Technology Reports

IEEE 802.11s Wireless LAN Mesh Network Technology

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A wireless LAN (WLAN) mesh network consists of WLAN devices with relay functions that communicate directly with each other instead of communicating via base stations. To solve problems like throughput degradation and congestion, a technology is proposed that enables coordination between routing, congestion control, and other functions on the MAC layer. With this technology, a high-speed wireless network can easily be constructed even at a location with no network infrastructure such as a WLAN access point.

1. Introduction

WLAN mesh network technology, which features flexible broadband network configurations independent of the fixed network, is attracting attention as an elemental technology for future ubiquitous networks consisting of various types of terminals including digital appliances, personal computers and mobile terminals [1].

Diverse scenes can be imagined for WLAN mesh networks. They can be used to achieve home networks, for extending the coverage area of enterprise WLAN networks, and for constructing ad hoc networks[*1]. A WLAN mesh network is formed by having neighboring terminals connect with each other directly by wireless means instead of going through centralized control equipment such as base stations. In this type of network, data sent out from a terminal arrives at its destination via a sequence of wireless terminals resulting in a multi-hop wireless network configuration.

Here, as a wireless system for interconnecting terminals, we apply WLAN technology conforming to the standard specifications of IEEE 802.11[*2], an international WLAN standard [2].

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*1 ad hoc network: A network configured by interconnecting mobile terminals without requiring base stations or access points.

*2 IEEE 802.11: An international wireless LAN standard established by the Institute of Electrical and Electronics Engineers (IEEE), a non-profit association in the United States.

WLAN technology is finding widespread use as a means of achieving broadband wireless communications, and it is an area of ongoing technical innovation especially in Quality of Service (QoS) technology[*3] [3] and wireless high-speed techniques (600 Mbit/s) [4].

WLAN mesh networks feature higher data transmission rate due to shortened communication distance, expanded network capacity through spatial frequency reuse, automatic network configuration, and improved robustness due to a route recovery mechanism.

However, multi-hop wireless networks are not problem free. For example, their operation can be affected by hidden terminals[*4] and exposed terminals[*5] that are associated with degradation of throughput[*6] characteristics, and they also suffer from network congestion [5]. These problems depend heavily on the routing protocol used to determine routes and on the radio access control scheme and radio resource management scheme implemented on the Medium Access Control (MAC) layer[*7]. To solve these problems so that the advantages of WLAN mesh networks can be used to the fullest, it is important that major functions implemented on the MAC layer operate in coordination with the routing protocol in real time [6].

Against the above background, we investigated a WLAN mesh network technology that implements the routing protocol on the MAC layer, and proposed the main results of that study to IEEE 802.11s [7].

The IEEE 802.11s task group was formed in May 2004 to standardize the technologies that would be needed to deploy WLAN mesh networks. This work involved the creation of usage models and requirements necessary for selecting proposed technologies and the preparation of formal procedures for making selections. A Call For Proposal (CFP) was issued in January 2005. By the time of a meeting held in March 2006, 2 candidates out of 15 submissions had survived, and these were eventually combined into a single draft version of a standard specification [8][9] based on the DoCoMo proposal. The plan from here on is to refine the specifications into a form that will win final approval. These standardization activities are expected to be completed by June 2008.

The following chapters will outline the system architecture of WLAN mesh networks and describe the main technological components of that architecture.

2. Overview of WLAN Mesh Networks

2.1 Device Types and Network Configuration

As shown in **Figure 1**, a WLAN mesh network consists of Mesh Points (MPs) equipped only with WLAN mesh network functions, Mesh Access Points (MAPs) equipped with a WLAN

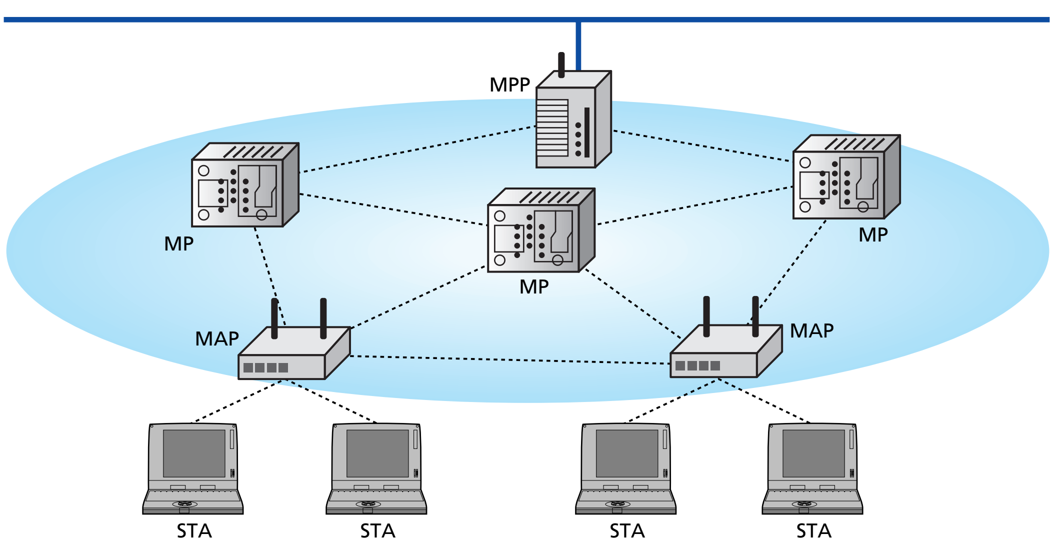

Figure 1 Configuration of a WLAN mesh network

*3 QoS technology: Techniques for securing optimal bandwidth according to the purpose of communications and guaranteeing the quality required by that type of communications.

*4 Hidden terminals: Terminals located in areas that cannot receive each other's signals nor determine the other's communication status. A phenomenon by which packets submitted simultaneously by hidden terminals collide and call quality degrades is called the "hidden terminal problem."

*5 Exposed terminals: Neighboring terminals whose mutual communications prevent other terminals from communicating. A phenomenon by which communications are suppressed in this way preventing required throughput from being attained and degrading call quality is called the "exposed terminal problem."

access point function in addition to MP functions, a MP collocated with a mesh Portal (MPP) equipped with a gateway function for connecting to an external network in addition to MP functions, and STAtions (STAs) that are legacy WLAN stations having no WLAN mesh network functions. A Wireless Distribution System (WDS) frame[*8] is used here to transfer data among the MP, MAP and MPP nodes.

2.2 Usage Model

The IEEE 802.11s standard envisions a small- to medium-scale WLAN mesh network configured with a maximum of 32 MPs (MAPs included). Practically, each MAP can be connected to many STAs enabling the entire network to accommodate several hundred terminals. Multiple WLAN mesh networks can also be interconnected to further expand network scale.

We expect WLAN mesh network technology to be applicable to a wide variety of usage environments. These might be home networks that connect digital appliances, personal computers, and other devices; office networks that make up corporate LANs; college campus networks and public access networks for commercial districts; and ad hoc networks for interconnecting mobile terminals [10].

2.3 System Architecture

Figure 2 shows system architecture for WLAN mesh network technology [11]. The following outlines the main functional blocks of this architecture.

1) Mesh Topology Learning, Routing and Forwarding

This block contains a function for discovering neighboring nodes, a function for obtaining radio metrics[*9] that provide information on the quality of wireless links, routing protocol for determining routes to transfer packets to their destinations using MAC addresses as identifiers, and a packet forwarding function. Here, to make efficient use of radio resources, routing protocol must make use of radio metrics and multiple frequency channels in accordance with radio conditions.

2) Mesh Network Measurement

This block contains functions for calculating radio metrics used by routing protocol and for measuring radio conditions within the WLAN mesh network for use in frequency channel selection.

3) Mesh Medium Access Coordination

This block includes functions for preventing degraded performance due to hidden and exposed terminals, functions for performing priority control, congestion control, and admission control, and a function for achieving spatial frequency reuse.

4) Mesh Security

This block contains security functions for protecting data frames carried on the WLAN mesh network and management frames used by control functions such as routing protocol. It assumes the use of WLAN security schemes defined by the IEEE 802.11i[*10] standard [12].

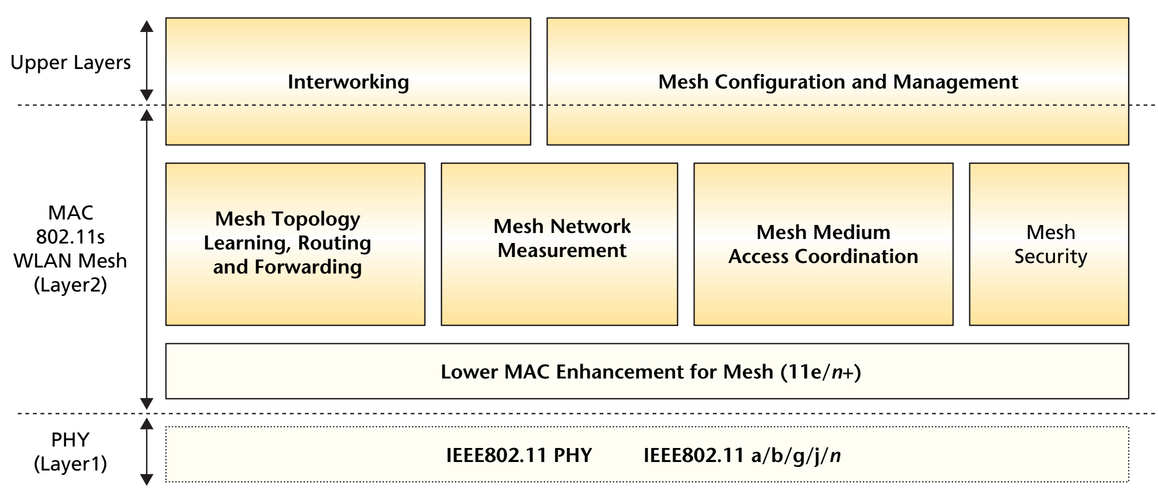

Figure 2 System architecture

*6 Throughput: Effective amount of data transmitted without error per unit time.
*7 MAC layer: A layer that has a control function for preventing packet collisions when sharing communication lines among multiple nodes. This layer is a lower sublayer of the data link in the OSI 7-layer model.
*8 WDS frame: Unit of data used for communicating between wireless access points.
*9 Radio metrics: Indices used in routing that take the quality of radio links into account.
*10 IEEE 802.11i: A standard defining wireless LAN security functions.

5) Interworking

As part of the IEEE 802 standard typical of wired Ethernet, a WLAN mesh network must conform to IEEE 802 network architecture. Accordingly, to connect to other networks, a transparent bridge[*11] function must be implemented in the MPP situated at the network boundary, and each WLAN mesh network must operate as a broadcast network so that forwarded packets can be delivered to all terminals connected to the LANs.

6) Mesh Configuration and Management

This block includes a WLAN interface used for automatic setting of each MP's Radio Frequency (RF) parameters (frequency channel selection, transmit power, etc.), for QoS policy management, etc.

3. Details of Elemental Technologies

Of the various elemental technologies making up WLAN mesh networks, routing technology, congestion control technology, and dynamic frequency channel allocation technology are considered to be especially important. These technologies are described below.

3.1 Routing Technology

Routing protocol and radio metrics are important elements in determining the performance of a WLAN mesh network. To date, however, many routing protocols [13] and radio metrics [14][15] have been proposed, and achieving interoperability between devices of different vendors has been a serious problem. In addition, the optimal routing protocol or radio metric depends on the usage model [16], and to complicate matters even further, future standard technologies and vendor propriety protocols are expected to be implemented in the years to come.

Against the above background, it is important to have a default routing protocol and radio metric that all devices will be required to implement to ensure interoperability, and to have an extensible framework that enables the implementation of various routing protocols and radio metrics optimized for different usage environments.

1) Extensible Framework

A framework that enables flexible selection of a routing protocol and radio metric is essential to achieving routing technology appropriate for the actual usage environment. At the same time, the formation of a WLAN mesh network requires that all MPs select the same routing protocol and radio metric.

Consequently, combination of routing protocol and radio metric is defined as a profile[*12], and a function is prescribed to notify the profile that is selected by each MP to neighboring MPs[17].

2) Routing Protocol

Layer-3 routing protocol, which has been extensively researched for some time, can be broadly divided into two types: proactive and reactive [16]. The proactive type establishes routes beforehand regardless of whether communications are in progress, while the reactive type establishes routes as needed for communication purposes. The characteristics exhibited by these schemes are heavily affected by external factors such as network size and the speed of mobile nodes. Nevertheless, it is desirable that a default routing protocol, which all terminals will be required to implement, be capable of minimizing protocol complexity while exhibiting high performance in diverse usage environments. With this in mind, we have proposed a scheme that builds upon the Ad hoc On-Demand Distance Vector routing (AODV) scheme [18], a reactive-type routing protocol. Our proposed scheme, called Radio Metric AODV (RM-AODV) [19], possesses the following features as enhancements to AODV.

a) Support of radio metrics

The proposed routing protocol periodically checks radio conditions with neighboring nodes to select routes that further stabilizes and minimizes the radio metric.

b) Support of multiple WLAN interfaces

For MPs having multiple WLAN interfaces, the proposed routing protocol includes functions for using them in parallel and for using the interface having the lowest utilization ratio of radio resources for any given destination. These functions allow routing that maximizes system capacity in accordance with continuously changing radio conditions.

c) Support for Legacy 802.11 Stations

A MAP that manages STAs not equipped with routing func-

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*11 Transparent bridge: Technology used for interconnecting LANs defined by IEEE 802.1D. It enables terminals belonging to different LANs to be seen by each other as if they were operating on the same LAN.

*12 Profile: Equipment configuration information. In IEEE802.11s, "profile" refers to routing-related configuration information.

tions enables a STA to participate in a WLAN mesh network by maintaining a route to the destination on behalf of that STA.

We note here that IEEE 802.11s adopts the Hybrid Wireless Mesh Protocol (HWMP), which incorporates RM-AODV with a function added for establishing tree-based routes beforehand [9].

3) Radio Metric

The quality of a WLAN mesh network depends on the quality of the wireless links, on interference, and on the utilization ratio of radio resources [20]. To reflect all of these conditions and to achieve easy implementation, we have adopted airtime[*13] as a default radio metric [9].

4) RM-AODV Operation Overview

Figure 3 shows RM-AODV operation. First, an MP performs a radio metric exchange with neighboring nodes. The radio metric quantifies the quality of a wireless link as determined by wireless data transmission rate, amount of traffic, amount of interference, and other factors (Fig. 3 (1)).

Next, the source node broadcasts a request packet throughout the entire network. If, however, the source node happens to be a MAP that accommodates STAs equipped with no routing protocol, it will send the request packet on behalf of the source STA.

At this time, each relay node adds the value of the radio metric for the upcoming wireless link to the existing value of the radio metric in the request packet so that an accumulated radio metric value can be delivered to the destination node. In the event that a relay node has more than one WLAN interface and the radio metric value is the same for each, the WLAN interface for which the request packet arrives first will be selected in order to take the congestion state of each interface into account (Fig. 3 (2)).

Finally, the destination node selects the route having the smallest radio metric tabulated over an entire route (Fig. 3 (3)), and notifies each relay node along that route of this selection

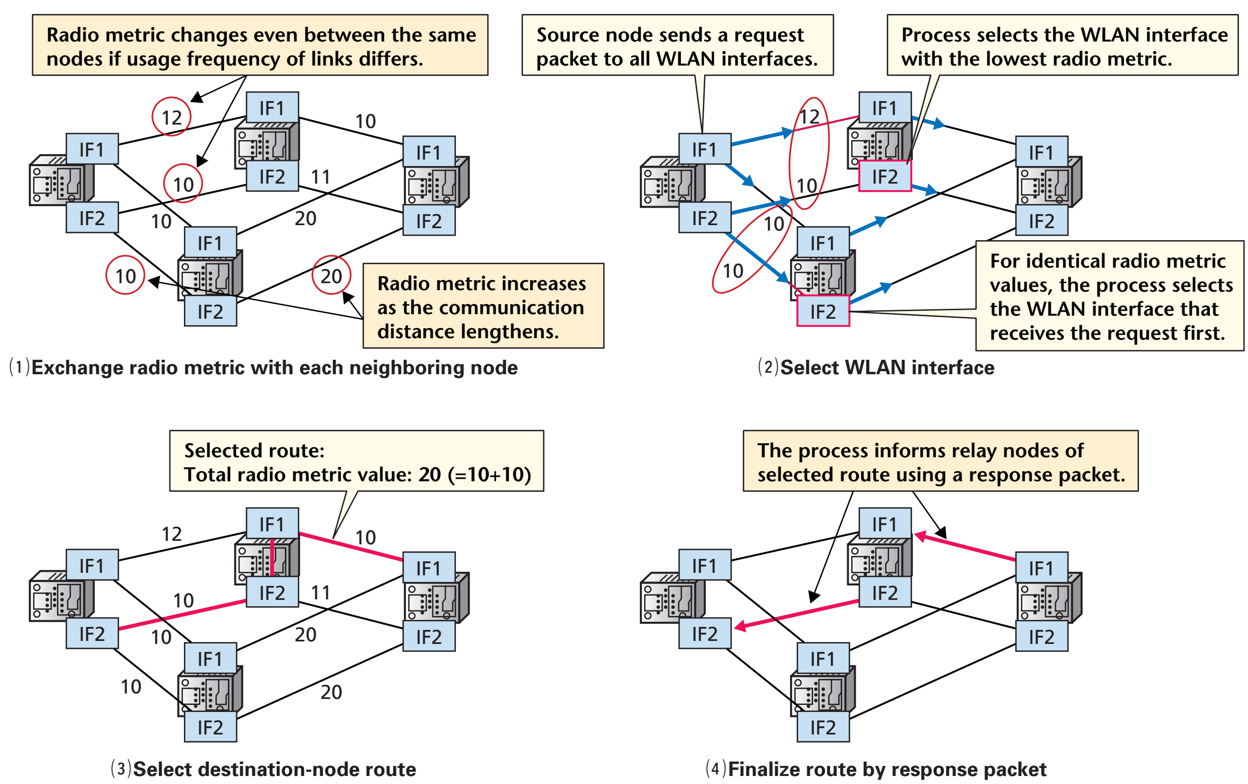

Figure 3 RM-AODV operation overview

*13 Airtime: The actual time taken for packet transmission on a wireless link. Used as an index for determining paths in IEEE 802.11s.

using a response packet (Fig. 3 (4)). In a manner similar to request-packet processing, a destination node that happens to be a STA will have its MAP reply with the response packet.

5) Characteristics Evaluation

We here present the results of evaluating the proposed protocol by computer simulation.

Figure 4 shows simulation results for 16 MPs placed randomly in a 50-m-square area. For comparison purposes, the figure shows characteristics when applying hop count (the number of relay nodes) versus those for a radio metric as criteria for routing, with the results for 1 and 2 WLAN interfaces shown for each. On comparing the conventional scheme using hop count and 1 WLAN interface with the proposed scheme using a radio metric and 2 WLAN interfaces, the latter is found to achieve 2.3 times the system capacity in terms of throughput by making uniform use of multiple WLAN interfaces.

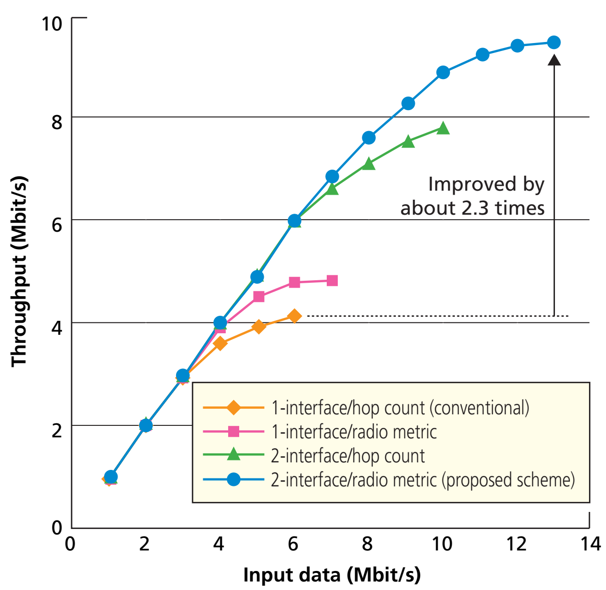

Figure 4 RM-AODV characteristics evaluation

3.2 Congestion Control Technology

In a WLAN mesh network that assumes packet transfer among MPs, the buildup of packets at relay equipment can cause transmission delays and drops in throughput to occur [21]. To prevent this problem from occurring in an efficient manner while minimizing revisions to existing specifications for the MAC layer, proposals have been made for congestion control technology that aims to adjust transmission rates between neighboring nodes through signaling [22][23].

The following outlines a congestion control method that prevents congestion at relay nodes by appropriately setting parameters known to have a high degree of freedom in the Enhanced Distributed Coordination Access (EDCA)[*14] [3]. This method has been defined as a mandatory function in the IEEE802.11s standard.

1) Principle Behind Generation of Congestion

Figure 5 shows the mechanism of congestion generation within a WLAN mesh network. The scenario shown depicts two-way communication between MP1 and MP5 via intermediary MPs. If we compare throughput characteristics for the links nearest the packet-originating nodes (links L_{1-2}, L_{5-4}) with those for the links nearest the packet-destination nodes (links L_{4-5}, L_{2-1}), we see that the latter represents a decrease to about 20% of the former.

We here examine the routes between MP1 and MP3 referring to **Figure 6**. If using EDCA as the radio access mechanism, the opportunity for packet transmission would normally be uniform among MP1, MP2 and MP3. In this case, however, MP2 acts as a relay node requiring it to send packets in both directions. This means that MP2 has relatively lower packet-transmission opportunity and that packet buildup and transmission-buffer overflow can occur in that node resulting in significantly degraded throughput characteristics.

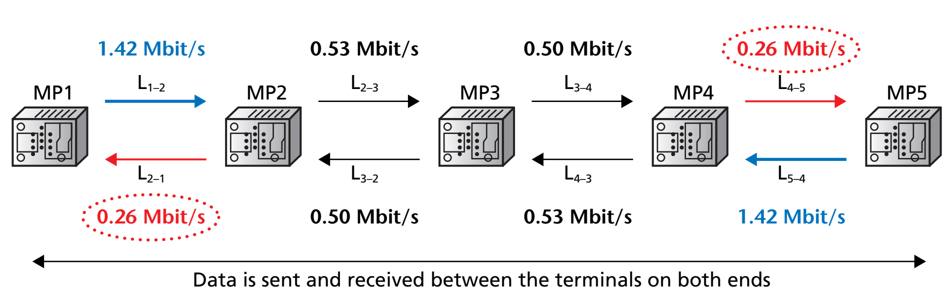

Figure 5 Mechanism of congestion generation in a WLAN mesh network

*14 EDCA: A radio access method for ensuring communication quality on wireless LAN standardized in IEEE802.11e.

2) Outline of Congestion Control Technology

Figure 7 shows the proposed congestion control technology. In the figure, MP(n) receives packets at transmission rate J(n–1) from upstream node MP(n–1) and sends packets to node MP(n+1) at transmission rate J(n). The following condition must be met here for congestion not to occur at relay node MP(n).

$$J(n-1) < J(n)$$

Accordingly, downstream node MP(n) needs to convey its maximum transmission rate to upstream node MP(n–1), and to do this, it sends a Congestion Control Request (CCR) packet. The upstream node now transmits packets at a transmission rate lower than the one specified in the CCR thereby solving the congestion at the relay node and improving end-to-end throughput as a result. Although Fig. 7 only shows packet traffic in one direction, the same type of processing would be needed in both directions in the case of bidirectional traffic.

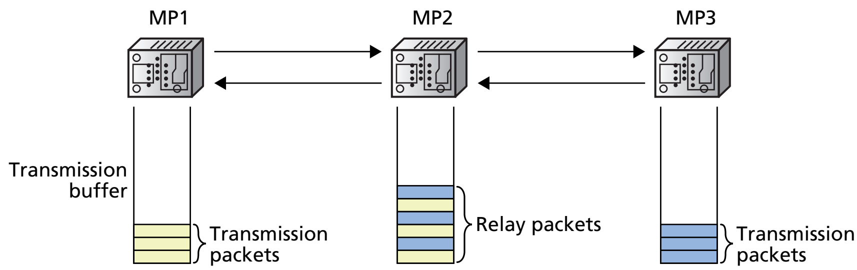

Figure 6 Buffer state at time of congestion

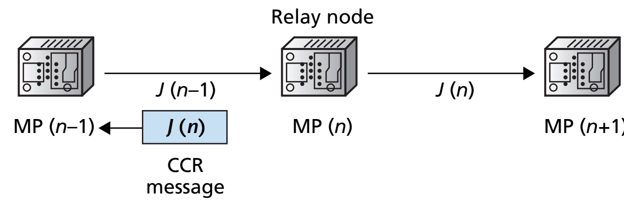

Figure 7 Overview of congestion control technology

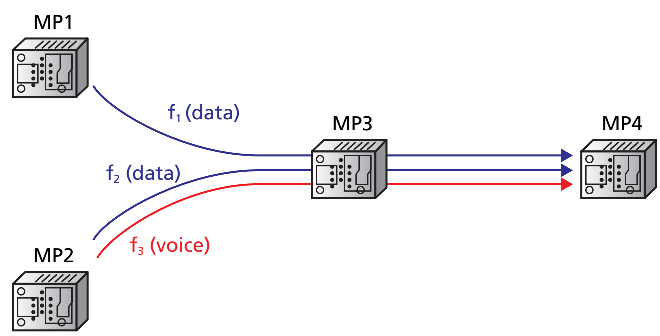

Figure 8 Simulation topology

To make such congestion control technology as effective as possible, it is important that studies be made on optimal settings for traffic-observation period and CCR-sending cycle and on transmission-rate control methods. It is desirable, in particular, that adaptive rate control be performed using EDCA to minimize changes to hardware.

3) Effect of Congestion Control Technology

We here present simulation results for a topology[*15] having multiple flows in a single network as shown in **Figure 8**. In this simulation, transmission rate is controlled by increasing or decreasing the value of Arbitration Inter Frame Space Number (AIFSN)[*16], an EDCA parameter. Symbols f_1, f_2 in the figure denote data traffic while symbol f_3 denotes voice traffic to which a higher QoS class has been set.

Because a CCR packet can specify the maximum rate for each of the four types of QoS classes specified in [3], it becomes possible even when applying congestion control to regulate data traffic flow without having to reduce the throughput of high-priority traffic such as voice calls.

Figure 9 shows simulations results. It can be seen that the application of congestion control improves total throughput by about 30%. Furthermore, since transmission rate can be specified for each QoS class, high-priority voice traffic (f_3) can be kept at a fixed rate while improving the throughput of data traffic (f_1, f_2) even when applying congestion control by the method presented here.

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*15 Topology: Positional relationship of devices, network configuration, etc.
*16 AIFSN: Time interval before beginning data packet transmission as defined in EDCA.

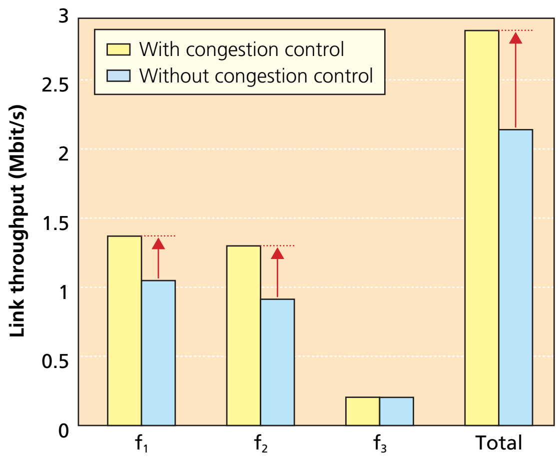

Figure 9 Throughput characteristics with and without congestion control

3.3 Dynamic Frequency Channel Allocation Technology

Four channels in the 2.4-GHz band and eight channels in the 5-GHz band are available for current WLAN equipment in Japan. In conventional systems, an access point selects an optimal frequency channel and instructs the terminal awaiting connection to use that frequency channel. A WLAN mesh network, however, has a distributed network configuration having no equipment that performs centralized control, and it is left to each MP to decide which frequency channel to use. To form a stable network and increase network capacity in this situation, it is important that a dynamic frequency channel allocation technology be adopted. The following describes two frequency channel selection methods defined as mandatory functions in IEEE 802.11s [7].

1) Single Channel Mode

Constructing a stable network to prevent network cutoffs from occurring requires that each MP select the same frequency channel. To this end, frequency channel priority information can be used to enable a common frequency channel to be selected for the entire network even if each MP chooses a frequency channel independently. This information is exchanged among neighboring nodes and the frequency channel used by the node with the highest frequency channel priority is selected as the common frequency channel.

2) Multi Channel Mode

In this mode, it is assumed that each MP possesses multiple WLAN interfaces and that multiple frequency channels will be used to good effect in a WLAN mesh network. Such an MP is able to dynamically allocate a frequency channel to each wireless link in accordance with network topology and traffic conditions. In the multi-channel-mode example shown in **Figure 10**, the WLAN interfaces that are to use the same frequency channel between MPs are grouped together as clusters[*17] and a frequency channel is determined for each cluster. This framework for allocating frequency channels can increase network capacity by load balancing [24] and can even solve the hidden-terminal and exposed-terminal problems [25].

4. Conclusion

This article presented an overview of WLAN mesh networks and described system architecture. It also described the elemental technologies needed to configure a WLAN mesh network, namely, routing, congestion control technology, and dynamic frequency channel allocation technology. For the future, we plan to continue researching WLAN mesh networks as a platform technology for ubiquitous networks.

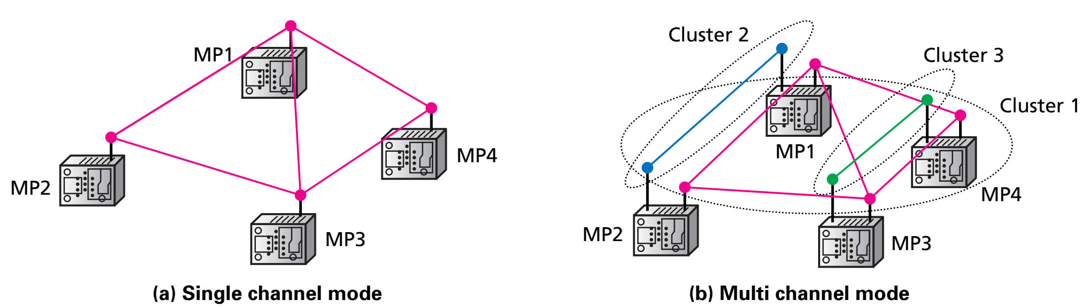

Figure 10 Overview of dynamic frequency channel allocation

*17 Cluster: In this article, a group of wireless LAN interfaces that use the same frequency channel within a wireless LAN mesh network.

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