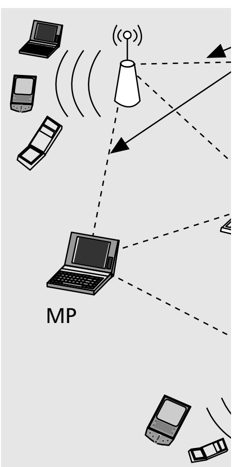
# EMERGING STANDARDS FOR WIRELESS MESH TECHNOLOGY

MYUNG J. LEE AND JIANLIANG ZHENG, CITY UNIVERSITY OF NEW YORK
YOUNG-BAE KO AND DEEPESH MAN SHRESTHA, AJOU UNIVERSITY, KOREA




The commercial success of Wi-Fi and the advances in many wireless technologies have in part stimulated the development of wireless mesh networks. The driving force, however, comes from the envisioned advantages of wireless mesh techniques themselves.

## ABSTRACT

Wireless mesh networking is a promising technology for numerous applications which appeals especially to those applications that cannot be directly supported by other wireless technologies. The commercial success of Wi-Fi and the advances in many wireless technologies have in part stimulated the development of wireless mesh networks. The persistent driving force, however, comes from the envisioned advantages of wireless mesh techniques themselves, including extended coverage, robustness, self-configuration, easy maintenance, and low cost. This article presents an overview of this emerging technology, focusing on the technical merits and related standards activities of IEEE and ZigBee that are actively applying the concept of multi-hop mesh techniques in the field of wireless networking technologies, ranging from personal area networks (PANs) to metropolitan area networks (MANs).

## INTRODUCTION

A disruptive technology, wireless mesh networking, is knocking on the doors of the communication industry. While this technology is not new conceptually, it was not until recently that researchers and enterprises, as well as consumers, have begun to think of this technology as something over the next hill rather than pie in the sky. Wireless networks have been making inroads into private residences, office buildings, universities, and other industrial and commercial venues around the globe in the past several years. This commercial success together with some emerging wireless technologies, especially radio technologies, suggest it is now time for wireless mesh networking to come into play. Seeing its potential to reshape the landscape of communications, major consumer-electronics companies as well as small startups are staking out this emerging technology and preparing for the market to take off.

Both the wired Internet and the public switched telephone network (PSTN) are essentially mesh networks that have long been present. In stark contrast to the wired Internet and the PSTN, wireless mesh technology allows designers to build electronic networks without ripping apart buildings or tearing up streets to wire miles of copper or fiber cables. Yet it has a flexible coverage and can seep where it is likely to be beyond the reach of other wired and wireless technologies. Besides, mesh connectivity significantly enhances network performance, including fault tolerance, load balancing, and throughput. In addition, the self-configuring and self-healing features of wireless mesh networks not only enable them to be deployed on the fly and on the cheap, but also enhance system resilience and reliability. Moreover, with minimal up-front investment and being easily adjustable and expandable, wireless mesh networks cater to the requirements of various consumers, large or small. With all these advantages, wireless mesh technology will open a world of possibilities and develop a burgeoning market in the foreseeable future, even though considerable research efforts are still needed.

As the World Wide Web has revolutionized the way people acquire information and succeeded in creating a huge market, engineers are now trying to weave another web, but one without threads. Although wireless mesh technology is still in its infancy, its potential to likely transform our world appears enormous. Some of the scenarios and applications where wireless mesh technology is likely to provide a more versatile or affordable solution than other wired or wireless technologies include, but are not limited to, the following:

- Extensive coverage areas, for example, offices, campus networking, stadiums, or spanning a sprawling facility
- Areas that are unwired, under-wired, or hard-to-wire, such as highways, conduits, golf courses, or farmlands
- Emergency situations such as fire fighting, disaster recovery, and military operations.

While a few companies have been rolling out proprietary wireless mesh products for some time, the involvement of international standard groups, the major driving force behind various technologies, has signaled the arrival of the wireless mesh era. As can be seen from Table 1, IEEE has been playing a key role in the devel-

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opment of wireless mesh standards with network coverage ranging from PAN to MAN. The remainder of this article presents an overview of wireless mesh standards activities of IEEE that includes IEEE 802.16, 802.11s, 802.15.5, and those of ZigBee.

## Standards for Wireless MAN Mesh

The IEEE 802.16 working group (WG) defines the physical (PHY) layer and the medium access control (MAC) sublayer standards targeted for wireless networking in metropolitan area networks (MANs). The IEEE 802.16 WirelessMAN standard [1], associated with Worldwide Interoperability for Microwave Access (WiMAX) and published in April 2002, was designed to operate in the licensed 10–66 GHz frequency range that requires line-of-sight (LOS) towers covering up to 5 km, similar to base stations (BS) in cellular communications. It builds a backhaul network for broadband wireless access at much lower cost, as compared to existing wired counterparts such as DSL and cable. This standard was initially created for point-to-multipoint (PMP) broadband applications, with an aim to provide higher data rate (up to 75 Mb/s) for each subscriber station (SS). Following this standard, IEEE 802.16 WG has set up several task groups (TGs) from 'a' to 'g' to address several extensions in fixed and portable/mobile broadband wireless access (BWA) in metropolitan areas as follows:

- ***a*** — Addition of a mesh mode
- ***b*** — Providing quality-of-service (QoS) feature
- ***c*** — Supporting interoperability
- ***d*** — Extensions of PHY layer
- ***e*** — Supporting mobility
- ***f*** — Supporting multihop functionality in IEEE 802.16e
- ***g*** — Providing efficient handover and QoS

To focus our attention on mesh-related activities, in the following subsection we describe the enhancement in the basic IEEE 802.16 standard (i.e., the 802.16a mesh mode) and the new study group named mobile multihop relay (MMR).

| Types of mesh networks and related marketing alliances | Corresponding standards used as a basis |
|---|---|
| WMAN mesh (WiMAX) | IEEE 802.16a |
| WLAN mesh (Wi-Fi) | IEEE 802.11s |
| LR-WPAN mesh (ZigBee) | IEEE 802.15.5 |

**Table 1.** *Wireless mesh standards.*

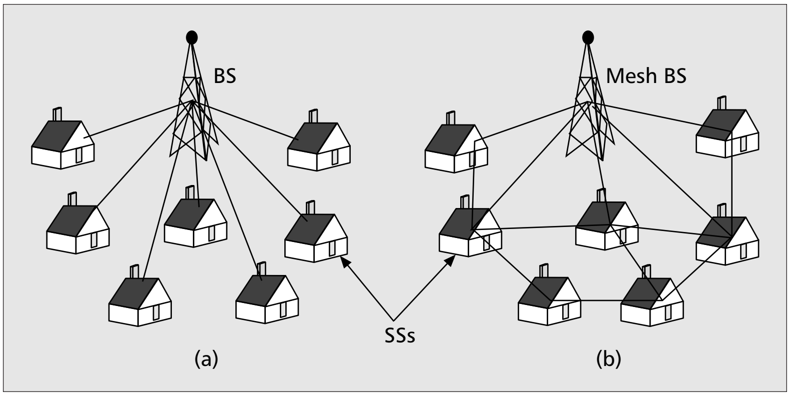



**Figure 1.** *Illustration for the IEEE 802.16a standards: a) point-to-multipoint mode; b) mesh mode.*

### IEEE 802.16 Mesh

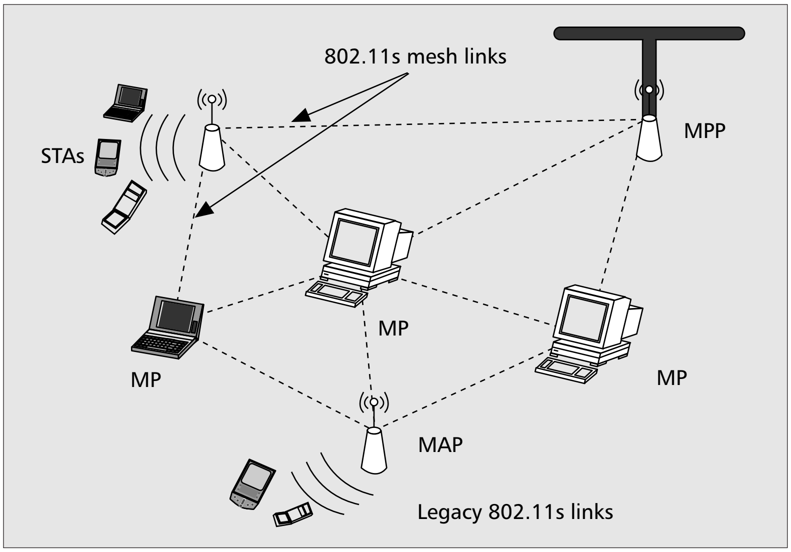
The IEEE 802.16a standard [2] incorporates what is known as the "mesh mode" in addition to the PMP mode defined in IEEE 802.16. This new standard operates in the licensed and unlicensed lower frequencies of 2–11 GHz that allows non-line-of-sight (NLOS) communications, spanning up to a 50 km range.

A key difference between the PMP mode and the mesh mode is the ability of latter to enable multihop communications. While the PMP mode requires each SS to be connected to a BS, neighbors can directly communicate with each other in the mesh mode (see Fig. 1). Hence, an SS in the mesh mode serves as a router relaying traffic between the SSs, until it arrives at the target BS (also called the "mesh BS") that connects the mesh to backhaul link and other external networks.

A new node joining the mesh network needs to go through the network entry and self-configuration process. Active nodes that are the part of mesh network periodically advertise MSH-NCFG (mesh network configuration) messages for any new node to synchronize with the existing network, which contains network configuration information such as the mesh BS identification number and base channel in use. The new node (also called a candidate node) actively scans for the existing network. Hearing the MSH-NCFG message, it establishes synchronization and initiates a network entry process. If there are many nodes sending MSH-NCFG messages, it chooses one potential sponsoring node and sends a MSH-NENT (mesh network entry) message with a request to join the mesh network. After authorization, it receives a 16-bit node identifier (i.e., node ID) upon request to the mesh BS, which uniquely identifies the node within a mesh during a normal operation and is carried by all unicast and broadcast frames.

Two types of TDMA-based packet scheduling mechanisms for channel access are available in the mesh mode: centralized scheduling and distributed scheduling. In the centralized approach, a mesh BS allocates the radio resources for all SSs within a certain hop range. In distributed scheduling, all nodes coordinate with each other for accessing the channel, including the mesh BS. Medium-access coordination between stations is performed by broadcasting the individual schedules to all neighboring nodes.

The IEEE 802.16a mesh mode has two limitations. First, its operation targets only fixed broadband applications. Second, it is not compatible with the existing PMP mode. To address these limitations, another study group (SG) called the "Mobile Multihop Relay (MMR)" was established in July 2005 under the 802.16 WG. The main purpose of this SG is to study the possibility for extending the PMP mode for an SS outside the coverage of a BS and to support mobile stations (MS) by using multihop relaying




■ **Figure 2.** *IEEE 802.11s network architecture.*

techniques using relay stations (RSs). An RS relays information between an SS/MS and a BS or between other RSs or between an RS and a BS [3]. Hence, unlike the mesh mode, dedicated RSs forms a treelike topology for relaying the traffic to the BS. The MMR SG submitted a project authorization request (PAR) for approval to create a TG named TGj at the March 2006 meeting.

## Standards for Wireless LAN Mesh

The IEEE 802.11 family of standards is currently the most successful wireless networking standards for wireless LANs. The initial specification was completed in 1999 (IEEE 802.11a/b) [4] and later extended in 2003 (IEEE 802.11g). It defines the PHY and MAC sublayer for the devices used in WLAN networking. It includes a dedicated device called an access point (AP), to which end-user devices or stations (STAs) with 802.11-compliant network interface cards connect for accessing network services. Such a set of STAs managed by a single AP is called a basic service set (BSS). An independent BSS (IBSS), also popularly referred to as an "ad hoc network," is a self-contained network in which STAs can directly communicate with each other without APs. A set of one or more BSS interconnected by a distribution system (DS) forms an extended service set (ESS), and can be regarded as a single 802 network segment. A DS contains either a single AP in a standalone network or a wired (cables)/wireless system that connects APs.

IEEE 802.11 standards continue to advance with various amendments, for example, 802.11e for QoS and 802.11n for data rates in excess of 100 Mb/s. These standards are still limited because of their dependency upon the wired network and unspecified wireless distribution system (WDS). Furthermore, 802.11 standards primarily aim at fulfilling one-hop communication needs and hence are affected by the problems of throughput degradation and unfairness when applied to multihop networks.

Motivated by the foregoing issues and limitations, a separate TG called "IEEE 802.11s ESS Mesh" was formed in May 2004 under the 802.11 WG to address the need for wireless mesh in WLANs. In the following subsections, we present a brief overview of the ongoing IEEE 802.11s activities followed by the description of its proposed network architecture and the primitive services provided by the medium access coordination function (MCF) sublayer.

### IEEE 802.11s: General Overview

The IEEE 802.11s extended service set (ESS) mesh aims at applying multihop mesh techniques to specify a WDS that can be used to build a wireless infrastructure for small-to-large-scale WLANs. Hence, the ESS or WLAN mesh can be considered as an IEEE 802.11-based WDS, a subset of the DS that consists of a set of devices interconnected with each other via wireless links, resulting in a 'mesh of connectivity.'

The activities of 802.11s TG comprise the specification of a new protocol suite for the installation, configuration, and operation of WLAN mesh. Its implementation shall be atop the existing PHY layer of IEEE 802.11a/b/g/n operating in the unlicensed spectrum of 2.4- and 5-GHz frequency bands. The specification shall include the extensions in topology formation to make the WLAN mesh self-configure as soon as the devices are powered up. A path selection protocol will be specified in the MAC layer instead of network layer for routing data in the multihop mesh topology. This standard is expected to support MAC-layer broadcast/multicast in addition to the unicast transmissions. This standard shall also accommodate devices that are able to support multichannel operations, or are equipped with multiple radios, with an aim to boost the capacity of the overall network. The specification is expected to be adopted as part of the working group standard by March 2008.

### Proposed IEEE 802.11s Network Architecture

The proposed WLAN Mesh architecture is depicted in Fig. 2. Any IEEE 802.11-based entity (either AP or STA) that partially or fully supports a mesh-relay function is defined as a mesh point (MP). The minimal MP operations include neighbor discovery, channel selection, and forming an association with neighbors. Besides, MPs can directly communicate with their neighbors and forward traffic on behalf of other MPs via bidirectional wireless mesh links. A set of MPs and the mesh links form a WDS, which distinguishes itself from the BSS as defined in the legacy IEEE 802.11[4].

The proposed WLAN mesh also defines a mesh access point (MAP), which is a specific MP but acts as an AP as well. The MAP may operate as a part of the WLAN mesh or in one of the legacy 802.11 modes. A mesh portal (MPP) is yet another type of MP through which multiple WLAN meshes can be interconnected to construct networks of mesh networks. An MPP can also co-locate with an IEEE 802.11 portal and function as a bridge/gateway between the WLAN mesh and other networks in the DS. To uniquely identify a WLAN mesh, a common mesh ID is assigned to each MP, similar to the use of service set identifier (SSID) to represent an ESS in legacy 802.11 networks.

## The Medium Access Coordination Function

The major components of the proposed 802.11s MCF are shown in Fig. 3. Built on top of the legacy physical layer specification, 802.11s shall explicitly provide the WLAN mesh services. These include topology learning, routing and forwarding, medium access coordination, mesh configuration and management, topology discovery and association, mesh measurement, interworking, and security functions [5].

For interworking of the WLAN mesh with other networks, the IEEE 802.1D standard shall be incorporated in the mesh portals (MPPs), which define the interworking framework and service access interface across all 802 standards. Similarly, security architecture shall be based on the IEEE 802.11i standard, which specifies security features for all WLAN networks. In the following subsections, we describe only the major services and functions germane to the mesh capability.

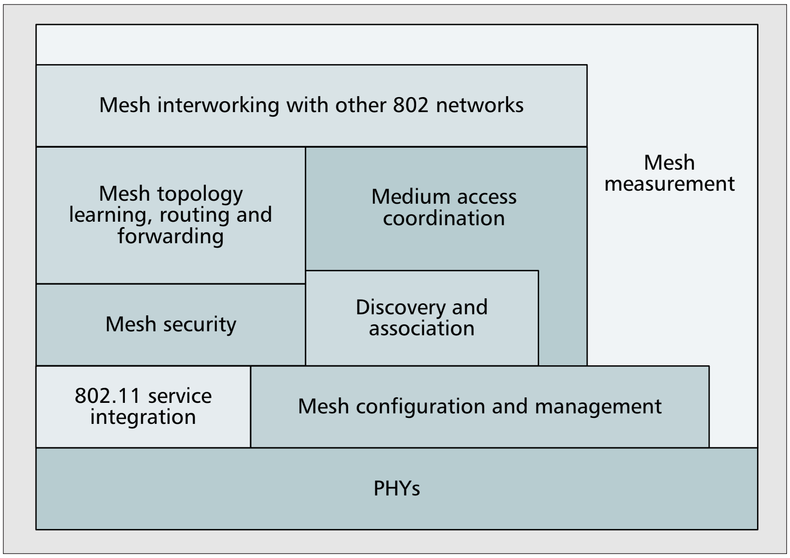



**Figure 3.** *Architecture for the 802.11s MCF sublayer.*

***Mesh Topology Learning, Routing, and Forwarding*** — This service set focuses on the peer-to-peer discovery of MPs. It enables automatic topology learning, establishes links, and eventually forms a dynamic data delivery path across the WLAN mesh.

**Topology discovery and formation**: A new node (a candidate MP) initially gathers information from neighboring MPs that belong to the active WLAN mesh, by either the active scanning (i.e., sending probe messages) or the passive listening (i.e., receiving periodic beacons) mechanism. Based on factors such as peer capability, power saving capability, security information, and link quality, two peers associate with each other, forming a partial or full mesh topology.

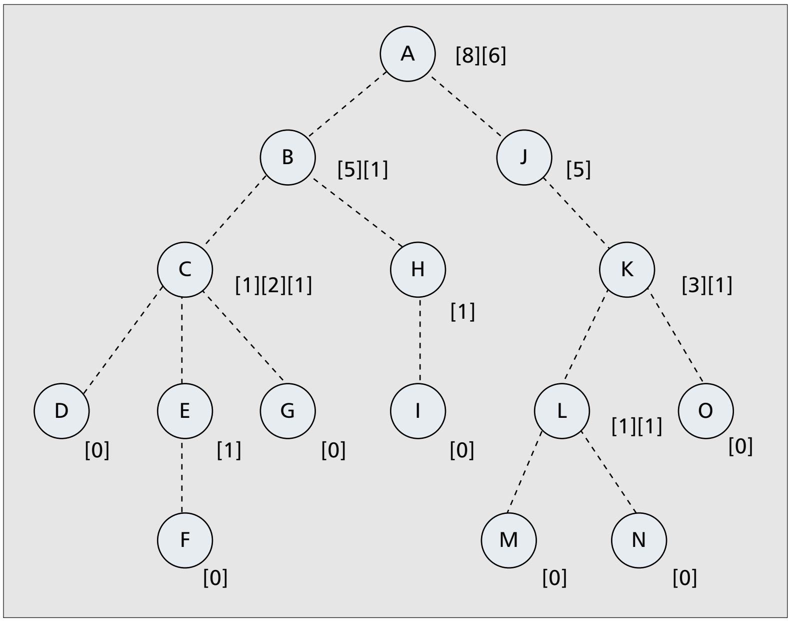
**Path selection protocol**: The MCF architecture provides an extensible framework such that the enhanced routing protocols and metrics tailored for particular applications can be implemented and used as required. A layer-2 path selection protocol is supposed to handle unicast and broadcast/multicast data delivery in the WLAN mesh. Since the network might have both nonmobile and mobile MPs, a hybrid routing protocol that includes both proactive and on-demand schemes is expected to be more suitable. Therefore, a hybrid scheme of using the ad hoc on-demand distance vector (AODV) and the optimized link state routing (OLSR) protocol is proposed to support wide range of application scenarios [6,7]. In addition, radio-aware metrics that reflects actual link condition are proposed, thereby making the routing protocols more robust against link failures. For example, an airtime metrics [6] reflects the cost of channel, path, and packet error rate. Similarly, another metric named weighted radio and load aware (WRALA) [7] is based on the protocol overhead at the MAC and PHY layers, size of the frame, bit rate, link load, and error rate.

**Forwarding scheme**: WLAN mesh traffic consists of 4-address data frames similar to that of the 802.11-1999 specification [4], with two new extensions for quality of service (QoS) and mesh control. Upon receiving such frames, the MP checks for its authenticity and its destination MAC address before forwarding. On arrival of the 3-address frame in MAP from the associated STA, the frame shall be converted to the 4-address format and forwarded towards the destination. Similarly, forwarding of multicast and broadcast traffic is also supported if they are 4-address data frames from the known source. The time-to-live subfield present in the data frame is decremented by every forwarding MP for controlling the broadcast traffic in the WLAN mesh.

***Medium Access Coordination*** — The medium access coordination of the proposal [6, 7] is based on the enhanced distributed channel access (EDCA) mechanism used in 802.11e [8]. The proposed MAC mechanisms facilitate congestion control, power saving, synchronization, and beacon collision avoidance. Using the proposed mechanisms, it shall be possible to enable multiple channel operations in multiradio or single radio, as well as mixed, environments. The multichannel MAC proposal is based on the common channel framework (CCF) [9], which is compliant to the legacy channel access mechanisms. It is primarily designed for efficient use of link capacity by enabling multichannel operations in nodes that are equipped with a single radio interface.

***Mesh Configuration and Management*** — Self-configuring paths and links offer one of the main advantages of mesh networks. Since their deployment can be unmanaged, autonomic management modules are required for their continuous operation. Protocols for association between MPs and the nodes outside the WLAN mesh can minimize the burden of manual configuration for the service provider.

Mesh management ensures the smooth operation of the network. Since any available MP can route packets, a failure of a particular device is not likely to affect the network as a




■ **Figure 4.** *Calculation of number of nodes along each branch.*

whole. However, the system should still be able to report the malfunctioning of devices. Furthermore, the interfaces need to support 802.11h so as to enable compliance with dynamic frequency selection (DFS) requirements. Support for radio frequency auto-configuration is expected to be provided for efficient multihop transmissions, power saving, and improving the total capacity.

## STANDARDS FOR WIRELESS PAN MESH

### IEEE 802.15.5

IEEE 802.15.4 [10] specifies the PHY layer and MAC sublayer functions of LR-WPANs. Currently, the ZigBee Alliance, which uses 802.15.4 as a basis, has been working on the specifications for network layer, application layer, and security of LR-WPANs. The IEEE 802.15.5 TG, kicked off in May 2004, is currently working to provide an architectural framework for interoperable, stable, and scalable wireless mesh topologies for WPAN devices. Here we briefly describe only the low-rate mesh architecture in the baseline document [11]. The proposal is based on the meshed tree approach; it addresses meshed tree routing, multicasting, and key predistribution.

***Adaptive Robust Tree*** — The tree defined in the proposal is called adaptive robust tree (ART) based on the facts that logical addresses are adaptively assigned during the tree formation procedure to reflect the actual network topology and that the tree is free of single point of failures (SPFs). In ART, each node keeps an ART table (ARTT) to track its branches. Each branch is assigned one or more blocks of consecutive addresses. Functionally, three phases are defined in ART: the initialization (or configuration) phase, the operation phase, and the recovery phase.

- During the initialization phase, nodes join the network and an ART tree is formed. After initialization, the network enters operation phase, in which normal communications start.
- During the operation phase, new nodes are still allowed to join the network, and if there is a substantial change of either the number of nodes or the network topology, the network may need to be reconfigured.
- If the tree is broken, then the recovery phase is triggered. Notice that recovery phase is different from the other two phases in that only the affected part of the tree needs to enter the recovery phase (other unaffected parts are still in operation phase).

An ART tree is formed during the initialization phase. The ART tree formation is functionally divided into two stages: association and address assigning. During the association stage, beginning from the root, nodes gradually join the network and a tree is formed. But this tree is not an ART tree yet, since no node has been assigned a logic address. After the tree reaches its bottom, a down-top procedure is used to calculate the number of nodes along each branch, as shown in Fig. 4. The numbers in brackets indicate the numbers of nodes within branches below a certain node. When the numbers of nodes are reported from bottom to top, each node can also indicate a desirable number of addresses. The ultimate result of address assignment is that each node has an ARTT built. During the operation phase, link failures or routing node failures will trigger the recovery phase. The ARTT is constructed in such a way that tree repair and recovery can be accomplished without changing any assigned address. The details of routing and tree repair/recovery can be found in [11].

***Meshed Adaptive Robust Tree*** — A meshed ART (MART) can be formed on top of an ART. In Fig. 5, where the original ART is connected using black lines, additional magenta lines are added so that the network now looks more like a mesh than a tree. But from each individual node's point of view, the network is still a tree. Any two nodes connected through a magenta line treat each other as a child and adds an ARTT entry for each other. For example, node K treats node H as a child, and vice versa. Note that ancestors and descendents, no matter whether they are one level or multiple levels away from the node, are not meshed (i.e., not connected to the node through the magenta lines). By forming a MART, it is possible to route a packet through a shorter path. Another advantage of MART is that some SPFs are removed. For instance, if the link between nodes J and K is broken, packets from node K to node H or I can still be routed.

### ZIGBEE

In this subsection, we briefly describe the standards activities of low-rate wireless personal area networks (LR-WPANs) in the ZigBee Alliance.

***Stack Architecture*** — The ZigBee stack architecture is depicted in Fig. 6. As mentioned above, the IEEE 802.15.4 [10] standard defines the PHY layer and the MAC sublayer for LR-WPANs.

The ZigBee Alliance has been working on the application (APL) layer, the network (NWK) layer, and the security services. To date, the ZigBee standard is the only market-ready wireless mesh standard.

There are three logical device types defined in a ZigBee network, namely, the ZigBee coordinator, the ZigBee router, and the ZigBee end device. A ZigBee coordinator is the 802.15.4 PAN coordinator and must be a full-function device (FFD). A ZigBee router is a FFD participating in a ZigBee network. A ZigBee router is not the ZigBee coordinator but may act as an 802.15.4 coordinator within its personal operating space. A ZigBee end-device is either a FFD or a reduced-function device (RFD), which is neither a ZigBee coordinator nor a ZigBee router. The capabilities and functionalities of these three types of devices are different in the network.

***Network Layer*** — The network (NWK) layer provides the data service and the management service to the APL layer. Here we focus on one of the most important functions of NWK layer — mesh routing.

ZigBee routing combines tree routing with on-demand nontree routing. Tree routes along a single tree branch are generally optimal if the tree has been optimized with respect to the routing cost(s) under consideration (e.g., hop count, link quality, and power). Therefore, optimal on-demand nontree routes are expected to be orthogonal with a high probability of tree routes in the sense that they mainly connect different tree branches. As a result, tree routes and nontree routes interconnect all nodes and form a mesh.

Through the primitive association supported by IEEE 802.15.4 [10], a logical tree, referred to as a cluster-tree [12], can be formed along with the setup of an LR-WPAN. The first node in the network will designate itself as the ZigBee coordinator and begin to accept association requests from other nodes. Any node already in the network can determine whether to allow other nodes to join it, that is, whether to act as a ZigBee router, depending on the availability of its resources such as memory and energy. In the cluster-tree, a node can have a maximum number of $C_m$ children and a node can be at most $L_m$ levels (i.e., hops) away from the root of the tree ($C_m$ and $L_m$ are two networkwide constants determined by the ZigBee coordinator). By knowing $C_m$, $L_m$, and its own address and tree level, a node can calculate the address blocks to be assigned to its children. Based on ZigBee Network Specification V 1.0 [13], a slightly different version of cluster-tree algorithm is used. Compared with the original cluster-tree [12], the new version distinguishes two types of devices when assigning logic addresses, that is, routers and end devices. A router is still assigned an address block, which can be further assigned to its children, but an end device only gets a single address and thus cannot have any children. Based on the above address-assignment logic, a node can easily determine how to forward a data packet by looking at the destination address, that is, whether to forward the data packet to one of its end-device children or to one of its router-capable children or to its parent. This routing scheme is referred to as cluster-tree routing.

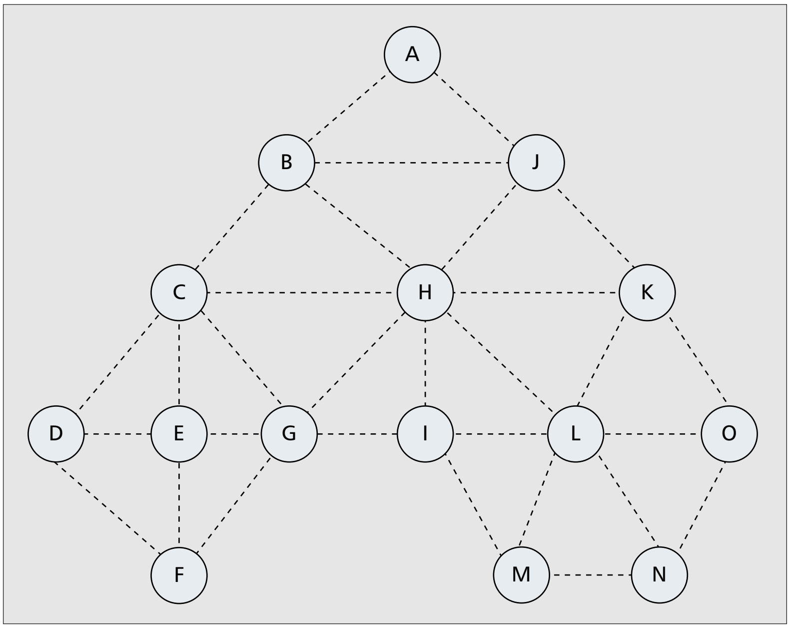



**Figure 5.** *Meshed ART.*

With the cluster-tree, a device can immediately begin to transmit data packets to other devices once it joins the network, without going through the route discovery procedure. However, most cluster-tree routes are not optimal in terms of hop count. Cluster-tree routing also results in uneven traffic distribution. That is, a node at a smaller tree level normally needs to handle more traffic than a node at a larger tree level. As such, a node at a smaller tree level dies more quickly than the other nodes due to its quick battery depletion. Without additional aiding mechanisms, single point of failure (SPF) and network partition could easily happen. Therefore, in ZigBee networks, cluster-tree routing is combined with another on-demand table-driven routing, which is currently based on the ad hoc on-demand distance vector junior (AODVjr) [14]. AODVjr is a simplified version of the AODV routing protocol [15], which is capable of finding optimal or near-optimal routes, and thus helps to reduce the message delivery latency. Nevertheless, it requires more memory compared with cluster-tree routing to store routing entries and also incurs higher control overhead. As most routes are formed on demand, the initial latency caused by route discovery is high. In general, AODVjr is suitable for devices with sufficient memories, and favors long communication sessions.

ZigBee routing combines cluster-tree routing and AODVjr routing, and makes tradeoffs between them according to network conditions and application requirements.

## Conclusion

Many forces are drawing researchers as well as manufacturers to wireless technologies. The explosive growth of wireless communications has

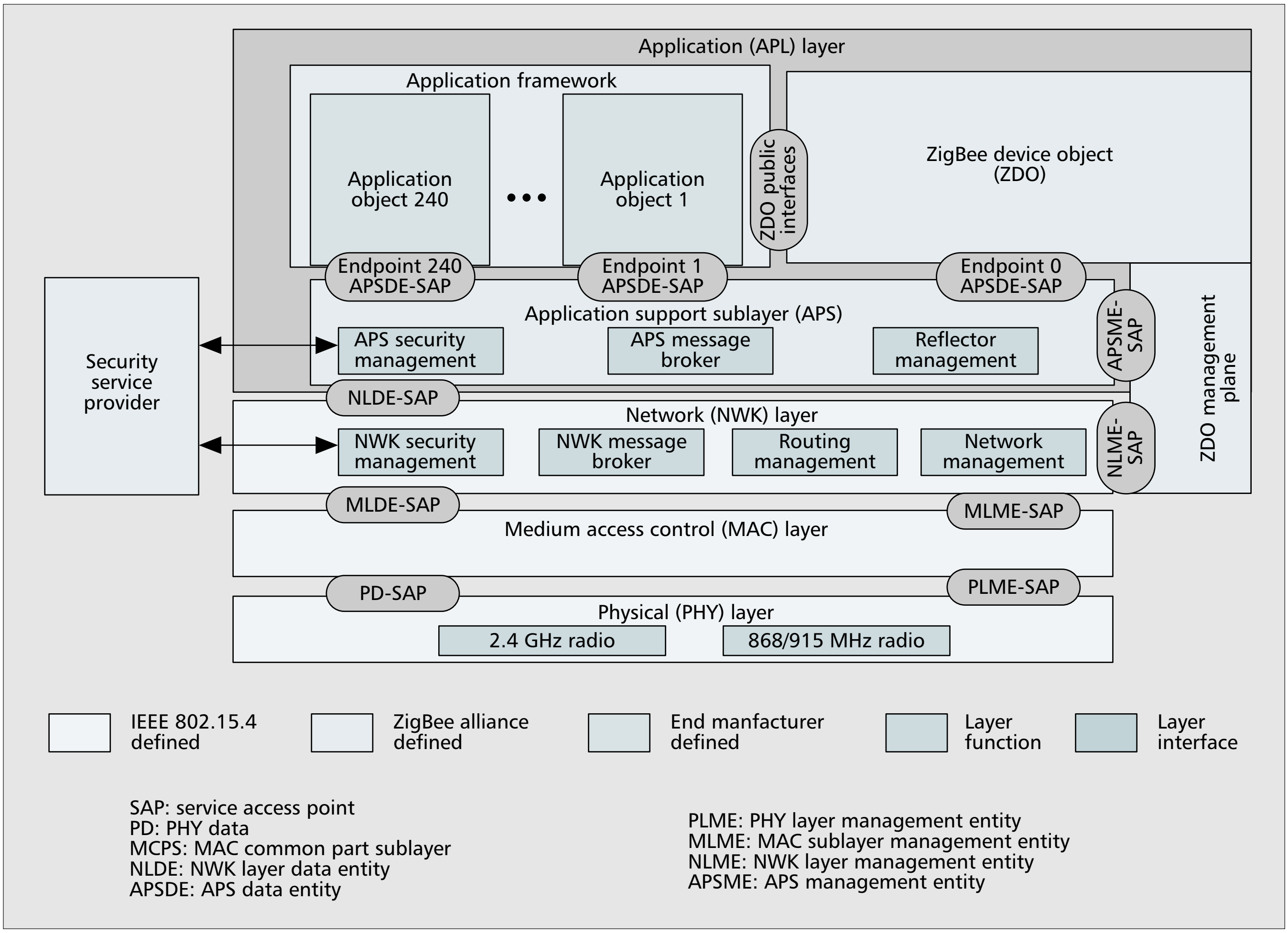



**Figure 6.** *ZigBee stack architecture.*

driven the cost of radio devices down and the quality up. With the ability to reduce installation costs, add flexibility, and ease deployment and maintenance hassles, the attractiveness of wireless technologies needs little reinforcement. Recently there has been a whole slew of research dedicated to wireless mesh networking. Behind this are some of the unique features of wireless mesh networks such as cost effectiveness, extended coverage, fault tolerance, load balancing, self-configuring, self-healing, and relatively smaller upfront investment.

Large companies and industry alliances are now actively involved in research on wireless mesh networks, and several IEEE standards task groups have also been established to work on new standards for wireless mesh networks. With all these efforts and other advances in wireless technologies, we are ushering in a new era — the wireless mesh era.

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## Biographies

MYUNG JONG LEE [SM] (lee@ccny.cuny.edu) received B.S. and M.S. degrees from Seoul National University, Korea, and a Ph.D. degree in electrical engineering from Columbia University, New York, in 1990. He is currently a professor with the Department of Electrical Engineering of City University of New York and the director of the SAIT–CUNY Joint Laboratory. He has been a visiting professor to Telcordia and Samsung AIT. His recent research interests are on various issues of wireless sensor/ad hoc networks. He has published more than 100 journal and conference papers, and holds 20 U.S. and international patents (pending included). He is the Chair of IEEE 802.15.5 WPAN Mesh Task Group and Vice Chair of ZigBee NWG. He received the CUNY Excellence Performance Award in 1999 and the Best Paper Award at IEEE CCNC 2005.

JIANLIANG ZHENG received his B.S. degree in applied physics from Harbin University of Science and Technology in China, his M.S. degree in physics from Shanghai Jiao Tong University in China, and his Ph.D. degree in electrical engineering from the City University of New York. He has published six journal papers and seven conference papers. He also holds five U.S. and international patents (pending). He has been actively participating in international standardizations, such as IEEE 802.15.5 Mesh WPAN TG and ZigBee Alliance. He contributed the IEEE 802.15.4 LR-WPAN ns2 simulation module as well as the ZigBee network ns2 simulation module. His research interests include wireless sensor networks and wireless mobile ad hoc networks, medium access control, wireless mesh routing, cross-layer design, embedded system, network security, and IPv6 technologies.

YOUNG-BAE KO is currently an assistant professor in the School of Information and Computer Engineering at Ajou University, Korea, leading the Ubiquitous Networked Systems (UbiNeS) Laboratory. Prior to joining Ajou University in 2002, he was with the IBM T. J. Watson Research Center, Hawthorne, New York, as a research staff member in the Department of Ubiquitous Networking and Security. He received his Ph.D. degree in computer science from Texas A&M University, and B.S and M.B.A. degrees from Ajou University. His research interests are in the areas of mobile computing and wireless networking. In particular, he is actively working on mobile ad hoc networks, wireless mesh/sensor networks, and various ubiquitous networked system issues. He was the recipient of a Best Paper award from ACM Mobicom 1998. He has served on the program committees of several conferences and workshops. He also serves on the editorial board of *ACM Mobile Computing and Communications Review*. See http://uns.ajou.ac.kr/~youngko for further details.

DEEPESH M. SHRESTHA (deepesh@ajou.ac.kr) received his B.E in computer engineering from Kathmandu University, Nepal, and his M.E in computer science from BITS, Pilani, India. He is currently a Ph.D. student in the Ubiquitous Networked System Laboratory at Ajou University, Korea. His research interests include routing and medium access control protocol design for wireless mesh and sensor networks.