi-Fi security issues, including handshaking and advanced encryption mechanisms, practical intrusion detection methods, analysis and countermeasures, and secure mesh networking.

Part IV: High Throughput 802.11

Wi-Fi data rates have continued to increase from 2 to 54 Mbit/s with current rates in the 802.11n draft amendment topping 600 Mbit/s. This development, coupled with the emergence of the 802.11s mesh amendment, may eventually render wired Ethernet redundant in the enterprise network. Despite the impressive progress in data rates, 802.11n products are backward-compatible with legacy 802.11b/g devices that operate in the 2.4 GHz unlicensed frequency band, even though the underlying physical layer transmission for 802.11 has changed dramatically over the last 7 years. Spread spectrum transmission that was used in first-generation 802.11 networks has given way to OFDM while multiple antenna MIMO-OFDM promises higher data rates, improved range performance, and better reliability for the future. To achieve higher speeds, channel bonding of two 20 MHz channels is allowed 802.11n. However, since there are only 3 non-overlapping 20 MHz channels in the 2.4 GHz band, this means that only one adjacent network operating in the remaining 20 MHz channel can co-exist. Hence, most 802.11n deployments in the 2.4 GHz band are not likely to include channel bonding. Because there are more non-overlapping channels in the 5 GHz band, the ratification of 802.11n may result in more widespread deployments of 5 GHz 802.11 networks, especially high-speed backhaul/backbone mesh deployments for enterprises and public municipal networks. Besides MIMO-OFDM and channel bonding, frame aggregation is another key feature of 802.11n. This feature allows the throughput efficiency to be improved by reducing the number of backoff delays required for frame transmission, thereby reducing the overheads per frame. Although 802.11n has yet to be ratified, dual-radio (2.4/5 GHz) products based on the draft amendment have started penetrating the WLAN market. The two chapters in this part describe the features and performance of this important amendment.

Part V: 802.11 Mesh Networks

Wi-Fi mesh networking will transform both enterprise and public networks. Because the same MAC and PHY layers can be used throughout the span of the network, such networks may see the distinction between WANs and LANs blurring for the first time in the history of computer networking. In addition to widespread municipal deployment, the multipoint capability of Wi-Fi mesh networks has been widely used in outdoor fairs and carnivals. Mesh networks are highly flexible networks with the ability to self-form and self-heal, thereby reducing the cost for backhaul deployment, system engineering, and

network management. Wi-Fi access points in a mesh network not only deliver wireless coverage to end-user devices, they also act as routing nodes for other access points in the network. Obstruction, noise, and interference can be avoided dynamically by a reroute to the next best possible route. Unlike long-range wireless solutions such as 3G, the shorter hops in a Wi-Fi mesh network lead to lower variations in throughput and channel fading. Moreover, proprietary mesh protocols can sometimes provide a form of information security for wireless packet routing. While mesh networks are scalable in deployment, throughput scalability poses a huge challenge, even with multiple radio nodes. In addition, municipal Wi-Fi networks face a variety of challenges: the need to ensure high quality end-user experience, to meet guaranteed connectivity from first responders and emergency services, and to offer committed service level agreements with business and home users in an interference-prone public environment. Unlike traditional telecommunication systems, a multi-layered architecture is typically required: backhaul, capacity injection, mesh, and access. Bandwidth management and traffic policing are crucial in determining smooth operation and acceptable quality of user experience. The six industry contributions in this section cover different aspects of Wi-Fi mesh networking and offer many useful tips on network design and deployment. Additional insights on the development of the 802.11s amendment are provided in Chapter 16.

Part VI: 802.11/Cellular Interworking

Broadband cellular technologies such as 3G were originally targeted to compete with Wi-Fi. However, like unified wired Ethernet/wireless Wi-Fi switches, cellular and Wi-Fi convergence with single number access (regardless of device make) has now become mainstream. During the last two years, the Wi-Fi Alliance has certified about 100 Wi-Fi phones, the majority of which are dual-mode cellular handsets. Such handsets offer users the ability to transfer calls between home, office, and cellular phones seamlessly. Although Wi-Fi operates on unlicensed spectrum, the higher data rates afforded by a Wi-Fi connection can result in better voice quality, in addition to solving the notorious cellular signal fade inside buildings. An interesting alternative to Wi-Fi/cellular convergence is the use of femtocells, which are essentially simplified cellular base stations that act like personal access points for the home or office. With the ability to work with an existing cellular handset, femtocells can be very attractive when compared to VCC and GAN/UMA-based Wi-Fi services that require a new dual-mode handset. This makes some sense since the cellular phone of today is a much more innovative (and expensive) device compared to the cellular phone of yesteryear. With advances in computing power and storage, many cellular smartphones now come equipped with the ability to take and store photos, view TV programs, share real-time video, play games, provide navigation, act as a remote monitoring device, in addition to voice transmission. Nevertheless, I believe that by integrating with Wi-Fi in a dual-mode handset, the reach and affordability of a cellular connection can become more attractive. The first chapter in this section provides a very detailed coverage of the underlying issues associated with Wi-Fi/cellular interworking. The second chapter proposes an architecture for Wi-Fi/cellular integration. The third chapter presents a comprehensive analytical framework for evaluating the performance of Wi-Fi/cellular networks.

Part VII: Coexistence

The success of Wi-Fi operating in unlicensed frequency bands has provided the impetus for regulatory bodies around the world to open up more radio spectrum for unlicensed use. For instance, the white space in the TV bands can create a new market for Wi-Fi in future. It has been demonstrated that a Wi-Fi device using this unlicensed spectrum can co-exist with high-definition TV operation. However, interference must be carefully managed in any unlicensed environment, more so when incompatible devices operate in the same radio band. Dynamic spectrum access will play a critical role in these environments. The 802.11n draft 2.0 amendment allows co-existence with legacy 802.11 devices as well as non-802.11 devices such as Bluetooth. Such co-existence can sometimes result in serious restrictions on an 802.11n network and one may not be able to use the 40 MHz bandwidth for higher speed operation on the 2.4 GHz band. The first chapter in this section gives a comprehensive overview of co-existence issues for a wide range of radio bands, from UHF to microwave to millimeter bands. It also recommends cognitive sensing solutions for secondary devices operating in the 802.22 TV bands. The second chapter focuses on 802.11n and Bluetooth coexistence, which will become increasingly important as 802.11n networks are deployed in the coming years.

Part VIII: 802.11 Network and Radio Resource Management

Radio bandwidth resource management is key to the success of any wireless network deployment. A dynamic resource allocation method is needed to assign bandwidth, channel, and power levels depending on current interference, propagation, and traffic conditions. Currently, Wi-Fi access points need proper setup and maintenance in order to perform optimally. However, with the emerging 802.11k amendment, tedious configuration procedures may be a thing of the past. In addition, one can increase the number of access points to improve reliability and capacity without having to consider frequency planning or conduct detailed site surveys. The two chapters in this section discuss the state of the 802.11k amendment, and the features and benefits of a cognitive WLAN architecture.

Part IX: 802.11 Range

In general, the range of a network determines its utility. Currently, there are long-range Wi-Fi solutions as well as Wi-Fi mesh, both allowing the deployment of Wi-Fi networks that cover a large area. The chapter in this section compares the tradeoffs between the range of Wi-Fi and the data rates, coverage, and capacity. It also discusses how range can be improved using advanced MIMO technologies.

Part X: 802.11 Hardware Design

The two chapters in this section focuses on 802.11 chip and antenna design for portable computers. The first chapter describes an integrated single-chip system-on-a-chip (SoC) that can meet both the cost and form factor requirements by implementing all of the functions of an IEEE 802.11g WLAN system in a single 0.18- μ m CMOS die. The

integrated SoC combines the RF transceiver, analog baseband filters, data converters, digital baseband, physical layer, and medium access controller. A brilliant chapter on antenna fundamentals and design for portable devices follows. The authors describe various antenna diversity methods for practical implementation and recommend that the best design at lowest possible cost should take into account the radiation characteristics of the antenna elements and their interaction, and the channel characteristics.

Part XI: Wi-Fi Hotspots

Currently, there are nearly 150,000 free and paid Wi-Fi hotspots around the world. A more recent trend is the strong emergence of community hotspot providers offering Wi-Fi routers for users to share their broadband Internet connections with others in exchange for being able to use other users' connections for free when they are away from home. The cost savings associated with this concept of network sharing have some parallels with content sharing (e.g., peer-to-peer file sharing). Unlike past Wi-Fi community networks that are solely operated by residential users, the scale of these new Wi-Fi community networks has become much more extensive and are no longer limited to a single community or even a single country. Similar to the current applications of the Internet, such networks now serve as a powerful platform for social networking and are becoming increasingly integrated with commercial public hotspots. The chapters in this section are written by technical authorities from some of the leading hotspot providers, including Pronto Networks, Wayport, and Boingo Wireless®.

Part XII: Wi-Fi Applications

Wi-Fi sensor networks have become more pervasive. An example is the city of Cambridge in Massachusetts, which is building a Wi-Fi-based sensor network that will monitor the weather and pollution. The CitySense network will eventually support some 100 sensors around the city. A Wi-Fi real-time location system (RTLS) allows an organization to track high-value assets in a fast and efficient manner. Besides increasing asset visibility, it also enhances device security, simplifies IT management, and tightens control on the network environment. Context-aware computing enables applications to discover and exploit contextual information (such as user location, time of day, nearby people and devices, and user activity). Wi-Fi can be invaluable in such a mobile computing platform. The chapters in this section have been carefully selected to cover some of the most unique Wi-Fi applications. These include sonobuoy sensor network deployment, RTLS, context-aware computing, and unmanned aerial vehicles.

Part XIII: Ultra WideBand (UWB)

UWB technologies promise to deliver data rates in the order of a gigabit/sec. Being more focused on the end-user device, UWB can serve as an excellent complement to longer range Wi-Fi network deployments. The first chapter in this part describes the fundamental concepts of UWB, including emerging standards, pulse radiation and reception, channel models, and new applications. The second chapter describes the Multiband OFDM Approach (MBOA) to UWB and offers key insights into emerging UWB technologies.

Part XIV: Public Wireless Broadband

Public wireless broadband promises to revolutionize many facets of our lives, specifically in pervasive content access and mobile entertainment, while having the added benefit of affordable subscription. The Internet and Wi-Fi have both become the defacto media for entertainment and social networking. Many Wi-Fi radios not only stream audio from Internet radio stations, but also stream music files from the computer. Wi-Fi Internet TV and video game systems have also become prevalent. Just like bundling computer sale with Internet access, many popular game systems are now bundled with free Wi-Fi access in public hotspots, allowing young male gamers to go online and challenge each other in multi-player games in public locations. For example, over 5 million unique users have logged on to the Nintendo® Wi-Fi Connection (<http://www.nintendowifi.com>) and played over 200 million game sessions since the service was first launched in November 2005. Other massively multiplayer online games (e.g., World of Warcraft) have attracted millions of subscribers. However, with the mobility afforded by Wi-Fi, this will add to the complexity of the backend systems already limited by the number of simultaneous users and what players can do in the virtual world. The final chapters of this book comprise three interesting essays that cover the impact of Wi-Fi on public networks, the mobilization of the Internet, and the solutions to the broadband problem in the U.S.

In compiling the chapters for this book, I humbly admit that I have gained invaluable knowledge from a group of highly accomplished contributors. Through my experience in interacting and collaborating with industry, I recognize the importance of practical perspectives. I believe the many chapters from our industry colleagues will enable the reader to appreciate some of the major engineering considerations when designing and deploying Wi-Fi networks. As a researcher, I also value the insights provided by theoretical analysis, simulation, and proof-of-concept prototypes and testbeds. To this end, I hope the chapters from academia will adequately address the key problems associated with current and emerging Wi-Fi technologies and applications.

I take the opportunity to thank all contributors for generously investing their time and efforts, their co-operation in observing the deadlines, and their patience in seeing this book put to print. In addition, I wish to express my sincere thanks to the following individuals:

- Frank Hanzlik and Greg Ennis (both from the Wi-Fi Alliance) for taking time from their busy schedules to write the thought-provoking foreword and the epilogue.
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- Phil Meyler, Emma Collison, and Anna Littlewood (all from Cambridge University Press) for their excellent support in ensuring the timely publication of the book. Much credit for the excellent layout of this book goes to Anna for her diligence in checking the manuscript and for providing numerous comments.

Sometime ago, I read about this initiative called One Laptop Per Child or OLPC (<http://laptop.org>). The first phase of this project aims to provide a rugged laptop to 100 million children in underdeveloped countries in the next few years at a cost of at least \$10 billion (i.e., roughly \$100 per laptop). This is about twice the current worldwide annual laptop sales at a much lower price per laptop. Each laptop is equipped with a screen that is readable in darkness or full daylight and has far more capabilities than commercial units costing ten times more, including the ability to function as a game console, a home theater, or an e-book. Although the power and display innovations are interesting, the most prominent feature in these laptops is the use of specially designed external antennas for Wi-Fi mesh networking (based on the draft 802.11s amendment). The flip-up antennas act as a switch to turn on the Wi-Fi radio without waking the CPU and provide better gain and range than the internal antennas in a typical laptop. Thus, Wi-Fi plays a vital role in this project and is a clear winner in the world of mobile computing.

On a more forward-looking note, research developed by scientists from the Massachusetts Institute of Technology allows electricity to be transferred wirelessly using magnetically coupled resonant objects. The design comprises two copper coils, each a self-resonant system. One of the transmitting coils is attached to a power source. Instead of flooding the environment with electromagnetic waves, the transmitting coil fills the space around it with a non-radiative magnetic field oscillating at MHz frequencies. The non-radiative field facilitates the power exchange with the other coil at the receiving unit, which is specially designed to resonate with the field. The overall effect is a strong interaction between the transmitting and receiving units, while the interaction with the rest of the environment is weak. For laptop-sized coils, power levels more than sufficient to run a laptop can be transferred efficiently over room-sized distances in virtually any direction, even with objects completely obstructing the line-of-sight path between the two coils. If this technology matures, then a truly wireless world beckons where both electric power and information can be exchanged over the airwaves.

I hope the technical depth and breadth of the chapters in this book will serve many readers well. The book can be used in a variety of ways: as a first course on WLANs, as a graduate-level textbook, or simply as a professional reference guide. I would greatly appreciate any feedback from readers regarding the book as well as suggestions of new topics for future editions. Please feel free to contact me via email (bennybing@ieee.org).

Benny Bing
Atlanta, GA, USA

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