Preface

A Brief Journey through “Wireless Mesh Networks: Architectures and Protocols”

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Introduction

Wireless mesh networking has emerged as a promising design paradigm for next generation wireless networks. Wireless mesh networks (WMNs) consist of mesh clients and mesh routers, where the mesh routers form a wireless infrastructure/backbone and interwork with the wired networks to provide multihop wireless Internet connectivity to the mesh clients. Wireless mesh networking has emerged as one of the most promising concept for self-organizing and auto-configurable wireless networking to provide adaptive and flexible wireless Internet connectivity to mobile users. This concept can be used for different wireless access technologies such as IEEE 802.11, 802.15, 802.16-based wireless local area network (WLAN), wireless personal area network (WPAN), and wireless metropolitan area network (WMAN) technologies, respectively. Potential application scenarios for wireless mesh networks include backhaul support for cellular networks, home networks, enterprise networks, community networks, and intelligent transport system networks. Development of wireless mesh networking technology has to deal with challenging architecture and protocol design issues, and there is an increasing interest on this technology among the researchers in both academia and industry. There are many on-going research projects in different universities and industrial research labs. Also, many startup companies are building mesh networking platforms based on off-the-shelf wireless access technologies and developing demanding applications and services. This book intends to provide a unified view of the state-of-the-art achievements in the area of protocols and architectures for wireless mesh networking technology.

The contributed articles in this book from the leading experts in this field cover different aspects of analysis, design, deployment, and optimization of protocols and architectures for WMNs. In particular, the topics include challenges and issues in designing architectures and protocols for WMNs, medium access control and routing protocols for WMNs, resource allocation and scheduling in WMNs, cost optimization in WMN nodes using energy harvesting technologies, cross-layer design for WMNs, and security in WMNs.

Issues in Architecture and Protocol Design for Wireless Mesh Networks

Chapter 1, authored by *V. C. Gungor, E. Natalizio, P. Pace, and S. Avallone*, provides a comprehensive introduction to the recent developments in the protocols and architectures of wireless mesh networks (WMNs) and also discusses the opportunities and challenges of wireless mesh networks. The major issues related to wireless mesh network architecture and management include network planning (e.g., placement of mesh routers, number and type of network interfaces in each router), network integration (i.e., integration of WPAN, WLAN, and WMAN technologies), network scalability (i.e., ability to deal with large network topology), and flexible and scalable network management. The protocols for wireless mesh networks should be able to exploit the advanced wireless technologies (e.g., cognitive/reconfigurable radio, multiple-input multiple-output (MIMO) radio), provide quality of service (QoS) to different types of applications, provide efficient network self-reconfiguration, topology control, power management, provide mobility support, and provide mechanisms for efficient encryption, authentication, and intrusion detection.

The authors have described the major research issues at the different layers in the protocol stack of a wireless mesh network. At the application layer, new protocols need to be designed for distributed information sharing and to address the pricing and incentive issues. Again, the application layer protocols need to work in cohesion with the lower layer protocols to meet the application requirements in an efficient manner.

Efficient transport protocols would be required for non-real-time and real-time applications in wireless mesh networks. Due to the dynamic characteristics of multi-hop communication environment in a wireless mesh network as well as the integration of different types of networking technologies, the traditional transport protocols (e.g., TCP-based protocols) may experience significant performance degradation. In particular, under-utilization of network resources may result due to the increased round-trip time (RTT), large variance in RTT estimate, and increased link error rate in the network as well as the end-to-end congestion detection and control mechanisms used in these protocols. Again, since the traditional TCP-friendly rate control protocols for multimedia delivery handle all non-congestion-related packet losses in the same way, they would suffer performance inefficiency. Design of dynamic adaptive transport protocol for high performance real-time data transport and real-time multimedia communications in wireless mesh networks is a grand research challenge.

For wireless mesh networks, simple (i.e., low overhead), scalable, distributed, load-balancing and link quality-aware routing protocols would be required for efficient multihop communications. Designing efficient routing protocols for multi-channel and multi-radio mesh networks is a major research challenge. An integrated design of routing, medium access control, and channel allocation (or scheduling) may lead to an efficient solution.

Multi-channel and multi-radio-aware MAC protocols are promising for wireless mesh networks. Channel allocation among multiple radios should be performed in a way so that the network connectivity is preserved and the co-channel interference remains below the acceptable limit while at the same time the maximum frequency reuse is achieved. Also, multi-rate transmission and adaptivity to dynamic network configuration are desirable.

High-speed physical layer techniques such as MIMO, beamforming and smart antennas, reconfigurable/cognitive radio will enable to increase the capacity and reliability of wireless mesh networks. These advanced physical layer techniques can be fully utilized by making the higher-layer protocols aware of the physical layer and using the low-cost software radio platform.

Specifications for wireless mesh networks are being standardized by the IEEE 802.11, IEEE 802.15, and IEEE 802.16 standard groups. 802.11s task group was set up by IEEE for installation, configuration, and operation of IEEE 802.11-based wireless mesh networks. IEEE 802.15.5 task group is working towards developing an architectural framework for mesh networking among IEEE 802.15-based WPAN devices. IEEE 802.16a standard for broadband wireless access in metropolitan area networks support mesh mode of operation for fixed broadband applications in which the subscriber stations can directly communicate with each other through multihop communications. The Mobile Multihop Relay (MMR) study group under the IEEE 802.16 working group is developing specifications for supporting mobile stations by using multihop relaying techniques through relay stations.

Recent field trials and experiments on wireless mesh networks (built from off-the-shelf wireless technologies) in several academic research testbeds and commercial installations have shown that the performance is not quite satisfactory. This reflects the need for development of novel architectures and protocol suites to address the issues such as QoS, scalability, heterogeneity, self-reconfuguration, and security for wireless mesh networks.

Chapter 2, authored by *J.-H. Huang, L.-C. Wang, and C.-J. Chang* first describes the major wireless mesh network architectures, namely, the backbone wireless mesh network, backbone with end-user wireless mesh network, and relay-based wireless mesh network architectures. In a wireless multihop backbone network, each of the base stations (or access points (APs)) operates as a relay to forward traffic from other base stations to the Internet gateway. In a backbone with end-user wireless mesh network, both the base stations and end users act as relays to forward traffic from neighboring nodes, and thereby, it improves the coverage of base stations and enhances network connectivity.

The authors address the scalability issue in wireless mesh networks from the network deployment perspective. The authors propose two scalable wireless mesh network deployment strategies, namely, cluster-based wireless mesh and ring-based wireless mesh for dense urban coverage and wide-area coverage scenarios, respectively. In a cluster-based wireless mesh, several adjacent access points, which are connected “wirelessly”, form a cluster and only one of the access points connects to the Internet. The ring-based wireless mesh is based on a mesh cell architecture where the cell is divided into several rings allocated with different channels. The central gateway (which is connected to the Internet) and the stationary mesh nodes in the cell form a multihop wireless mesh network. The authors investigate the tradeoff between capacity and coverage for these two scalable wireless mesh architectures. With multiple available channels, the scalability can be improved through proper frequency planning and proper design of the deployment parameters in these networks. Note that, while a larger cell size is preferred from the coverage viewpoint, a smaller cell size would be preferable to achieve a higher data rate.

The authors apply a mixed-integer nonlinear programming (MINLP)-based optimization approach to determine the optimal deployment parameters (i.e., separation distance for access points in a cluster-based wireless mesh network) under given coverage and rate constraints where the objective is to maximize the ratio of total offered traffic load to the cost for a cluster of access points. Two AP placement strategies, namely, the increasing-spacing and the uniform-spacing strategies are considered. In case of increasing-spacing placement strategy, access points are deployed with increasing separation distance from the central access point. In case of uniform-spacing placement strategy, all the cells in a cluster have the same radius. Numerical results show that the increasing-spacing strategy outperforms the uniform-spacing strategy and there exists an optimal value of the number of access points which maximizes the objective function.

For the ring-based wireless mesh network, an MINLP formulation is used to determine the optimal number of rings in a cell and the optimal width of each ring for which the desired tradeoff between throughput and coverage can be achieved. Numerical results assuming IEEE 802.11a-based wireless access show that the ring-based wireless mesh improves both the coverage and the cell throughput significantly compared to the single-hop network.

Information Theoretic Characterization of End-to-End Performance in Cellular Mesh Networks

Chapter 3, authored by *Ö. Oyman and S. Sandhu*, provides results on information-theoretic characterization of end-to-end performance in terms of physical channel and system parameters in an orthogonal frequency division multiplexing (OFDM)-based multihop cellular mesh network. Specifically, the capacity is defined as the end-to-end (instantaneous) conditional mutual information which is a function of the random fading channel parameters and the transmit signal-to-noise ratio. This conditional mutual information can be computed for each hop considering practical link adaptation mechanisms based upon which an end-to-end link quality parameter can be obtained.

Through simulation, the authors demonstrate that, for users at the edge of a cell, multihop relaying can provide capacity and coverage gains over direct transmission. Also, multihop relaying improves the end-to-end capacity compared to single-hop communication, specially at the low outage probability regime. The optimal number of hops, which maximizes the end-to-end mutual information is observed to be sensitive to the channel parameters.

Based on a Markov chain model, the authors also analyze the end-to-end throughput and latency over a multihop network which supports automatic repeat request (ARQ)-based error control at each hop along a routing path. Based on this analysis, the routing metric at each hop can be obtained, and subsequently, the throughput-maximizing (or latency-minimizing) routing path can be determined.

To this end, the authors present a centralized resource allocation framework for user scheduling, subcarrier allocation, and multihop route selection in orthogonal frequency division multiple access (OFDMA)-based relay-assisted cellular mesh networks. In this framework, the base station decides on the allocation of time and frequency resources across users and it also coordinates the actions of the relay terminals. To reduce system design complexity, multihop route selection and subcarrier allocation are performed separately. The link quality metrics are used to choose the multihop routing paths for each user such that the end-to-end capacity is maximized. The end-to-end route metrics for all users over all subcarriers are then used for scheduling the subcarriers. The authors also demonstrate how the information theoretic analysis of end-to-end capacity can be used to determine the optimal policies for network entry and handoff.

Medium Access Control and Routing Protocols for Wireless Mesh Networks

Chapter 4, authored by *J. C. Hou, K.-J. Park, T.-S. Kim, and L.-C. Kung*, provides a comprehensive survey on the state of the art in design and implementation of medium access control (MAC) and routing protocols for wireless mesh networks. The objective of a MAC protocol in such a network is to maximize network capacity (e.g., through improved spatial reuse) while providing required quality of service (QoS) performances to the users. The major issues related to MAC design in a wireless mesh network are - controlling the sharing range of the wireless medium and increasing spatial reuse, exploiting availability of multiple channels, and exercising rate control. The spatial reuse can be improved by either reducing the transmit power (while maintaining network connectivity) or increasing the carrier sense threshold (while mitigating MAC-level interference). Capacity improvements can be achieved by using multiple radio interfaces in each mesh node where orthogonal channels are assigned to the radios. Distributed dynamic assignment of channels among the radios as well as joint optimization of routing and channel assignment are challenging research problems. Network throughput can be maximized through dynamic adaptation of data rate according to the channel condition, that is, by selecting the highest possible data rate for a given signal-to-interference-plus-noise ratio (SINR) that allows correct decoding of packets at the receiver.

The authors summarize the related works on transmit power control, carrier sense adaptation, and exploiting spatial-temporal diversity which are intended to improve the spatial reuse/capacity of the network. In the literature, the transmit power control problem in wireless ad hoc/sensor/mesh networks has been studied by using graph-theoretic approaches in the context of topology maintenance. The major objective here is to mitigate MAC interference while preserving network connectivity. The graph-model-based topology control algorithms aim at keeping the node degree in the communication graph low with the assumption that low node degree implies low interference. However, in a graph model, since node degree may not adequately capture the physical interference, graph-model-based topology control may result in low network capacity and volatile network connectivity. There have been other approaches for transmit power control which aim at maximizing network capacity.

A number of studies in the literature focused on adaptation of carrier sense threshold to improve the level of spatial reuse. The selection of the optimal carrier sense threshold depends on the factors such as the SINR threshold, level of channel contention (i.e., traffic load), transmit power, network topology, hidden/exposed nodes, type of flows (i.e., single hop or multihop), bidirectional handshakes, packet size, and MAC overhead. The relationship between the transmit power and the carrier sense threshold impact network capacity. For example, with low transmit power and high carrier sense threshold, a large number of concurrent transmissions can be supported, with each transmission sustaining a low data rate. Several works in the literature addressed the problem of joint control of transmit power and carrier sense threshold. Again, transmit power can be jointly optimized with rate control to maximize network capacity. For a rate-adaptive MAC protocol, data rate is generally increased/decreased on consecutive transmission success/packet loss. The rate control problem at the MAC layer has been studied quite extensively in the literature.

In a wireless mesh network, the spatial diversity that exists among the multihop paths, can be exploited to improve network capacity. Again, capacity can be improved through multi-channel and multi-radio design for wireless mesh networks. Specifically, in the MAC layer, multiple channels can be exploited to achieve higher throughput as well as to mitigate the fairness problem in a multihop environment. Multiple radios in a node enable it to communicate with other nodes in a full-duplex manner with minimal interference.

The major objective of a routing protocol for wireless mesh networks is to determine high-throughput routes (i.e., interference-mitigated routes) between nodes so that the maximal end-to-end throughput can be achieved. Instead of using the conventional hop-count-based route metric, link quality-based route metrics have been proposed for routing in wireless mesh networks. In the literature, routing protocols have been proposed for single-radio single-channel, single-radio multi-channel, and multi-radio multi-channel wireless mesh networks. In a multi-channel and multi-radio mesh network, by properly assigning the different channels to the different radios, intra- and inter-flow interference can be avoided and interference-free/mitigated routes can be constructed.

To this end, the authors introduce a modular programming environment to enable cross-layer design and optimization in wireless mesh networks. In this environment, physical layer (PHY)/MAC parameters and events can be exported to higher-layer protocol modules. Controlled transparency, flexibility, and easy integration and portability are some of the features of this programming environment.

Channel Assignment Strategies in Multi-channel and Multi-radio Wireless Mesh Networks

Chapter 5, authored by *M. Conti, S. K. Das, L. Lenzini, and H. Skalli*, deals with the problem of assigning channels to radio interfaces in a multi-channel and multi-radio wireless mesh backbone network. The key challenges associated with the channel assignment problem are outlined and a survey on the existing channel assignment schemes is provided.

The objective of a channel assignment strategy is to ensure efficient utilization of the available channels (e.g., by minimizing interference) while maximizing connectivity in the network. However, since these two requirements are conflicting with each other, the goal is to achieve a balance between these two. The major constraints which need to be satisfied by a channel assignment scheme include: fixed number of channels in the network, limited number of radios in a mesh node/router, common channel between two communicating nodes, and limited channel capacity. Also, a channel assignment scheme should take the amount of traffic load supported by each mesh node into consideration.

Optimal channel assignment in an arbitrary wireless mesh backbone is an NP-hard problem (similar to the graph coloring problem). The existing channel assignment schemes in the literature are, therefore, mostly heuristic based. These schemes can be classified into three categories: fixed, dynamic, and hybrid channel assignment schemes. Fixed assignment schemes assign channels to the radios either permanently or for a long time interval. With dynamic channel assignment, the radios can frequently switch from one channel to another. Hybrid channel assignment strategies apply a fixed assignment for some radios and a dynamic assignment for other radios.

Fixed channel assignment schemes can be further classified into two categories: common channel assignment (CCA) schemes and varying channel assignment (VCA) schemes. In CCA, all the radios in all of the mesh nodes are assigned the same set of channels. In VCA, radios of different nodes are assigned different sets of channels. The authors have described a number of such VCA schemes.

With dynamic channel assignment, when two mesh nodes need to communicate with each other, they need to switch to the same channel. The key challenge in this case is how to coordinate the switching decisions. The authors have described a number of dynamic channel assignment schemes.

Hybrid assignment strategies are attractive since they allow for simple coordination algorithms (as for the fixed assignment schemes) and also provides the flexibility of dynamic channel assignment. The authors have described two such hybrid channel assignment schemes.

The key issues considered in the design of the existing channel assignment schemes are network connectivity, constraint on topology, interference minimization, effects of link revisits, traffic awareness, switching overhead (for dynamic and hybrid schemes), and control philosophy (i.e., centralized or distributed). Considering these factors, the authors provide a qualitative comparison among the different schemes.

Resource Allocation for Wireless Mesh Networks

Resource Allocation and Transmission Rate Control

Chapter 6, authored by *Y. Xue, Y. Cui, and K. Nahrstedt*, presents a generalized theoretical framework for resource allocation and transmission rate control in wireless mesh networks. The objective of this framework is to achieve optimal resource utilization and rate fairness among flows on an end-to-end basis. Based on this theoretical framework, the authors also present a price-based distributed algorithm for resource allocation which converges to the globally optimal solution.

The resource allocation problem is first formulated as an optimization problem for an abstract network model consisting of a set of resource elements (e.g., wireless links) which are shared by a set of flows. The objective is to maximize the aggregated utility (i.e., satisfaction) for all flows under constraints on capacities of the resource elements. Different fairness models such as weighted proportional fairness and max-min fairness can be implemented through the appropriate choice of the utility function. The solution of the optimization achieves both optimal resource utilization (i.e., Pareto optimal rate allocation) and fair allocation of transmission rate among end-to-end flows. Based on the Lagrangian form of the optimization formulation, a price-based decentralized solution can be obtained which depends on local decision of each resource element and exchange of control signals among them.

The authors show that for a multihop wireless mesh backbone network, a resource element is a facet of the polytope defined by the independent sets of the conflict graph of this network. It can be approximated by a maximal clique of the contention graph which basically represents a maximal distinct contention region in the network. The resource constraints in the network can then be represented by the achievable channel capacities in all of the maximal cliques in the contention graph. Subsequently, the end-to-end rate allocations can be obtained for the flows. For distributed implementation, a flow adapts its rate as a function of price it pays to all resource elements, where the price for a resource element is a non-negative, continuous, and increasing function of the total traffic served by that resource element. The authors show that the rate adaptation algorithm is stable and at the equilibrium each flow maximizes its utility.

Resource Allocation in Solar/Wind-Powered Mesh Nodes

Chapter 7, authored by *A. A. Sayegh, T. D. Todd, and M. N. Smadi*, presents some experimental results on resource allocation in hybrid solar/wind powered WLAN mesh nodes. Resource allocation in such a node involves assigning solar panel or wind turbine size, and battery capacity, and this resource allocation depends on the geographic location of the node. A sustainable energy WLAN mesh node includes a wind turbine and/or solar panel which are connected to a battery through a charge controller. The charge controller disconnects the battery from the power source to protect it from under- and over- charging. Specifically, when the residual battery energy falls below the maximum allowed level of discharge, the charge controller disconnects the node load and the node then experiences a radio outage. In a hybrid configuration, both solar panel and wind turbine are used.

The authors investigate the short-term statistics of the energy available from solar panel and wind turbines at two different locations, namely, Toronto, Ontario and Phoenix, Arizona. In the city of Toronto, a time distribution example of solar power and wind power shows positive correlation between them which suggests that a hybrid solar/wind powered node may not be cost effective. In the city of Phoenix, comparison of solar power and wind power shows that solar power dominates the wind power, and therefore, wind power alone or a hybrid wind/solar solution may not be feasible. However, the short-term statistics may not be sufficient to assess the optimal dimensioning of the power source in the mesh node. The long-term statistics would be required instead. Examples of long-term statistics show that performance metrics such as radio outage probability for the wind source and the solar source depends on the seasonal correlation between solar power and wind power in a geographic location. The desired level of sustainability of a given hybrid system for the different geographical locations can be obtained by properly choosing the wind turbine and battery sizes.

To minimize the total cost of a hybrid node (i.e., cost of battery, solar panel, and wind turbine) under given constraints on outage probability, battery size, solar panel and wind turbine size, the authors use an optimization formulation. This optimization model is solved numerically. To this end, the authors show that power saving at mesh access points can greatly reduce the cost which is almost proportional to the power consumption in the node.

Scheduling, Routing, and Cross-Layer Design

Link Scheduling and Routing in Wireless Mesh Networks

Chapter 8, authored by *L. Badia, A. Erta, L. Lenzini, and M. Zorzi*, presents a comprehensive survey on the state-of-the art of routing and link scheduling in wireless mesh networks. As has been mentioned before, for a wireless mesh network, the objective of a routing algorithm is to discover efficient paths to obtain high system throughput. Link scheduling at the medium access control layer is used to activate the communication links with an objective to ensuring the desired level of network connectivity under interference constraints. The interference models, which are particularly important when designing link scheduling (or activation) and routing algorithms, can be of three types - *physical*, *protocol*, and *measurement-based* interference models. With a *physical* interference model, the feasibility of simultaneous link activations is determined by the SINR at the receivers. Note that, the packet error rate at a receiver is a monotonically decreasing function of SINR. With a *protocol* interference model, simultaneous transmissions result in incorrect decoding of a received packet. The measurement-based interference model takes an *a priori* approach to interference characterization.

The existing works on link scheduling and routing in wireless ad hoc and/or sensor networks are often not suitable in the context of wireless mesh networks due to the dissimilar design/optimization goals and/or oversimplified interference models. Designing a framework for joint scheduling and routing which considers the network requirements, resource constraints (e.g., number of radios, channels), radio transceiver constraints, and realistic interference models is an interesting research challenge.

The authors propose a graph-based approach to design a framework for joint link scheduling and routing through link activation. In this framework, the radio transceiver constraints (e.g., half-duplexity) and link directionality are taken into account. The interference is characterized by a physical interference model which is more accurate than that under protocol interference models from the viewpoint of theoretical analysis of wireless mesh networks. The authors assume a centralized space time division multiple access (STDMA) scheme to obtain an efficient transmission scheme through link activation. The mesh access point nodes in the mesh backbone network finds the link activation patterns in a centralized manner and communicates it with the other nodes. The authors obtain the performance bounds for the minimal time scheduling problem/shortest-time link activation pattern (i.e., obtaining the link activation pattern which delivers a given amount of traffic from non-gateway mesh nodes to the gateway mesh nodes in the shortest possible time). The authors also carry out some numerical investigations on the performance of the proposed framework for different interference models.

Quality-Aware Routing Metrics in Wireless Mesh Networks

Chapter 9, authored by *C. E. Koksal*, presents a comparative study among seven different link cost metrics for routing in wireless mesh networks. The cost metric for a link refers to the cost of forwarding a packet along that link. The considered link cost metrics are: hop count, per-hop round trip time (RTT), per hop packet pair delay (PktPair), quantized loss rate, expected transmission count (ETX), modified ETX (mETX), and effective number of transmissions (ENT).

The traditional hop count-based routing (i.e., minimum hop routing), although simple and requires minimal amount of measurement, does not perform satisfactorily in presence of link variability. Per-hop round trip time is a delay-based link cost metric, which is calculated by a mesh node as the exponentially weighted moving average of the RTT samples for each of its neighbors. This metric takes into account the factors such as queueing delay, channel quality, and channel contention. However, since RTT varies with varying load, using this routing metric may lead to route instability (due to the self interference effect). With this routing metric, the optimal path assignments may change more frequently compared to the hop count, which may result in reduced network throughput. Also, this metric responds to channel variability at time scales longer than tens of packets.

The PktPair metric is obtained as the difference between the times of reception of two successive packets. Therefore, it does not take into account the queueing and processing delay at a node. Although it suppresses the route instability effect to some extent, the overhead associated with it is higher than that due to per hop RTT. The quantized loss rate is based on the end-to-end packet loss probability. This metric does not take the link bandwidth into account, and therefore, low bandwidth paths could be chosen for routing.

ETX for a wireless link refers to the estimated expected number of transmissions required to transfer a packet successfully over that link. This metric depends only on the link level packet errors due to channel impairments, and therefore, the effects of self interference is reduced. ETX can improve the throughput performance significantly compared to the hop count metric, however, it may perform poorly under highly variable and bursty error situations. The mETX metric overcomes the limitations of ETX in the presence of channel variability. This metric is a function of the mean and the variance of the bit error probability summed over a packet duration. It offers a higher throughput performance compared to the ETS metric. However, the main drawback of this metric is the complexity of estimation of the mean and variance of bit error probability. Also, estimation error may impact its performance significantly.

The ENT metric is structurally similar to the mETX metric and it uses the exactly same parameters and the channel estimation procedure as mETX. It is used to find routes which satisfy certain desired end-to-end performance (e.g., packet loss rate at the transport level) requirements. The metric mETX can be considered as a special case of the ENT metric.

The authors also present a unified geometric framework to compare the different routing metrics. This framework combines the mean and standard deviation of the bit error rate process. In this framework, it is possible to define a feasible region using which links can be selected to achieve the desired routing performance.

Cross-Layer Solutions for Traffic Forwarding in Wireless Mesh Networks

Chapter 10, authored by *V. Baiamonte, C. Casetti, C. F. Chiasserini, and M. Fiore*, deals with the problem of joint design of MAC and routing schemes for multihop communication in IEEE 802.11-based wireless mesh networks. Specifically, the authors consider the problem of designing efficient relaying schemes based on the cross-layer design principles which take into account the quality of the wireless links in an 802.11-based multi-rate WLAN.

For traffic flow from a mesh gateway to wireless mesh nodes, the authors present two schemes for packet forwarding, namely, the split queues (SQ) approach and the access category (AC) approach. With the former approach, two queues are maintained at each node for relay traffic and local traffic. With the latter approach, several queues are implemented at the MAC layer, each of which is associated with a priority level (e.g., implementable through the access categories defined in IEEE 802.11e EDCA). Prioritizing relay traffic over local traffic provides an incentive to the nodes to act as relays. Simulation results for a network topology with single and multiple relays serving TCP and UDP flows show that the AC approach can provide significant gain in throughput while the SQ approach can provide very high fairness in throughput.

The authors present a fair relay selection algorithm (FRSA) which is an extension of the optimized link state routing (OLSR) protocol designed for wireless ad hoc networks. OLSR is a table-driven and a proactive protocol which exchanges topology information periodically with other nodes in the network. The route from a given node to any destination node in the network is formed by relay nodes. A relay node announces to the network that it has reachability to the nodes which have selected it as the relay node. The proposed FRSA is a relay quality-aware routing extension of OLSR. In FRSA, each node performs a relay quality-aware routing to its two-hop neighborhood. Simulation results show that a significant throughput gain with fair channel access can be achieved with FRSA when compared to OLSR.

Multiple Antenna Techniques for Wireless Mesh Networks

Chapter 11, authored by *A. Gkelias and K. K. Leung*, discusses the research challenges associated with the deployment of multiple antenna technologies in wireless mesh networks. In particular, the authors focus on the design of medium access control and routing algorithms in wireless mesh networks employing smart antenna technology. Multiple antenna technology includes fixed beam antenna techniques, adaptive antenna techniques, and multiple-input multiple-output (MIMO) coding techniques which can be highly beneficial to improving overall performance of wireless mesh networks. However, employment of multiple antenna (or smart antenna) techniques in a wireless mesh networking environment gives rise to unique problems such as deafness, hidden and exposed terminals, and multi-stream interference. Novel medium access control and routing protocols need to be designed to address the above problems.

The authors first describe the wireless mesh network and channel characteristics considering different propagation scenarios, interference characteristics in different scenarios, and other constraints such as the limitations in total effective radiation power. Then an overview of the different smart antenna techniques is provided. Two basic types of smart antennas, namely, directional antennas (fixed beams) and adaptive antenna arrays, are considered. Directional antenna techniques, which include switched-beam antennas, steered-beam antennas (or dynamically phased array antennas), can provide high SINR gain in presence of strong line-of-sight component, however, their performances degrade in multi-path environments. Adaptive antenna techniques, which include adaptive antenna arrays and MIMO techniques, can provide high gain in the direction of desired signals and nulls in the direction of undesired signals (i.e., interference). In particular, the MIMO techniques can exploit the multi-path fading effects to enhance the transmission rate (i.e., multiplexing gain) or enhance the transmission reliability (i.e., diversity gain) without additional bandwidth requirements.

One of the major issues related to the use of multiple antenna (or smart antenna) techniques in wireless mesh networks is to mitigate the deafness problem. This problem arises due to the use of directional antennas when a transmitter fails to communicate with its intended receiver. However, deafness can be also exploited in some cases to mitigate interference. Directional transmission may also augment the classical hidden/exposed terminal problem in wireless networks. Again, in presence of directional antennas, unsuccessful transmissions due to packet collision and deafness need to be treated differently at the higher layers. In a MIMO-based wireless mesh network, the medium access control protocol should use the optimal number of simultaneous transmissions, allocate appropriate number of streams per transmitter-receiver pair, and perform power allocation accordingly. Also, the tradeoff between multiplexing and diversity gain should be taken into account. The routing protocols in a MIMO-based wireless mesh network should consider the MIMO parameters for route discovery and maintenance. If the higher layer protocols are not carefully designed, the multiple antenna techniques can have negative impact on the overall network performance.

The authors then discuss several distributed medium access control protocols for multiple antenna-based multihop wireless networks. The interactions between medium access and routing protocols in presence of smart antennas have been evaluated in some works in the literature. These works primarily focused in improving network connectivity. Design and implementation of efficient quality of service (QoS)-aware routing protocols which exploit the multiple antenna techniques is a grand research challenge.

Security in Wireless Mesh Networks

Chapter 12, authored by *W. Zhang, Z. Wang, S. K. Das, and M. Hassan*, addresses the security issues in wireless mesh networks. The main challenges for securing wireless mesh networks arise due to the requirements of authentication, secure routing, secure location information (of mesh routers), and to defend against virus attacks.

Authentication is required to distinguish malicious information from legitimate information. An authentication mechanism is generally implemented with the help of public key infrastructure (PKI) and certification authority (CA). With the PKI mechanism, each user has a pair of cryptographic keys: public key and private key. A message encrypted with the public key (which is known to all the users) can only be decrypted by using the corresponding private key, and vice versa. The CA involved in the authentication procedure signs the binding of an entity's identity and its public key with its private key. It is assumed that the signed certificates by the CA are globally trusted in the network. Due to the absence of any pre-established trusted network infrastructure in wireless mesh networks, distributed CA schemes are desirable. The authors describe a number of such CA schemes.

The routing protocols for a wireless mesh network are vulnerable to both external and internal attacks. External attackers can inject fabricated routing information into the network or maliciously alter the contents of routing messages. An internal attack is launched from within a node when an attacker gains full control of the node. To prevent external attackers from sending fabricated routing information, cryptography-based authentication methods incorporated in the routing protocols can be used. The authors describe several of such schemes. Also, several possible approaches to detect and counter measure the internal attacks to routing protocols are discussed.

Securing the location information of wireless mesh routers is crucial for certain type of routing schemes (e.g., geographic routing schemes). Two methods for securing location information are generally used - correctly computing the location information and verifying the location claims. The authors review several works based on these two methods.

Computer viruses also pose threats to security in wireless mesh networks. There have been research efforts towards modeling the virus propagation problem in wireless networks. Epidemic theory used in Biology is one popular technique used to investigate the virus spreading problem. Two schemes which use Epidemic theory to model the propagation of viruses and compromised nodes, respectively, are discussed.

The authors also outline a number of security-related research issues in wireless mesh networks. These include securing the medium access control protocols, defending against denial of service (DoS) attacks at the different layers in the protocol stack, designing cross-layer framework for self-adapted security mechanisms, customizing the security schemes based on the type of network (in a heterogeneous wireless mesh environment), and trust establishment and management. All of these issues represent fertile areas of future research in wireless mesh networks.

Conclusion

We have provided a summary of the contributed articles in this book. We hope this summary would be helpful to follow the rest of the book easily. We believe that the readers will find the rich set of references in each of the articles very valuable. We would like to express our sincere appreciation to all of the authors for their excellent contibutions and their patience during the publication process of the book. We hope this book will be useful to both researchers and practitioners in this emerging area.

2

Architectures and Deployment Strategies for Wireless Mesh Networks

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2.1 Introduction

Nowadays the development of the next-generation wireless systems (e.g., the fourth-generation (4G) mobile cellular systems, IEEE 802.lln, etc.) aims to provide high data rates in excess of 1 Gbps. Thanks to its capability of enhancing coverage with low transmission power, wireless mesh networks (WMNs) play a significant role in supporting ubiquitous broadband access [1]- [10].

Fig. 2.1 illustrates a multi-hop wireless mesh network, where only the central gateway G has a wireline connection to the Internet and other nodes (like node S) access to the central gateway via a multi-hop wireless communication. Each node in the WMN should operate not only as a client but also a relay, i.e., forwarding data to and from the Internet-connected central gateway on behalf of other neighboring nodes. The main difference between ad hoc networks and wireless mesh networks is the traffic pattern [2], as shown in Fig. 2.2. In a WMN, there will exist a central gateway and most traffic is either to/from the central gateway as shown in Fig. 2.2(a). In an ad hoc network, however, traffic flows are arbitrary between pairs of nodes, such as the flow between nodes $S1$ and $D1$ in Fig. 2.2(b).

In general, the advantages of wireless mesh networking technology can be summarized into five folds. First, WMN can be rapidly deployed in a large-scale area with a minimal cabling engineering work so as to lower the infrastructure and deployment costs [1]- [5]. Second, mesh networking technology can combat shadowing and severe path loss to extend service coverage area. Third, by means of short range communications, WMN can improve transmission rate and then energy efficiency. In addition, the same frequency channel can be reused spatially by two links at a shorter distance. Fourth, due to multiple paths for each node, an appealing feature of WMNs is its robustness [9], [10]. If some nodes fail (like node B in Fig. 2.3), the mesh network can continue operating by forwarding data traffic via the alternative nodes. Fifth, WMN can concurrently support a variety of wireless radio access technologies, thereby providing the flexibility to integrate different radio access networks [6]- [8]. Fig. 2.4 shows an example of integrated wireless mesh network, where 802.16 (WiMAX), 802.11 (WiFi), and 802.15 (Bluetooth and Zigbee)

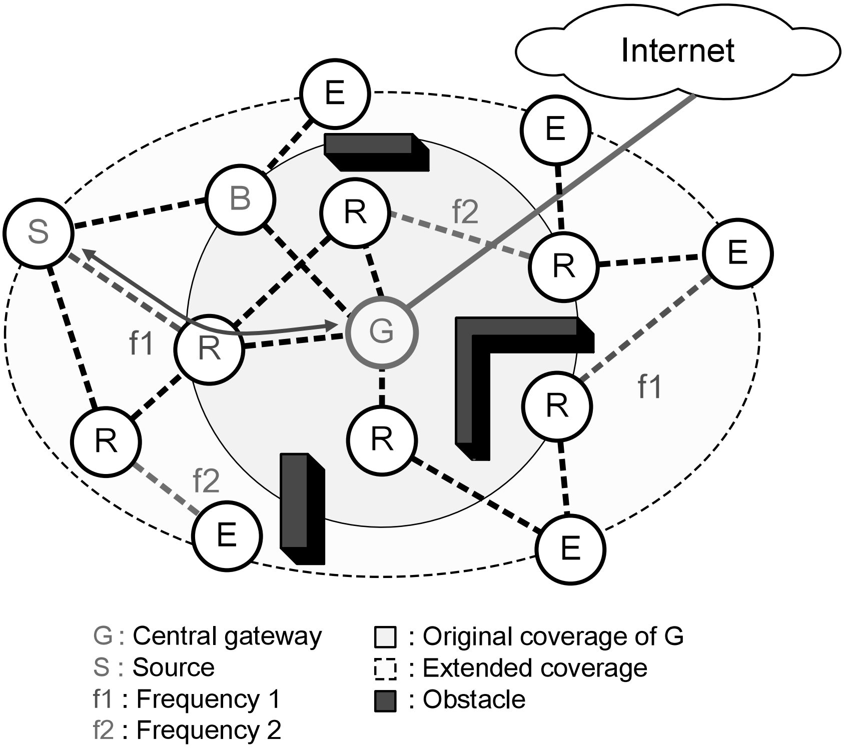
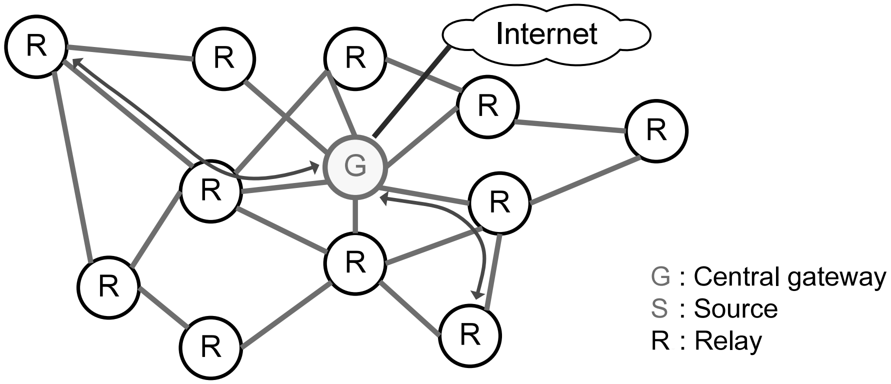


Fig. 2.1. Conceptual illustration of a multi-hop wireless mesh network.

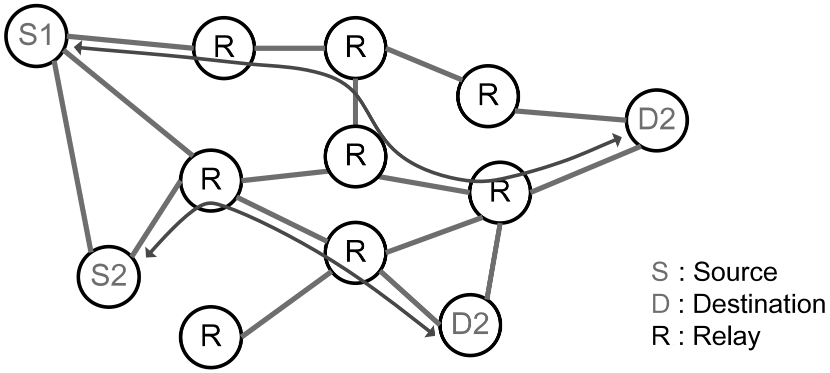
technologies are used for the wireless metropolitan area network (WMAN), the wireless local area network (WLAN), and the wireless personal area network (WPAN), respectively.

However, when the coverage area increases to serve more users, multi-hop networking suffers from the scalability issue [10]. This is because in the multi-hop WMNs throughput enhancement and coverage extension are two contradictory goals. On one hand, the multi-hop communications can extend the coverage area to lower the total infrastructure cost. On the other hand, as the number of hops increases, the repeatedly relayed traffic will exhaust the radio resource. In the meanwhile, the throughput will sharply degrade due to the increase of collisions from a large number of users. Therefore, it becomes an important and challenging issue to design a scalable wireless mesh network, so that the coverage of a WMN can be extended without sacrificing the system overall throughput.

In this chapter, we first discuss the major architectures of WMNs and briefly overview the existing mesh networking technologies, including the IEEE 802.11s and IEEE 802.16 systems. Then, we address the scalability issue of the WMN from a network deployment perspective. We introduce two scalable-WMN deployment strategies for the *dense-urban coverage* and *wide-area coverage scenarios* as shown



(a) Wireless mesh network



(b) Ad hoc network

Fig. 2.2. Comparisons of a wireless mesh network and an ad hoc network.

in Figs. 2.5 and 2.6 ([11, 12]). First, the cluster-based wireless mesh network for the dense-urban area is shown in Fig. 2.5. In this WMN, several adjacent access points (APs) form a cluster and are connected to the Internet through the same switch/router. In each cluster, only the central access point AP_0 connects to the Internet through the wires. Other APs are interconnected by wireless links. By doing so, the network deployment in the urban area becomes easier because the cabling engineering work is reduced. Second, a scalable multi-channel ring-based WMN for wide-area coverage is shown in Fig. 2.6, where the central gateway and stationary mesh nodes in the cell form a multi-hop WMN. Note that the mesh cell is divided into several rings allocated with different channels. In the same ring, the mesh nodes can follow the legacy IEEE 802.11 medium access control (MAC) protocol to share the radio

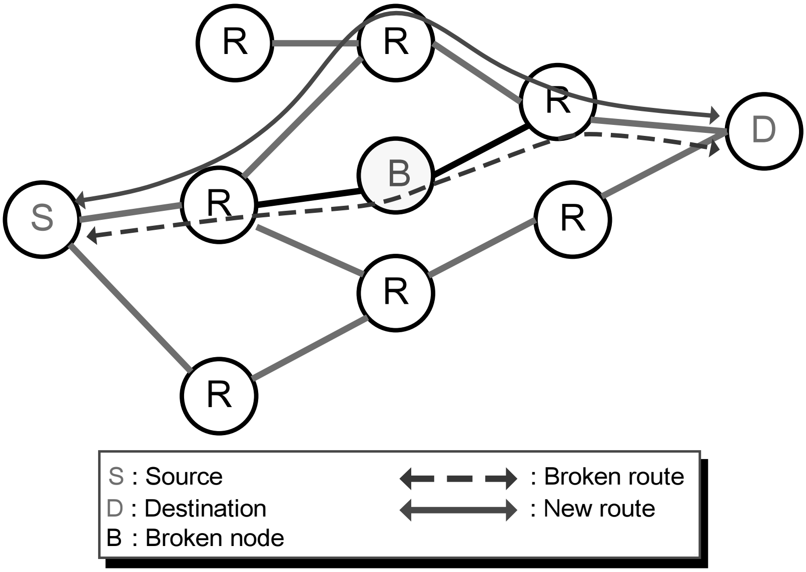


Fig. 2.3. Robustness of wireless mesh network.

medium. Besides, mesh nodes in the inner rings will relay data for nodes in the outer rings toward the central gateway. Based on this mesh cell architecture, the service coverage of the central gateway/AP can be effectively extended with a lower cost.

We will also investigate the optimal tradeoff between capacity and coverage for these two scalable WMNs. Most traditional wireless mesh networks are not scalable to the coverage area because the user throughput is not guaranteed due to the increase of collisions. By contrast, the WMNs shown in Figs. 2.5 and 2.6 are more scalable in terms of coverage because frequency planning with multiple channels can be easily applied in this architecture to resolve the contention issue. Thus the throughput can be ensured by properly determining the deployment parameters. We will apply the mixed-integer nonlinear programming (MINLP) optimization approach to determine the optimal deployment parameters, aiming to maximize the capacity and coverage simultaneously.

The rest of this chapter is organized as follows. Section 2.2 presents the major network architectures for WMNs. Sections 2.3 and 2.4 discuss the mesh networking technologies in the IEEE 802.11s and IEEE 802.16 systems, respectively. Section 2.5 describes the proposed scalable wireless mesh networks for the dense-urban coverage and the wide area coverage. In addition, we apply the optimization approach to determine the optimal deployment parameters, aiming at maximizing the coverage and capacity. At last, concluding remarks are given.

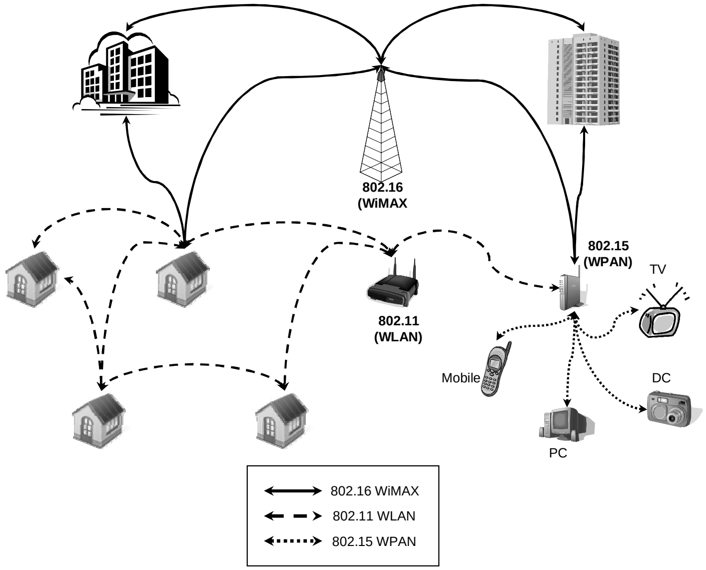


Fig. 2.4. An integrated 802.15/11/16 (WPAN/WLAN/WMAN) wireless mesh network.

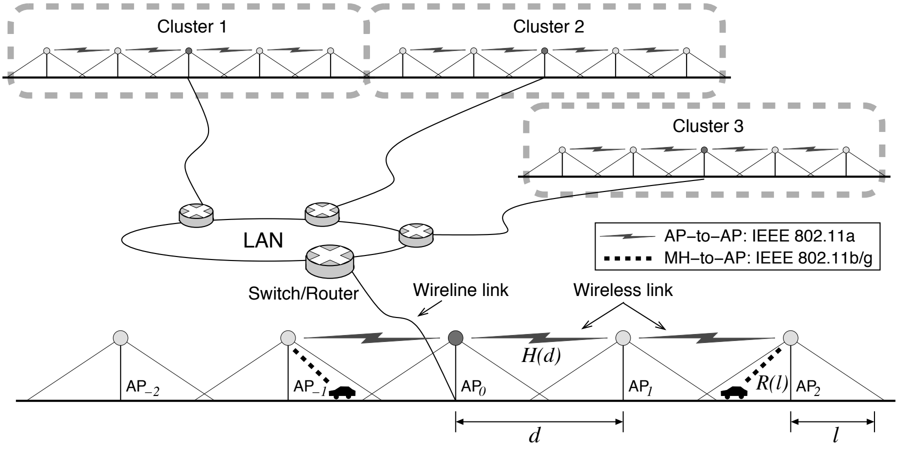


Fig. 2.5. Clusters of access points in the wireless mesh network for the dense-urban coverage.

2.2 Architectures for Wireless Mesh Networks

A wireless mesh network is an economical and low-power solution to support the ubiquitous broadband services. To provide uniform data-rate coverage, one straightforward solution is to densely deploy base stations (BSs) or access points (APs)

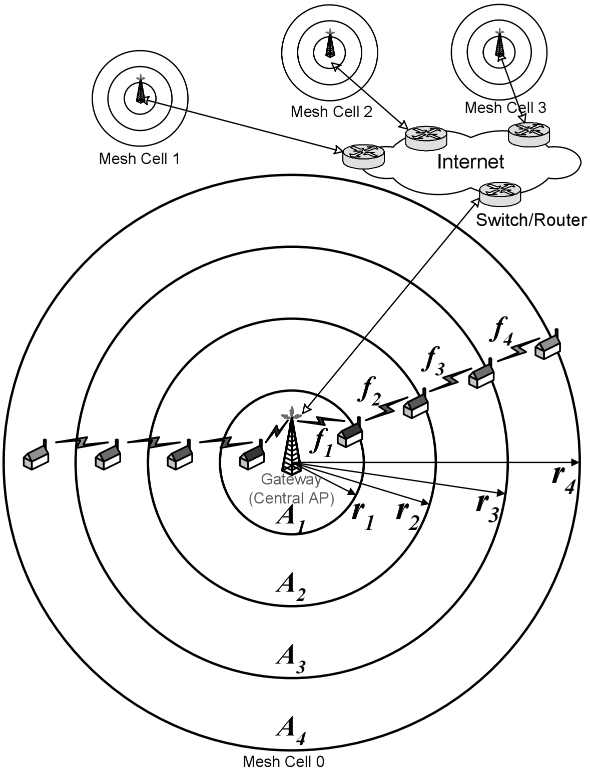


Fig. 2.6. Ring-based cell architecture in the wireless mesh network for wide-area coverage, where each ring is allocated with different allocated channel.

in the service area.[1] Fig. 2.7 shows an example of conventional broadband cellular/hotspot network, where all BSs are connected to the Internet via cables. Clearly, such a network architecture is not very feasible due to the high costs of expensive infrastructure and cabling engineering. Recently, mesh networks have become an interesting option for deploying the wireless broadband networks. In the WMN, only the central gateway has wireline connections to access the Internet directly. All the BSs are interconnected via wireless links. By means of low-power multi-hop communications, the coverage can be significantly extended. In addition, deploying such a network is easier owing to less cabling engineering work.

In the following, we discuss the major WMN architectures.

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[1] Usually, the term *base station* is used for the traditional cellular systems, while *access point* used for the WLAN-based systems. Unless otherwise indicated, the term base station will refer to both the cellular BS and the WLAN AP.

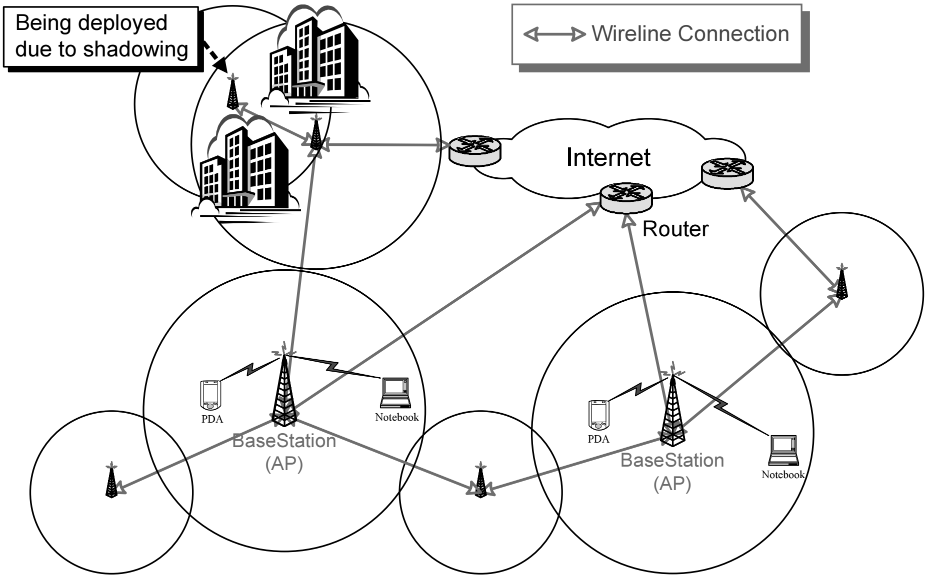

Fig. 2.7. Conventional cellular/hotspot broadband network architecture.

2.2.1 Backbone Wireless Mesh Network

Fig. 2.8 shows an example of *backbone wireless mesh networks*. In the figure, each base station also operates as a wireless relay to forward neighboring BS's traffic to the gateway. Such a wireless multi-hop backbone network provides the flexibility to integrate WMNs with the existing wireless communication systems. The base stations can concurrently integrate 2G/3G/WLAN/4G radio access technologies to provide voice and high-rate data services, and flexibly employ the emerging broadband radio technologies in the backbone networks.

The backbone WMN has the advantage of incremental deployment [2]. If necessary, more gateways can be added, by simply connecting more base stations to the Internet via wineline. Deploying more gateways in the WMNs can improve not only the network capacity but also the reliability. That is, if one gateway fails, the traffic can be delivered by alternative routes and gateways.

2.2.2 Backbone with End-user Wireless Mesh Network

Fig. 2.9 illustrates an example of *backbone with end-user WMNs*, where both the base stations and the end users play a role of wireless relays to forward neighboring nodes' traffic. That is, the end users are also capable of routing and self-organization.

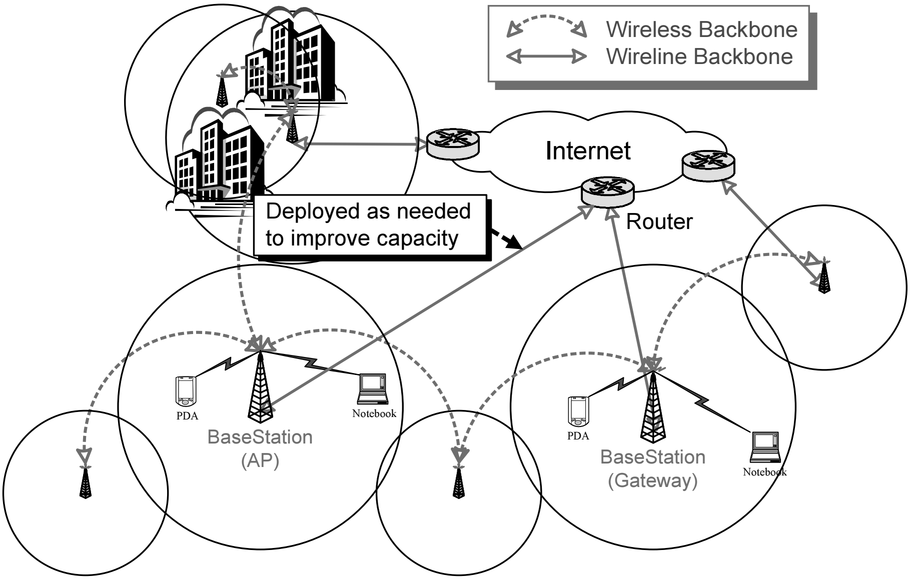

Fig. 2.8. Backbone wireless mesh network.

The end-user WMNs can improve the coverage of base station and network connectivity, thereby reducing the infrastructure costs due to fewer base stations needed. Noteworthily, the mobility issue in the end-user WMNs is challenging, since the network topology and connectivity will frequently change as users move. The mobility issue in end-user WMN includes seamless handoff, fast route selection, network organization and management.

2.2.3 Relay-Based Wireless Mesh Network

Fig. 2.10 shows an example of *relay-based wireless mesh networks*. The relay in this WMN acts as the *lightweight* BS/AP, which permits an economical design for the relays. The relaying systems can employ either *amplify-and-forward* or *decode-and-forward* schemes. In the amplify-and-forward scheme, the relays simply function as analog repeaters, thereby augmenting their own noise levels. In general, the relays in WMNs will operate in a decode-and-forward fashion. The relays can be digital repeaters, bridges, or routers, all of which will completely decode and encode the received signals before forwarding.

The objectives of deploying relays are to extend the coverage as well as to improve user throughput. If the density of relays is high enough, all the users can be served by nearby relays with a very short separation distance, thereby enhancing the link capacity between the relays and users. Then, the goals of robust and uniform data rate in the wireless networks can be achieved in a more economical way.

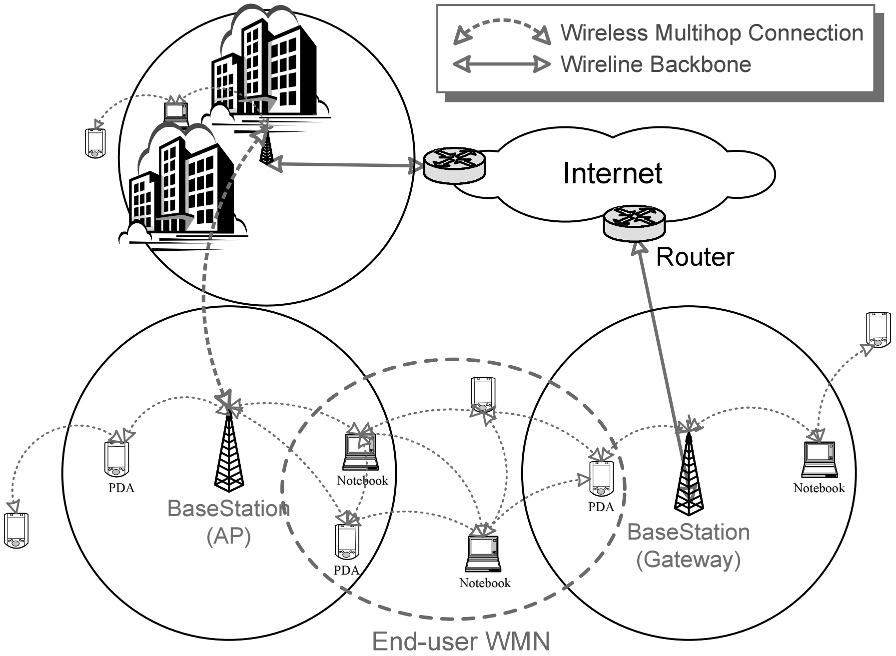

Fig. 2.9. Backbone with end-user wireless mesh network.

2.3 IEEE 802.11s Mesh Networking Technology

The IEEE 802.11 standards aim at defining the physical (PHY) layer and the MAC sublayer protocols for the wireless local area network. The IEEE 802.11b can achieve the peak rate of 11 Mbps, while the IEEE 802.11a/g WLANs achieve 54 Mbps. Furthermore, the IEEE 802.11e addresses the quality of service (QoS) issue, and the 802.11n intends to provide a data rate in excess of 200 Mbps. However, the IEEE 802.11a/b/e/g/n standards mainly focus on the one-hop infrastructure-based communications, where the stations (STAs) are directly connected to the APs. Due to lack of a scalable distributed MAC protocol, the legacy IEEE 802.11 WLANs will face the scalability issue that degrades the throughput severely in the multi-hop communications.

Therefore, the IEEE 802.11s task group (TG) is established to address the multi-hop issue for WLAN. This TGs aims to standardize the meshed WLANs by defining the PHY and MAC layer protocols to support broadcast/multicast/unicast transmissions under self-configured mesh network topology. In the IEEE 802.11s network, the WLAN mesh is defined as a set of mesh points interconnected via wireless links with the capabilities of automatic topology learning and dynamic path selection [13]. Fig. 2.11 shows an example of IEEE 802.11s WLAN mesh. In the figure, there are two classes of wireless nodes. The *mesh points* (MPs) are the nodes supporting wireless mesh services, such as mesh routing selection and forwarding, while the *non-*

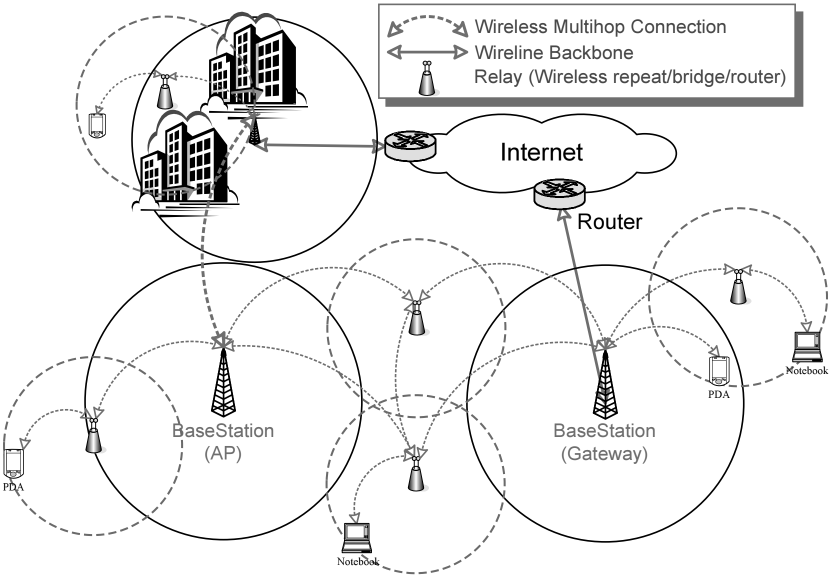

Fig. 2.10. Relay-based wireless mesh network.

mesh nodes are the pure client STAs. In addition to mesh services, the mesh access point (MAP) also provides wireless access services. The pure client STAs do not participate in the WLAN mesh, but they can associate with the mesh APs to connect to the mesh networks. The WLAN mesh can connect to other networks by the mesh portals (MPPs). Multiple WLAN meshes can also be connected by the MPP.

The IEEE 802.11s employs the IEEE 802.11e enhanced distributed channel access (EDCA) as the basis of the medium access mechanism. The enhanced MAC derived from the legacy 802.11 standard is compatible with the existing WLAN devices. To improve the network throughput and channel efficiency in the multi-hop communications, the intra-mesh congestion control and the multi-channel common channel framework (CCF) are suggested in the IEEE 802.11s [13]. By implementing a simple hop-by-hop congestion control mechanism at each MP, the intra-mesh congestion control can relieve the local congestion problem. This mechanism includes three essential elements, including the local congestion monitoring, the congestion control signaling, and the local rate control. The basic idea of the intra-mesh congestion control is to actively monitor the local channel utilization, and detect the local congestion. Through the congestion control signaling, a node can notify the upstream-hop nodes and the neighboring nodes of the local congestion. Once receiving the congestion notification, the nodes will employ the local rate control to relieve the congestion. The CCF framework provides the multi-channel MAC operation for the MP with single/multiple radio interfaces in order to boost the overall network capacity with multiple channels. In CCF, the MP in backoff will exchange the RTS/CTS-like channel negotiation message with the destination node. After suc-

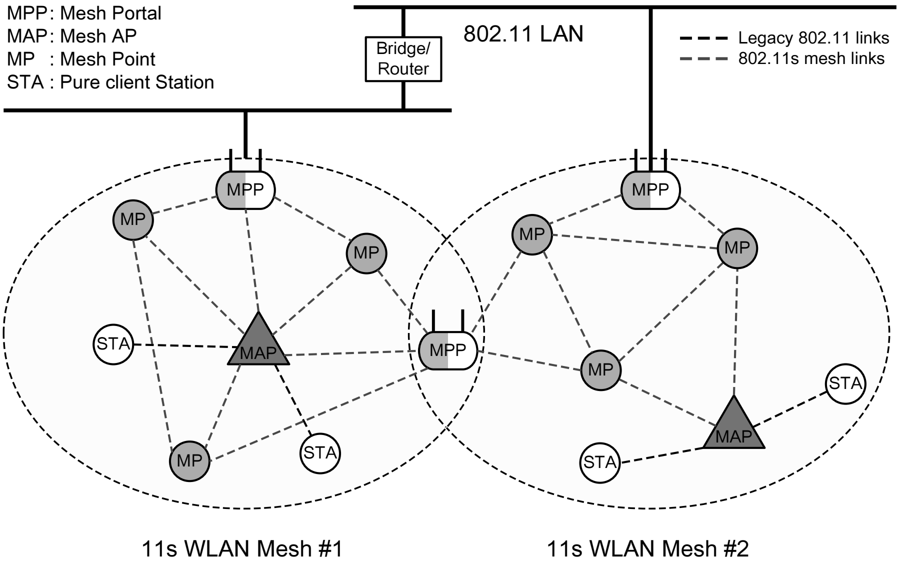

Fig. 2.11. The network architecture for the IEEE 802.11s WLAN mesh network.

cessful channel negotiation, MP pairs switch to the agreed channel to send/receive the data and acknowledge (ACK) frames. One advantage of CCF is that it can accommodate the legacy channel access mechanisms. That is, the common control channel for the nodes without supporting the CCF will appear as a traditional 802.11 channel.

In the IEEE 802.11s, the default hybrid wireless mesh protocol (HWMP) combines the flexibility of reactive on-demand route discovery and the efficiency of proactive routing [13, 14]. Specifically, the reactive on-demand mode in HWMP is based on the radio-metric ad hoc on-demand distance vector (RM-AODV) protocol, while the proactive mode is implemented by the tree-based routing. Such a combination in HWMP can achieve the optimal and efficient path selection. In addition, the HWMP can support various radio metrics in the path selection, such as throughput, QoS, load balancing, power-aware, etc. The default metric is the *airtime cost*, which considers the PHY and MAC protocol overhead, frame payload, and the packet error rate to reflect the radio link condition. To conclude, supporting the hybrid reactive and proactive schemes with a variety of radio metrics, the HWMP has an appealing benefit of flexibility and can be applied to a wide range of application scenarios, including fixed to mobile mesh networks.

2.4 IEEE 802.16 Mesh Networking Technology

The IEEE 802.16 WirelessMAN standard aims to define the PHY and MAC layer protocols to provide the broadband wireless services in the metropolitan area environment [15]. This standard supports the *point-to-multipoint* (PMP) broadband com-

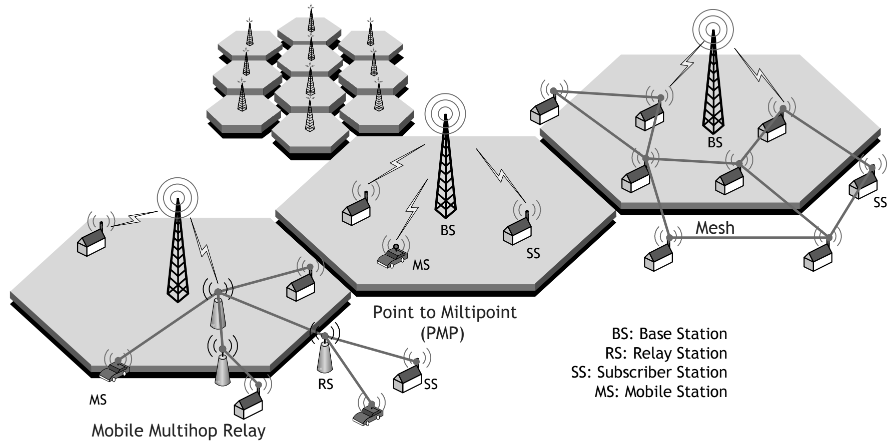

Fig. 2.12. An example of IEEE 802.16 networks. *Middle*: point-to-multipoint (PMP) mode. *Right*: mesh mode. *Left*: mobile multihop relay (MMR) mode.

munications, which operates in the licensed 10-66 GHz frequency band and requires the line-of-sight (LoS) link between the BS and the subscriber station (SS). In addition to the PMP mode, the IEEE 802.16a extension introduces the *mesh mode* to the IEEE 802.16 networks [16]. The mesh mode uses the lower frequency band of 2-11 GHz and allows the non-line-of-sight (NLoS) communications.

Fig. 2.12 shows an example of IEEE 802.16 network. In the figure, the SS in the PMP mode has to directly connect to the BS. On the contrary, the SS can communicate with the neighboring SSs in the mesh mode (see Fig. 2.12). Furthermore, the SS in the mesh mode can act as the wireless relay to forward others' traffic toward the central BS. Consequently, the coverage of BS can be extended, so that the infrastructure costs is substantially reduced.

However, the currently-developed mesh mode in IEEE 802.16 standard is not compatible with the original PMP mode. In the physical layer, the mesh mode has different frame structures and only supports the OFDM operation in both licensed and unlicensed bands. In the MAC layer, the network entry procedure in the mesh mode is also different. In addition, the mesh mode does not support the mobility of SS. Therefore, the IEEE 802.16 working group (WG) establishes the "*Mobile Multihop Relay (MMR)*" study group (SG), and then creates the 802.16j TG. The TG-j intends to enhance the normal PMP frame structure and develop the new relay networking protocols, with the goals of coverage extension and throughput enhancement. Different to the mesh mode, the MMR mode in the IEEE 802.16j extension focuses on efficiently providing the multi-hop relay connections between SSs/mobile stations (MSs) and the BS with a tree topology, as shown in Fig. 2.12. The MMR mode is required to be backward compatible to the PMP mode, and will support both the OFDMA and OFDM operations.

To design a practical mobile multihop relay system, many important issues still need to be addressed, including the enhanced frame structure, backward-compatible network entry procedure, synchronization and security in the multi-hop communications. To support the 802.16e MSs, the mobility management, the seamless handoff, the optimal and fast multi-hop route selection are essential issues in the 802.16j MMR systems. As for the radio resource management in MMR systems, the main challenges include interference management, spectrum efficiency, frequency reuse strategy, and scheduling policy.

2.5 Deployment Strategies for Scalable Wireless Mesh Networks

This section addresses the key challenge in WMN — the scalability issue from a network deployment perspective. We propose two scalable-WMN deployment strategies for the dense-urban and wide-area scenarios [11, 12].

2.5.1 Related Works

First, we discuss the issue of AP placement in WMNs for dense-urban coverage. Most works were based on the architecture that all the access points are directly connected to the Internet through cables [17]- [21]. In [17], an integer linear programming (ILP) optimization model was proposed for the access point placement problem, where the objective function was to maximize the signal level in the service area. In [18], an optimization approach was proposed to minimize the areas with poor signal quality and improve the average signal quality in the service area. The authors in [19] and [20] proposed optimization algorithms to minimize average bit error rate (BER). In [21], the AP deployment problem was also formulated as an ILP optimization problem with the objective of minimizing the maximum of channel utilization to achieve load balancing. In [17]- [21], the concept of wireless multi-hop communication was considered.

With respect to the performance issues for wireless mesh networks, it has been studied mainly from two directions [1]- [2], [22]- [25]. On one hand, from a coverage viewpoint, authors in [22] compared the coverage performance of a multi-hop WMN with that of a single-hop infrastructure-based network by simulations. On the other hand, from a capacity viewpoint, it was shown in [23] and [24] that the throughput per node in a uniform multi-hop ad hoc network is scaled like $O(1/\sqrt{k \log k})$, where k is the total number of nodes. Moreover, the authors in [2] showed that the achievable throughput per node in a multi-hop WMN will significantly decrease as $O(1/k)$ due to the bottleneck at the central gateway. To resolve the scalability issue of multi-hop network, authors in [25] proposed a multi-channel WMN to improve the network throughput. Fewer papers considered both the capacity and coverage performance issues for a WMN, except for [1] in a single-user case. The scalability issue of WMN was not well addressed in [1]- [2], and [22]- [25].

Table 2.1. Link data rates versus coverage ranges for the IEEE 802.11a/b WLANs.

(a) Transmission performance of IEEE 802.11a

Data link rate (Mbps)	54	48	36	24	18	12	9	6
Indoor range* (m) [26]	13	15	19	26	33	39	45	50
Outdoor range* (m) [26]	30				180			304
Link capacity† (Mbps) [27]	27.1	25.3	21.2	15.7	12.6	9.0	7.0	4.8

* 40 mW with 6 dBi gain patch antenna.

† PER = 10% and packet length = 1500 octets.

(b) Transmission performance of IEEE 802.11b.

Data link rate (Mbps)	11	5.5	2	1
Indoor range§ (m) [26]	48	67	82	124
Outdoor range§ (m) [26]	304			610

§ 100 mW with 2.2 dBi gain patch antenna.

2.5.2 Scalable Cluster-based Wireless Mesh Network for Dense-Urban Coverage

Architecture and Assumptions

This section presents the cluster-based WMN in the dense-urban area as shown in Fig. 2.5. In each cluster, only the central AP_0 has the wireline connection to the Internet. Other APs ae connected with wireless links. By this cluster-based WMN, the WLAN system can be rapidly deployed in the urban area with less cabling engineering work.

Specifically, in the proposed cluster-based WMN, the IEEE 802.11a WLAN standard is mainly used for data forwarding between APs, while the IEEE 802.11b/g is for data access between APs and user terminals. Recall that the IEEE 802.11a WLAN are assigned with eight non-overlapping channels for outdoor applications in the spectrum of 5.25 to 5.35 GHz and 5.725 to 5.825 GHz, whereas the IEEE 802.11b/g WLAN has three non-overlapping channels in the spectrum of 2.4 to 2.4835 GHz. To avoid the co-channel interference, frequency planing is applied to ensure two buffer cells between the two co-channel APs. Thus, the inter-cell co-channel interference is reduced and will not be considered in this work.

To deploy the WMN in a dense-urban environment, the coverage range of an AP is a key parameter. Table 2.1 shows the relationship between coverage range and link capacity for both the IEEE 802.11a/b WLANs [26]. Actually, these coverage ranges may vary depending on the environments. However, the proposed optimization approach is general enough to evaluate the performance of WMN with the various coverage ranges in different environments.

A. Throughput Model between Access Points

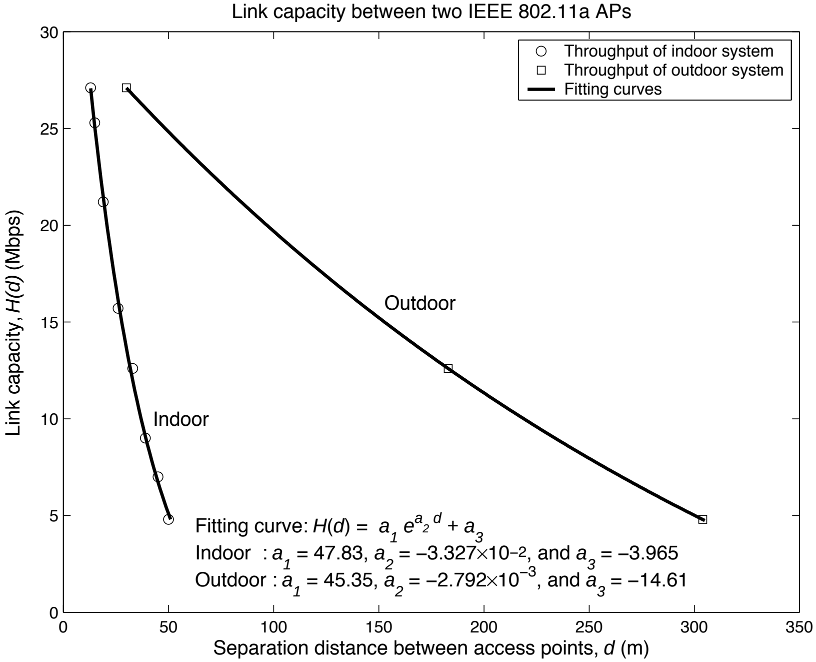

Fig. 2.13. The outdoor/indoor 802.11a link capacity performance $H(d)$ at a separation distance between access points d.

The throughput model between two APs follows the IEEE 802.11a WLAN specifications. Table 2.1 (a) lists the coverage range and link capacity for the IEEE 802.11a WLAN [26,27]. As shown in Fig. 2.13, the radio link capacity $H(d)$ is a function of the separation distance d.

In this WMN, the maximum separation distance between two APs is limited by the maximum reception distance d_{max}. In addition, since the access points are mounted on the streetlamps, the separation distance d between access points should be $d = \Omega L_S$, where Ω is a positive integer and L_S is the separation distance between streetlamps.

B. Throughput Model between an AP and Users

The design of cell size in WMN for urban coverage can be considered from two folds. First, the maximum cell radius should be less than l_{max} to maintain an acceptable data rate. Second, the cell radius should be larger than l_{min} to lower the handoff probability.

In each cell, users share the medium and employ the carrier sense multiple access with collision avoidance (CSMA/CA) MAC protocol to communicate with an AP. We assume that the users are uniformly distributed on the road with density D_M (users/m). If the cell coverage (in radius) is l, the average number of users in a cell is $k = 2lD_M$. According to the method in [28], the cell saturation throughput $R_b(k)$

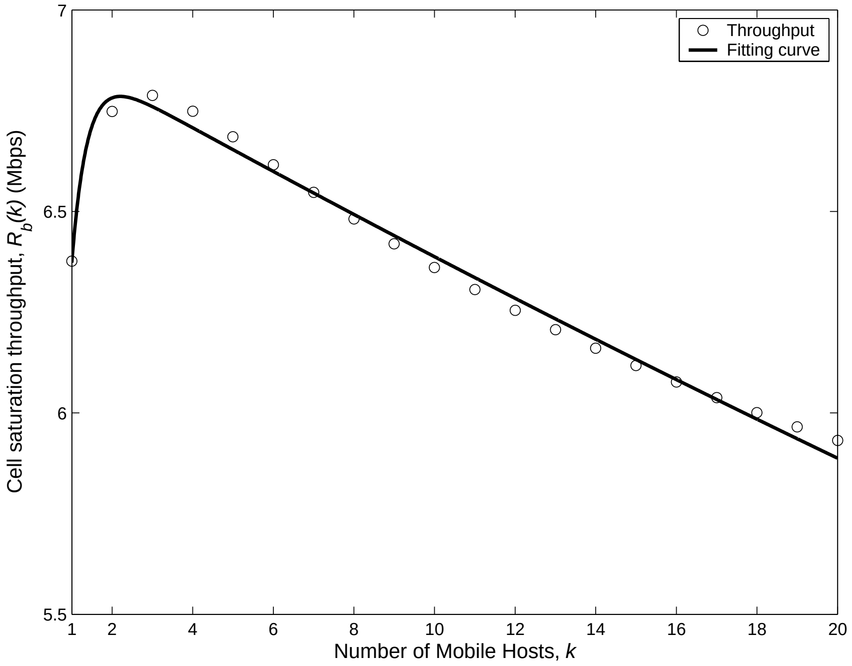

Fig. 2.14. The cell saturation throughput versus the number of users for the IEEE 802.11b WLAN.

of the IEEE 802.11b WLAN for various numbers of users k is shown in Fig. 2.14, where data rate is 11 Mbps and average packet payload is 1500 bytes.

Optimal Access Point Placement

A. Problem Formulation

Radio link throughput and coverage are two essential factors in placing APs in a WMN for dense-urban coverage. From the view point of coverage, a larger cell is preferred because less number of APs are required. From the standpoint of throughput, however, a smaller cell size will be better since it can achieve a higher data rate in the wireless link. In this work, we formulate an optimization problem to determine the best separation distance for APs with consideration of these two factors.

Fig. 2.15 illustrates an example of the cluster-based WMN. Since access points will be symmetrically deployed to the central access point AP_0 in a cluster, only one side of the cluster needs to be considered. The notations in Fig. 2.15 are explained as follows:

– n : the number of APs in the single side of the cluster;
– d_i : the separation distance between AP_{i-1} and AP_i;
– $H(d_i)$: the radio link capacity between AP_{i-1} and AP_i at a distance d_i, according

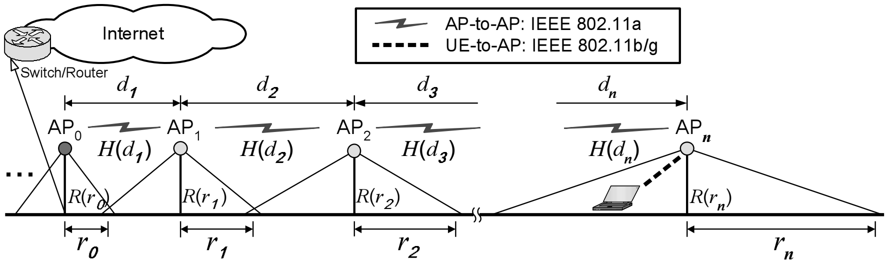

Fig. 2.15. A cluster of APs in the dense-urban environment (this is an example for the increasing-spacing placement strategy, where $d_1 \leq d_2 \leq \cdots \leq d_n$).

to the

IEEE 802.11a WLAN specification;
– l_i : the cell radius of AP_i;
– $R(l_i)$: the aggregated traffic load from all the users associated to AP_i, in which $R(l_i) = 2l_i D_M R_D$ and R_D is the average demanded traffic of each user.

Clearly, the separation distance between two APs can be written as

$$d_i = l_i + l_{i-1}, \quad \text{for } i = 1, 2, \ldots, n \tag{2.1}$$

and the aggregated traffic load in a cell should be constrained by the cell saturation throughput, i.e.,

$$R(l_i) \leq R_b(k). \tag{2.2}$$

In the considered scenario as depicted in Fig. 2.15, the total service area in a cluster of APs is $[2l_0 + 2\sum_{i=1}^{n} 2l_i]$. Therefore, the total carried traffic load of a cluster of APs through the wireline connection can be given as

$$2\left[l_0 + 2\sum_{i=1}^{n} l_i\right] D_M R_D.$$

The total cost for deploying a cluster of APs with one wireline connection is $(2n + 1 + \rho)$, which includes the total cost of $(2n + 1)$ access points and the fixed overhead cost due to the wireline connection ρ. For convenience, in this work the wireline overhead ρ has been normalized by the cost of one access point.

In this work, the AP placement problem will be formulated as a mixed-integer nonlinear programming (MINLP) problem with the following decision variables: n and $l_0, l_1, \ldots, l_n$. The objective is to maximize the ratio of the total carried traffic load to the cost for a cluster of APs. In the following, we discuss the two AP placement strategies: the increasing-spacing and the uniform-spacing placement strategies.

B. Increasing-Spacing Placement Strategy

Fig. 2.15 illustrates an example for the proposed increasing-spacing placement strategy, where $d_1 \le d_2 \le \cdots \le d_n$. In a cluster, the aggregated carried traffic load of the wireless link between AP_{i-1} and AP_i is a decreasing function of i. That is, the further the AP_i from the central AP_0, the less the carried traffic load in the wireless link between AP_{i-1} and AP_i. Accordingly, it is expected to deploy access points with increasing separation distance (i.e., $d_1 \le d_2 \le \cdots \le d_n$) to deliver a higher traffic load for a cluster of APs. The system parameters according to the increasing-spacing AP placement strategy can be obtained by solving the following MINLP optimization problem:

$$\underset{n,l_0,l_1,\ldots,l_n}{\mathbf{MAX}} \frac{\text{Total carried traffic load in a cluster of APs}}{\text{Total cost for deploying a cluster of APs}} = \frac{2\left[l_0 + 2\sum_{i=1}^{n} l_i\right] D_M R_D}{(2n+1+\rho)} \tag{2.3}$$

subject to

$$2l_i D_M R_D \le R_b(k),\ i = 1,2,\ldots,n \tag{2.4}$$

$$H(d_i) \ge \sum_{j=i}^{n} R(l_j) = \sum_{j=i}^{n} 2l_j D_M R_D,\ i = 1,2,\ldots,n \tag{2.5}$$

$$d_i = l_i + l_{i-1},\ i = 1,2,\ldots,n \tag{2.6}$$

$$l_{min} \le l_i \le l_{max},\ i = 0,1,\ldots,n \tag{2.7}$$

$$d_i \le d_{max},\ i = 1,2,\ldots,n \tag{2.8}$$

$$d_i = \Omega_i L_S,\ i = 1,2,\ldots,n. \tag{2.9}$$

In the following, we will explain the above constrains. Constraint (2.4) means that in each cell the total carried traffic load is constrained by the cell saturation throughput. Constraint (2.5) states the condition that the radio link capacity $H(d_i)$ between AP_{i-1} and AP_i should be greater than the aggregate carried traffic load from the cells served by AP_i, AP_{i+1}, …, and AP_n. Constraint (2.6) is the relationship between the separation distance d_i and the cell radius l_i. Constraint (2.7) refers to the limits of cell radius, i.e., l_{min} and l_{max}. According to (2.8), the maximum separation distance between two access points is limited to d_{max}. With respect to (2.9), it is a limit on the separation distance d_i due to the distance between streetlamps.

C. Uniform-Spacing Placement Strategy

Referring to Fig. 2.5, the uniform-spacing placement strategy is to make all the cells in a cluster have the same radius, and thus the access points are uniformly deployed in the service area. Therefore, there are additional constraints for this placement, i.e., $l_i = l$ and thus $d_i = d = 2l$. Accordingly, $R(l_i) = R(l)$ and

Table 2.2. System parameters for numerical examples.

Symbol	Item	Nominal value
D_M	Road traffic density	0.08 users/m
L_S	Distance between two street lamps	30 m
R_D	Traffic demand of each user	0.2 Mbps
l_{min}	Min. of cell radius	45 m
l_{max}	Max. of cell radius	300 m
d_{max}	Max. distance between APs	300 m

$H(d_i) = H(d)$. Then, the MINLP formulation of access point placement problem can be modified as

$$\underset{n,l}{\textbf{MAX}} \frac{(2n+1) \times 2lD_M R_D}{(2n+1+\rho)} \tag{2.10}$$

subject to

$$R_b(k) \geq R(l) = 2lD_M R_D \tag{2.11}$$

$$H(d) \geq nR(l) = n \times 2lD_M R_D \tag{2.12}$$

$$d = \Omega L_S. \tag{2.13}$$

Numerical Examples of Cluster-Based WMN

We compare the performance of the increasing-spacing placement strategy and the uniform-spacing placement strategy. The system parameters in the numerical examples are summarized in Table 2.2.

Fig. 2.16 compares the achieved profits of the objective function for the increasing-spacing and the uniform-spacing placement strategies with various wireline overheads ρ. Fig. 2.16 demonstrates the advantage of the increasing-spacing placement strategy over the uniform-spacing placement strategy. The achieved profit of the objective function is a concave function of the number of APs, n, as depicted in Fig. 2.16. Therefore, there exists an optimal solution of n to maximize the profit of the objective function. For example, when the wireline overhead $\rho = 4$, $n = 3$ will achieve the best performances for both placement strategies. The corresponding cell radii for the increasing-spacing placement strategy are $(l_0, l_1, l_2, l_3) = (113.3$ m, 66.7 m, 143.3 m, 156.7 m$)$ and that for the uniform-spacing placement strategy is $l = 105$ m, respectively. Accordingly, the corresponding separation distances for the increasing-spacing placement strategy are $(d_1, d_2, d_3) = (180$ m, 210 m, 300 m$)$ and that for the uniform-spacing placement strategy is $d = 210$ m, respectively. In this case, the increasing-spacing placement strategy can achieve 15% higher profit of the objective function than the uniform-spacing placement strategy. In Fig. 2.16, we can also observe that the best number of APs in a cluster can vary for different strategies. When the wireline overhead $\rho = 2$, $n = 2$ will achieve the best performance for the increasing-spacing placement strategy, and $n = 1$ for the uniform-spacing placement strategy. In this case, the achieved

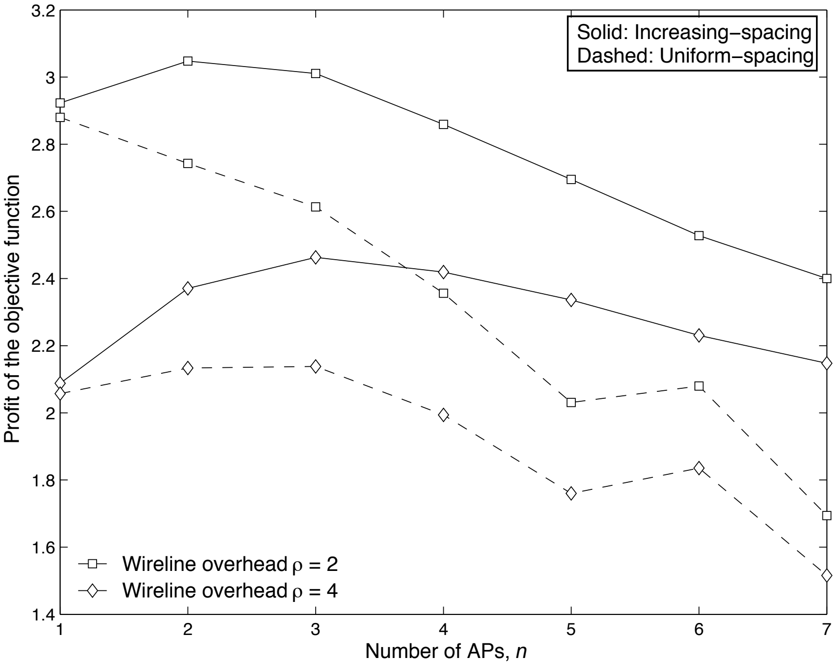

Fig. 2.16. Comparison of the increasing-spacing and the uniform-spacing placement strategies in terms of the achieved profit of the objective function for different wireline overheads ρ.

profit of the objective function for the increasing-spacing placement strategy is about 6% better than that for the uniform-spacing placement strategy.

Fig. 2.17 shows the sum of carried traffic load and the total service area for a cluster of $(2n+1)$ APs according to the increasing-spacing and the uniform-spacing placement strategies. One can observe that the total carried traffic load with the increasing-spacing placement strategy increases faster than that with the uniform-spacing placement approach as the number of APs in a cluster increases. Furthermore, the increment of the traffic load for the uniform-spacing strategy will gradually diminish or even decrease (see $n = 6$ to $n = 7$). Since the profit of the objective function is proportional to the total carried traffic load, and inversely proportional to the cost of a cluster of APs, the achieved profit of the objective function is a concave function of n as shown in Fig. 2.16.

2.5.3 Scalable Ring-Based Wireless Mesh Network for Wide-area Coverage

Network Architecture

Fig. 2.6 illustrates the scalable ring-based wireless mesh network for wide-area coverage. In each mesh cell, all users are connected to the central gateway in a multi-hop fashion. Each intermediate node operates as a wireless relay to forward data traffic to

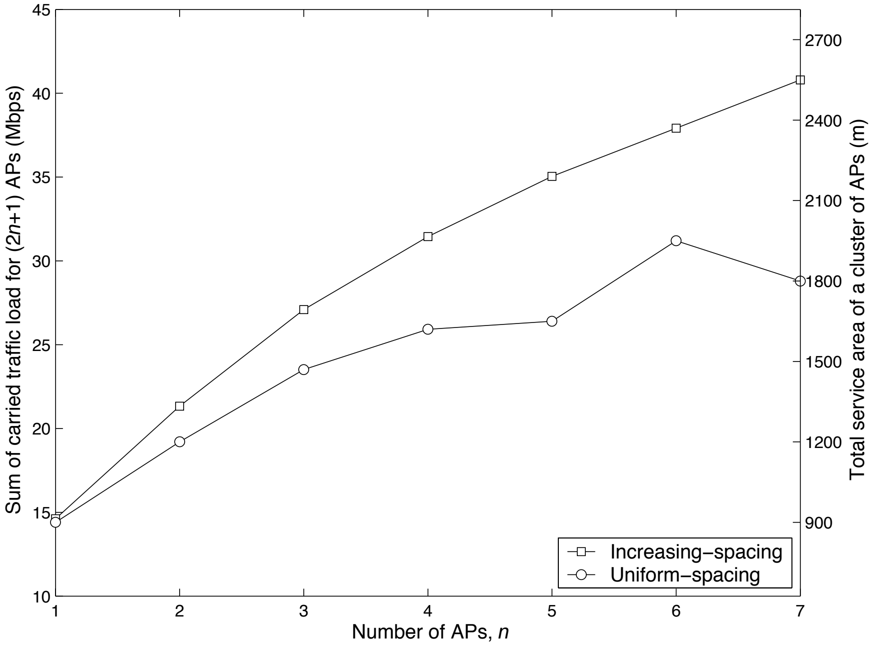

Fig. 2.17. Performance comparison of the increasing-spacing and the uniform-spacing placement strategies, from the viewpoint of one cluster.

the gateway. The gateway connects to the backbone network via a wired or wireless connection. Using this mesh architecture, the cabling engineering work for WMN deployment can be reduced.

In this work, we consider a multi-channel wireless mesh network. In this WMN, each mesh cell is divided into several rings, denoted by A_i, $i = 1, 2, \cdots, n$. The user in the ring A_i will connect to the central gateway via an i-hop communication. We assume that each node can concurrently receive and deliver the forwarded traffic as [7, 10, 25]. That is, each node is equipped with two radio interfaces, and the users in ring A_i will communicate with the users in rings A_{i-1} and A_{i+1} at two different channels f_i and f_{i+1}, respectively. By doing so, the multi-hop mesh network becomes scalable to the number of users since the contention issue can be resolved by the multi-channel arrangement in a ring-based network.

We assume that frequency planning is applied to avoid the co-channel interference, and thus the inter-ring co-channel interference will not be considered in this work. In a multi-channel network [25], the dynamic frequency assignment can flexibly utilize the available channels, but it needs a multi-channel MAC protocol that is sometimes complicated. In the considered ring-based WMN, however, the fixed frequency planning is simple because it only needs to consider the width of each ring to ensure an enough co-channel reuse distance.

The carried traffic load in each mesh node includes its own traffic and the forwarded traffic from other users. Assume that all the nodes in the inner ring A_i share the relayed traffic from the outer ring A_{i+1}. Suppose that the user density is ρ. The average number of nodes c_i in the ring A_i can be expressed as

$$c_i = \rho a_i = \begin{cases} \rho \pi r_i^2 \,, & \text{for } i = 1 \\ \rho \pi (r_i^2 - r_{i-1}^2) \,, & \text{for } 1 < i \leq n \end{cases} \tag{2.14}$$

where a_i and $(r_i - r_{i-1})$ are the area and the width of ring A_i, respectively. Let R_D and R_i be traffic load generated by each node and the total carried traffic load per node in ring A_i, respectively. Then,

$$\begin{aligned} R_i &= \frac{c_{i+1}}{c_i} R_{i+1} + R_D \\ &= \left[\frac{\sum_{j=i+1}^{n} c_j}{c_i} + 1 \right] R_D. \end{aligned} \tag{2.15}$$

For the outermost ring A_n, $R_n = R_D$.

Coverage and Capacity Maximization

A. Problem Formulation

In the following, we formulate an optimization problem to determine the best number of rings in a cell and the optimal width of each ring so as to achieve the optimal tradeoff between throughput and coverage. To begin with, we discuss the constraints in the optimization problem for the considered ring-based WMN as shown in Fig. 2.6.

- The relay link capacity $H_i(d)$ for a user in ring A_i should be greater than the traffic load carried at each node R_i, i.e., $H_i(d) \geq R_i$, where d is the separation distance between the node and the next-hop node. This constraint guarantees the minimum throughput for each user.
- The maximum reception range should be larger than the ring width $(r_i - r_{i-1})$, i.e., $(r_i - r_{i-1}) \leq d_{max} = d_1$.
- The ring width should be greater than the average distance d_{min} between two neighboring nodes, i.e., $(r_i - r_{i-1}) \geq d_{min}$, where $d_{min} = 1/\sqrt{\rho}$ m is dependent on the user node density ρ.

B. MINLP Optimization Approach

From the above considerations, the optimal coverage issue in a wireless mesh network can be formulated as an MINLP problem with the following decision variables: n (the number of rings in a mesh cell) and $r_1, r_2, \ldots, r_n$. The objective function is to maximize the coverage of a mesh cell as follows. In this scalable ring-based WMN, the ring-based frequency planning resolves the collision issue as cell coverage increases. Accordingly, the optimal coverage and capacity will be achieved simultaneously, since more users in a mesh cell can also lead to higher cell capacity. The

Table 2.3. System parameters for numerical examples.

Symbol	Item	Nominal value
ρ	User node density	$(100)^{-2}\mathrm{m}^{-2}$
R_D	Demanded traffic of each user node	0.5 Mbps
d_{min}	Min. of ring width, i.e., $(1/\sqrt{\rho})$	100 m
d_{max}	Max. reception range	300 m
l_{RC}	Sensing range $(\gamma_I d_{max})$	450 m

optimal system parameters for the ring-based WMN can be analytically determined by solving the following optimization problem:

$$\underset{n,r_1,r_2,\ldots,r_n}{\mathrm{MAX}} \quad r_n \text{ (Coverage of a mesh cell)} \tag{2.16}$$

subject to

$$H_i(d) \geq R_i \tag{2.17}$$

$$d_{max} \geq (r_i - r_{i-1}) \geq d_{min} \tag{2.18}$$

where the cell coverage is defined as the cell radius r_n. A cross-layer analytical model to evaluate $H_i(d)$ was developed in [12].

Numerical Examples of Ring-Based WMN

Table 2.4. Relevant network parameters for an IEEE 802.11a WLAN.

PHY mode for data frame, m_a	$1 \sim 8$
PHY mode for control frame, m_c	1 (6Mbps)
Propagation Delay, δ	1 μs
SIFS	16 μs
DIFS	34 μs
Empty slot time, σ	9 μs
m_{bk}	6
Initial Contention Window, W	16

The system parameters are summarized in Tables 2.3 and 2.4. We considers a simple case where all the ring widths in a cell are the same, i.e., $(r_i - r_{i-1}) = r$. The control frames (RTS/CTS/ACK frames) are transmitted with PHY mode $m_c = 1$ for reliability. The mesh nodes are uniformly distributed with density $\rho = (100)^{-2}$ nodes/m. We assume the sensing range $l_{RC} = \gamma_I d_{max}$, where γ_I is 1.5. As in [29], the chosen data frame payload sizes for eight PHY modes are {425, 653, 881, 1337,

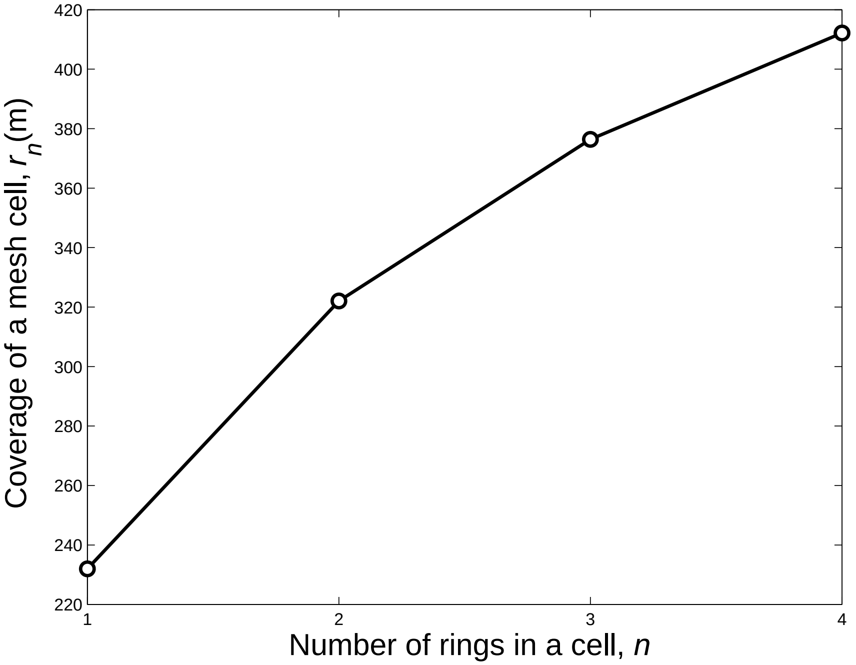

Fig. 2.18. Cell coverage versus the number of rings n in a mesh cell, where the demanded traffic per user is $R_D = 0.5$ Mbps.

1793, 2705, 3617, 4067 $(4095 - MAC_{hdr} - MAC_{FCS})\}$ bytes. Referring to the measured results [26], the corresponding average reception ranges are $d_j = \{300,$ 263, 224, 183, 146, 107, 68, 30$\}$ m. It is true that these reception ranges vary for different environments. However, the proposed optimization approach is general enough to evaluate the performances of different WMNs by adopting various reception ranges.

In Fig. 2.18, the achieved cell coverage against the number of rings in a mesh cell for $R_D = 0.5$ Mbps is shown. One can observe that the optimal achieved cell coverage is 412 m with $n = 4$. Compared with the coverage of the single-hop network $(n = 1)$, the multi-hop mesh network improves the coverage by 77%. Fig. 2.19 illustrates the capacity performance against the number of rings in a cell, for $R_D = 0.5$ Mbps. In this example, the corresponding optimal cell throughput is 26.7 Mbps with $n = 4$. Compared with $n = 1$, the multi-hop mesh network improves the cell throughput by 215%.

Figs. 2.18 and 2.19 show that the proposed ring-based WMN can enhance the cell coverage and throughput compared with the single-hop network. More importantly, we find that the optimal number of rings is equal to $n = 4$ for $R_D = 0.5$ Mbps. In these figures, it is shown that the more the number of rings in a mesh cell, the better the coverage and capacity. However, the constraints on the mesh link throughput and the separation distance between the mesh nodes determine the optimal solution.

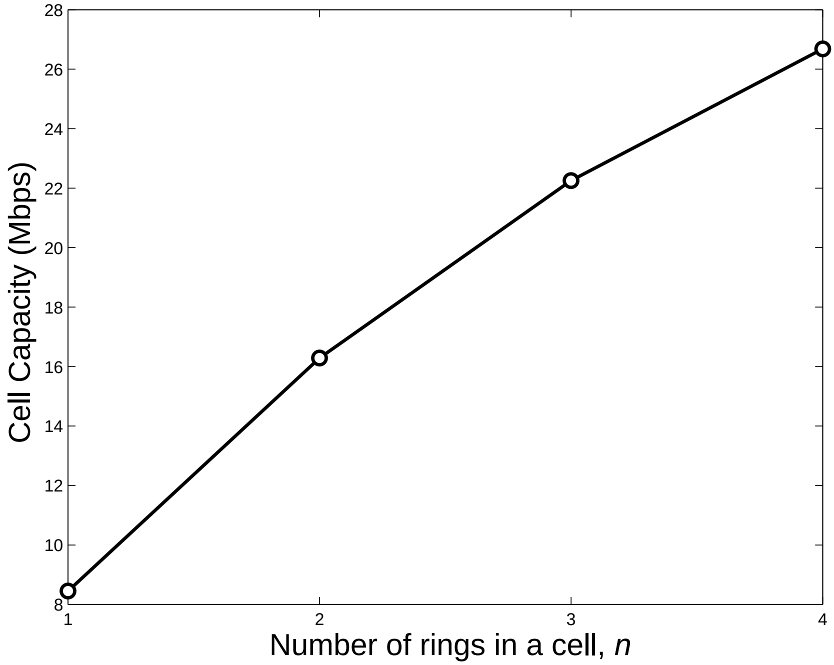

Fig. 2.19. Achieved cell capacity versus the number of rings n in a mesh cell, where $R_D = 0.5$ Mbps.

Fig. 2.20 shows the ring width for various number of rings n in a cell. Referring to this figure, when the number of rings increases, the ring width decreases. In general, when the number of rings n in a cell increases, the cell coverage also increases as shown in Fig. 2.18. For handling the increment of relay traffic as n increases, each ring width will decrease to shorten the hop distance and thus improve the link capacity. However, since the ring width should be larger than the average distance between two neighboring nodes, there exists a maximum value of n. In this example, the maximum allowable number of rings in a mesh cell is $n = 4$.

Conclusion

Wireless mesh networking is a promising solution for the next-generation communication system to support ubiquitous broadband services with low transmission power. In this chapter, we have provided a brief overview on the mesh networking technologies for the IEEE 802.11s and IEEE 802.16 systems. Then, we address the key challenge in WMN — the scalability issue from a network deployment perspective. We present two scalable-WMN deployment strategies for the typical WMN application scenarios, including the dense-urban and wide-area scenarios. The proposed WMNs are scalable in terms of coverage, since the frequency planning with multiple

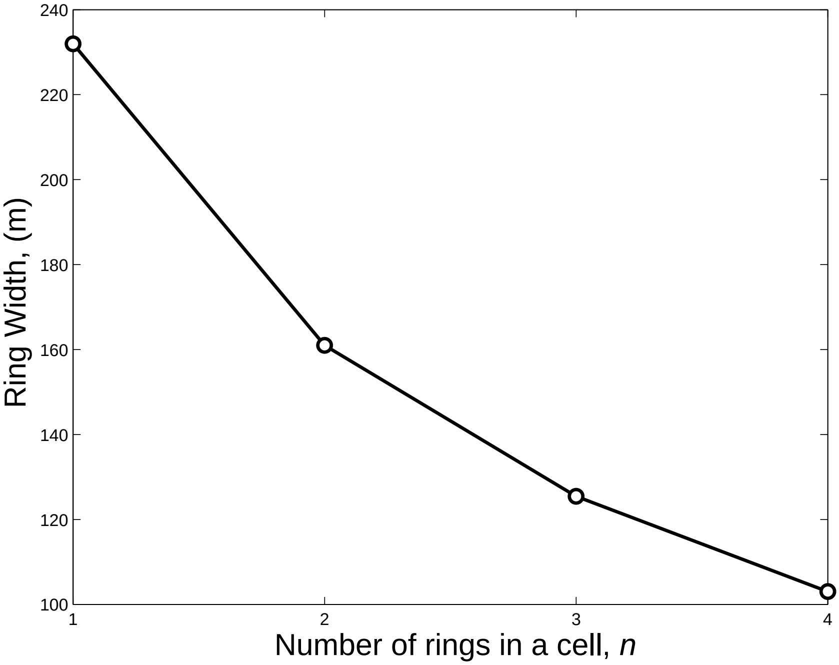

Fig. 2.20. Ring width r versus the number of rings n in a cell, where $R_D = 0.5$ Mbps.

available channels can effectively resolve the contention issue and thus the throughput can be ensured by properly designing the deployment parameters. This chapter also investigates the optimal tradeoff between capacity and coverage for the scalable WMNs. We have applied the mixed-integer nonlinear programming (MINLP) optimization approach to determine the optimal deployment parameters, subject to the tradeoffs between throughput and coverage.

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