Mesh-type Broadband Fixed Wireless Access System

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Abstract

The mesh-type fixed wireless access (FWA) system, which uses directional antennas and forms a wireless mesh network, is an attractive way of providing broadband services because it offers significantly enhanced frequency utilization efficiency and makes service area expansion easy. This paper outlines the mesh-type broadband FWA system and evaluates by computer simulation its frequency utilization efficiency under free-space loss propagation conditions and user station accommodation rates in Shinjuku ward, Tokyo. Results are compared with conventional point-to-multipoint FWA systems.

1. Introduction

The demand for broadband access to the Internet is increasing along with the rapid deployment of Internet technologies and services for broadband. Fixed wireless access (FWA) systems are expected to play an important role in deploying high-speed Internet access services rapidly to supplement ADSL (asymmetric digital subscriber line) systems and FTTH (fiber to the home) systems. Point-to-multipoint (P-MP) systems [1] and point-to-point (P-P) systems [2] that use the quasi-millimeter and millimeter bands are now in commercial use. If we consider that such FWA systems offer broadband services to many users who are deployed widely, the following problems must be considered. In P-MP systems, the total interference power cannot be sufficiently reduced because the base stations must use wide-beam antennas. Accordingly, their frequency utilization efficiency is too low. In both systems, each user station can be only one hop from the base station, so some hops are quite long. Therefore, the user stations and base stations need large high-power amplifiers and high-gain antennas, which raises the costs. In the P-P system, each base station needs as many antennas as the number of user stations accommodated.

To solve these problems, the mesh-type broadband FWA system (hereafter, shortened to mesh system) has been proposed [3], [4]. It can use directional antennas to greatly reduce the interference and transmission power. In addition, the stations should be much cheaper and the services areas should be easier to expand, because signals are relayed in a hop-by-hop manner, which shortens the distances between stations. Its frequency utilization efficiency has been evaluated under autonomous distributed control [5], [6]. These evaluated efficiencies reflect the degradation caused by non-optimum channel assignment followed by autonomous distributed control in which each station selects its own channels based on radio statements made in a limited area surrounding the station. Therefore, the theoretical frequency utilization efficiency that this system can offer was not clarified in these studies. Moreover, although its routing methods for selecting appropriate paths and traffic sharing methods have been studied to enhance the frequency utilization efficiency [7], [8], the effect on service area expansion has not been quantitatively evaluated.

In this paper, therefore, we focus on the theoretical frequency utilization efficiency and user station accommodation rate of a mesh system and evaluate them by computer simulation in comparison with P-MP systems. We evaluated the frequency utilization efficiency under optimum channel assignment to

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obtain the theoretical value, and line-of-sight (LOS) rate based on three-dimensional geographical information to obtain the accommodation rate. The simulation results show that its frequency utilization efficiency is 4.5 to 6 times higher under free-space loss propagation and the distance between stations to achieve an accommodation rate of 95% in Shinjuku ward is 55% less than in conventional P-MP systems.

2. Mesh-type broadband FWA system

Figure 1 shows a typical mesh system. It consists of route stations and user stations. The route stations are connected to the wired backbone network. The user stations are connected to the route stations and/or other user stations to relay signals by wireless transmission. A user station is classified as either a "relay station" or an "end station", according to its role. In addition, a "channel" and "path" are defined between the stations. **Figure 2** illustrates these definitions. A "relay station" is a user station that transmits and receives not only its own signals, but also those of other user stations to relay them. An "end station" is a user station at the edge of the wireless network; it handles only its own signals. A "path" is the connection between stations and a "channel" is a line set up in the path, as shown in Fig. 2. All stations use directional antennas and they are connected on a point-to-point basis.

As indicated in Fig. 1, the mesh system offers several advantages. For example, because user stations can pass information to other user stations, the inherent problem of non-line-of-sight (NLOS) transmission in the P-MP system is resolved. Therefore, the mesh system is expected to expand service areas more than a P-MP system. In addition, the short distance between user stations eliminates the need for large high-power amplifiers and large antennas in user stations, resulting in cheaper stations. Furthermore, the use of directional antennas reduces the interference power from other channels. Therefore, the mesh system is expected to offer high frequency utilization efficiency when many user stations are widely deployed.

3. Simulation evaluation of performances of mesh systems

3.1 Frequency utilization efficiency of mesh systems

To focus on the theoretical frequency utilization efficiency that a mesh system can offer, which is considered to be its potential one, we evaluated its frequency utilization efficiency under optimum channel

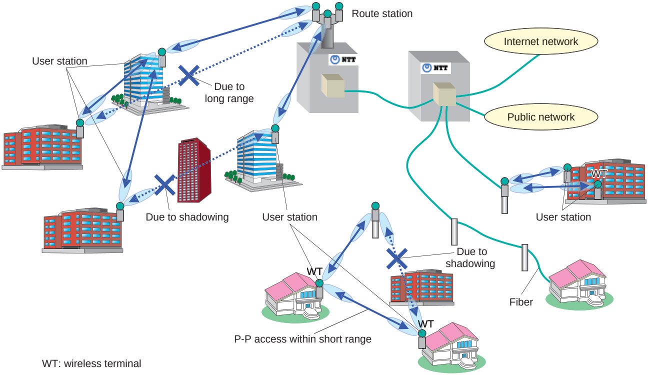


Fig. 1. Mesh-type broadband FWA system.

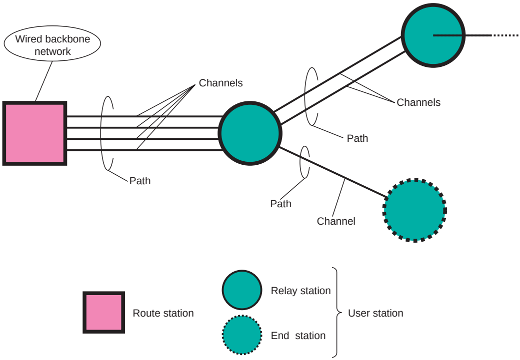


Fig. 2. Definitions in mesh systems.

assignment assuming central control.

(1) Calculation steps

We assume that each user station wants services with a guaranteed bit rate, so each path between a route station and a user station in the mesh system needs an additional channel to relay information from a route station to a user station. Carrier waves are added as relay channels in this evaluation. On the other hand, in the P-MP system, a carrier is allocated to a sector, where we assume that the bandwidth of the assigned carrier equals the bandwidth per user multiplied by the number of user stations. **Figure 3** shows the number of channels and carriers in both systems. Under this assumption, we conducted computer simulations to evaluate the frequency utilization efficiency on downlinks (paths from the route stations to the user stations) for the mesh and P-MP systems as follows.

1. C/I (desired carrier-to-interference power ratio) values of all channels on downlinks were calculated.
2. The "offered C/I" for each user station was derived from the calculated C/Is. It is defined as the minimum C/I in all channels assigned for a user station because it impacts the transmission rate between a route station and the user station in tree-type wireless networks (described in the next section).
3. The "95%-guaranteed C/I" was derived from the offered C/I. It is defined as the lowest 5% of the offered C/I values of all user stations, and it means the C/I that guarantees to connect 95% of all user stations to the route stations.
4. In order to sensitively reflect the C/Is in the frequency utilization efficiency, we assume that the system has a link adaptation function that can adaptively change the transmission rate according to the radio transmission quality. We used the HiSWANa [9] or HIPERLAN Type 2 [10] standard as an example of a link adaptation model. **Table 1** shows the required C/Ns (carrier-to-noise ratios) for each transmission rate of HiSWANa, where the transmission quality threshold was set to a packet error rate (PER) of 0.1. The 95%-guaranteed C/I was converted into frequency utilization efficiency based on the required C/Ns. Assuming that the interference level was much larger than the noise level, the required C/N was converted into the required C/I, and the 95%-guaranteed C/I was used to determine the transmission rate. Finally, the frequency utilization efficiency was derived from the transmission rate [11].

(2) Simulation models

All the simulation models used to evaluate the frequency utilization efficiencies were the same as the

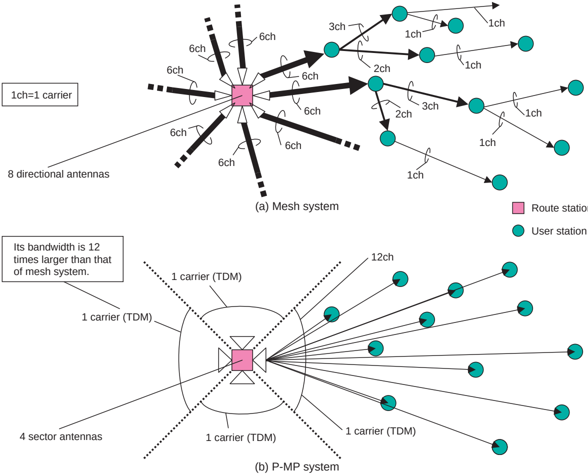


Fig. 3. The number of channels and carriers.

Table 1. Required C/N to achieve PER of 0.1 for HiSWANa or HIPERLAN Type 2.

(bandwidth: 18 MHz, temperature: 300 K, noise figure: 10 dB, margin: 4 dB)

PHY mode	Modulation	Coding rate	Transmission rate (Mbit/s)	Receive sensitivity (dBm)	Required C/N (dB)
0	BPSK	1/2	6	–85	3
1	BPSK	3/4	9	–83	5
2	QPSK	1/2	12	–81	7
3	QPSK	3/4	18	–79	9
4	16QAM	9/16	27	–75	13
5	16QAM	3/4	36	–73	15
6	64QAM	3/4	54	–68	20

ones described in ref. [11]. We considered that the route stations formed cell configurations to accommodate as many widely deployed user stations as possible.

Figure 4 shows the cell configuration and user station sites in each cell. The cell configuration is based on squares and a route station is placed at the center of each cell. The simulation target is 6×6 cells. The frequency utilization efficiency was evaluated only for the central 2×2 cells, which suffer interference from the surrounding cells. Each cell is divided into 7×7 lattice boxes and a user station is randomly placed in each of the 48 lattice boxes other than the central one.

Figure 5 shows route construction in the mesh system. We assumed a tree-type wireless network, in

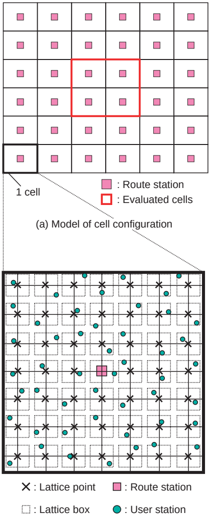


Fig. 4. Model of cell configuration and user station sites in a cell.

which each user station was connected to the route station in its cell by 1, 2, or 3 hops. The routes in the tree-type wireless networks were designed as shown in Fig. 5, where the points representing the user stations were replaced by lattice points (the centers of the lattice boxes), so that each path accommodated almost the same number of user stations.

In a mesh system, each route station has 8 antennas and each user station has 1, 2, or 3 antennas. They are directional antennas with beamwidth of 5, 10, 20, or 30°. In the P-MP system, each route station (called a base station in conventional FWA systems) has four sector antennas whose beamwidth is 90° and each user station has the same directional antenna as in the mesh system. **Figure 6** shows the antenna patterns, where D(θ) is the antenna gain function of angle θ,

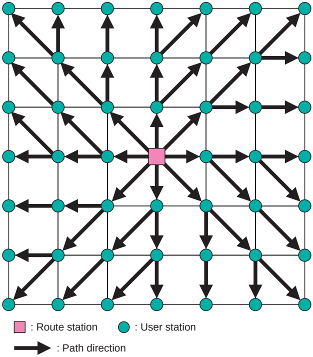
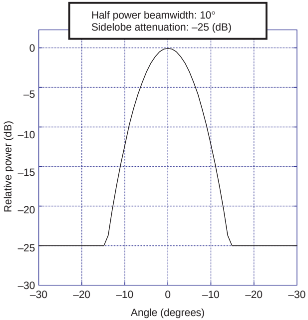


Fig. 5. Model for route construction in mesh systems.



$$D(\theta) = \begin{cases} \cos^{\Theta_H}(\theta) & (-\theta_\alpha \le \theta \le \theta_\alpha) \\ \alpha_B & (\theta < -\theta_\alpha,\ \theta_\alpha < \theta) \end{cases}$$

$$\alpha_B = \cos^{\Theta_H}(\theta_\alpha),\ \Theta_H = \log_{10}[2 - \{\cos(\theta_H/2)\}]$$

Fig. 6. Antenna pattern.

θ_H is half power beamwidth, and α_B is the sidelobe attenuation level, when the half power beamwidth is 10° and the sidelobe attenuation level is –25 dB.

In the P-MP system, the carrier assignment is optimized by the cluster assignment mechanism. One carrier is allocated per sector and the cluster size is four. So the total number of carriers is 4.

In the mesh system, the carrier assignment is optimized by a simulated annealing algorithm [11], [13]. This algorithm produces carrier assignment in the mesh system with the lowest sum of the I/C (interference-to-desired carrier power ratio) in all channels.

Moreover, we assumed free-space propagation in calculating the path loss, no adjacent channel interference, and a constant load in all channels. We assumed that the desired signal level was the same for all user stations. The above simulation parameters are summarized in **Table 2**.

(3) Simulation results

Figure 7 shows the 95%-guaranteed C/I as a function of antenna half power beamwidth for sidelobe attenuation levels of –15 dB and –25 dB; the number of carriers was 16, 24, and 48 in mesh systems. As shown in Fig. 7, the mesh system offered 12 to 20 dB higher 95%-guaranteed C/I than the P-MP system at half power beamwidth of 5°. Moreover, decreasing the antenna half power beamwidth increased the 95%-guaranteed C/I. From here onwards, we clarify that the channel capacity is improved by using directional antennas. **Figure 8** shows the frequency utilization efficiency as a function of the number of carriers for sidelobe attenuation levels of –15 dB and –25 dB, and the half power beamwidth of 5°. As shown in Fig. 8, when the number of carriers was less than 11, the mesh system offered lower frequency utilization efficiency than the P-MP system. Note that the maximum number of transmitting and receiving channels used by a user station was 11 in this mesh topology model; this degradation occurred because the maximum number of channels per user station exceeded the number of carriers. This means that some transmitting and receiving channels at a user station shared the same carrier, so the interference power in the channels could not be reduced sufficiently by using directional antennas. As a result, the C/I of those channels degraded significantly. Therefore, the number of carriers must exceed the maximum number of transmitting and receiving channels used by a user station if mesh systems are to offer sufficient frequency utilization efficiency. In contrast, when the number of carriers was 12 or more, the mesh system offered 4.5 to 6 times higher frequency utilization efficiency than the P-MP system. For this number of carriers, when the antenna sidelobe attenuation level was –15 dB, the frequency utilization efficiency of the mesh system improved with the number of carriers. In contrast, when the antenna sidelobe attenuation level was –25 dB, increasing the number of carriers decreased the frequency utilization efficiency. When the antenna sidelobe attenua-

Table 2. Simulation parameters.

Parameter		Value	
		Mesh systems	P-MP systems
Cell	Configuration	Square model	
	Number	6 × 6 cells (Evaluated cells: 2 × 2 cells in the center)	
User station	Point	Random point in each lattice box	
	Number in a cell	48 (3 hops)	48
	Average interval between user stations	1/7 × cell Length	
Half power beamwidth	Route station	5, 10, 20, 30°	90° (4 sector area)
	User station		5,10, 20, 30°
Sidelobe attenuation (s)		–15, –25 (dB)	
Number of carriers (f)		6, 10, 12, 16, 24, 48	4
Method of carrier assignment		Simulated annealing	Cluster assignment mechanism
Access scheme		Point-to-point	TDM (Number of user stations accommodated in a sector area: 12)
Bandwidth per carrier		18 (MHz)	18 × 12 (MHz)
Propagation model		Free-space-loss	

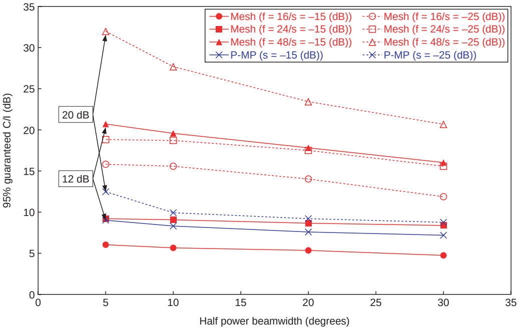


Fig. 7. 95% guaranteed C/I.

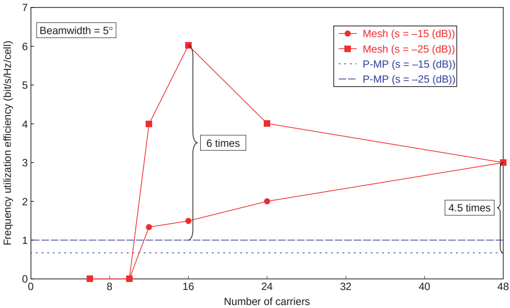


Fig. 8. Frequency utilization efficiency.

tion level was –15 dB, the 95%-guaranteed C/I was much lower than the required C/I for the maximum transmission rate in HiSWANa (called "saturation C/I" hereafter). Therefore, when the number of carriers was small, the decrease in transmission rate caused by the interference power was larger than the improvement in frequency utilization efficiency.

On the other hand, when the antenna sidelobe attenuation level was –25 dB, the 95%-guaranteed C/I was close to the saturation C/I even when the number of carriers was small. Therefore, the improvement was larger than the decrease. Accordingly, the optimum number of carriers in terms of maximizing the frequency utilization efficiency depends on the antenna sidelobe attenuation level.

3.2 User station accommodation rate in mesh systems

Next, we evaluated the rate of accommodating user station in mesh systems compared with that of the P-MP system by a LOS simulator [14]. For a mesh system, the accommodation rate means the number of user stations that can be connected to route stations, either directly or via relay channels, divided by the total number of user stations, which are widely deployed. For a P-MP system, on the other hand, this rate refers only to direct connections (i.e., it excludes relaying). The simulator can evaluate LOS rates reflecting real geographical conditions. Specifically, it can judge whether or not there is a physical line of sight between any two points in the real world, taking into account buildings, based on three-dimensional geographical information such as land elevations and data about buildings. Moreover, it also forms tree-type wireless networks with the minimum total hop numbers and distances between the stations based on all the evaluated line-of-sight statements.

(1) Simulation conditions

The simulation conditions used to evaluate the user station accommodation rates are described below.

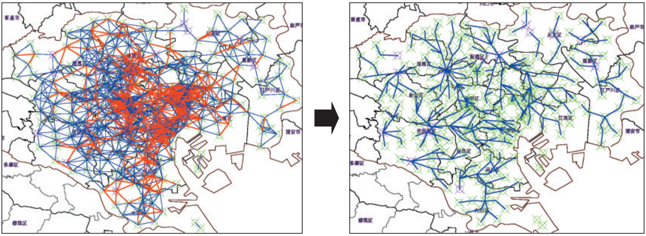
1. The evaluated area was Shinjuku Ward in Tokyo.
2. Route stations were placed as follows. First, the evaluated area was divided into 15 hexagons with centers 1500 m apart. Then, a circle of radius 750 m with its center coinciding with that of the hexagon was drawn in each hexagon, and one point was randomly selected in each circle. Finally, one route station was placed at the top of the highest building in each circle whose center point is the selected point and radius is 300 m. Moreover, the antennas of the route stations were set at 15 m high from the tops of the buildings. The number of route stations was 15.
3. User stations were placed as follows. First, the evaluated area was divided into 208 hexagons with centers 400 m apart. Then, a circle of radius 200 m with its center coinciding with that of the hexagon was drawn in each hexagon, and one point was randomly selected in each circle. Finally, one user station was placed at the top of the highest building in each circle whose center point is the selected point and radius is 50 m. Moreover, the antennas of user stations were set at 1 m high from the top of the buildings. Therefore, the total number of user stations was 208. Though user station locations are not limited in a real system, we used this simple model as an example of user station placement used in the physical LOS calculation for the first step of evaluating the accommodation rate. Note that this placement is appropriate only for stations acting as relays.
4. When a given station could not see the whole of another antenna in the LOS simulator, we judged the path between the two stations to be non-LOS, where the shape of each antenna was assumed to be square.
5. Tree-type wireless networks were automatically formed based on all the evaluated line-of-sight statements according to the above process.

Figure 9 shows examples of results obtained with the LOS simulator for the 23 wards of Tokyo.

(2) Simulation results

Table 3 shows accommodation rates (AR) in the P-MP system as a function of the maximum range (MR) defined to be the longest distance within which user stations can be connected to the route stations. Table 3 also shows i) the number of user stations that are outside circles having a radius of MR from the centers of any route station divided by the total number of user stations (hereafter denoted OMR: outside maximum range rate) and ii) the number of user stations that are inside such circles and the centers of some route stations, but are non-LOS from them divided by the total number of user stations (hereafter denoted IMR-NLOS). **Figure 10** shows the definitions of MR, OMR, IMR-NLOS, and AR. As shown in Table 3, only 30% of user stations can be accommodated in an P-MP system when MR is 500 m, but the accommodation rate is about 90% when MR is 1400 m. However, about 7% of user stations within MR are non-LOS from some route stations. To achieve an accommodation rate of over 95%, MR must be more than 1800 m.

Figure 11 shows accommodation rates in a mesh system as a function of the maximum hop numbers, for the maximum range of 400, 500, 600, 700, and 800 m. When there is only one hop, the evaluated system corresponds to the P-MP system. When there are multiple hops, the accommodation rate is defined as the rate of user stations that can connect to a route station either directly or in a hop-by-hop manner. As shown in Fig. 11, when MR is 500 m, a mesh system with three hops achieves an accommodation rate of about 73%, which is about 2.4 times larger than that of a P-MP system. Though further increasing the hop number improves the accommodation rate, above

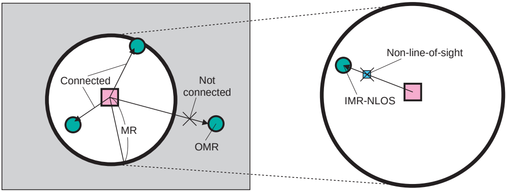


Results of judging whether or not two points are physically in line of sight

Tree-type wireless networks are automatically formed based on all the line-of-sight statements

Red lines: non line-of-sight
Blue lines: line-of-sight

Fig. 9. Examples of results obtained with the LOS simulator.



: Route station
: User station

MR: Range of route station
OMR: Ratio of user stations that are outside any range
IMR-NLOS: Ratio of user stations that are within some ranges and are NLOS with a route station in the ranges
AR: Ratio of user stations that can connect to a route station (1-OMR-IMR-NLOS)

Fig. 10. Definitions of rates in P-MP system.

four hops the improvement is slight and it saturates at about 84%. Increasing MR also improves the accommodation rate. A mesh system with three hops achieves an accommodation rate of 95% when MR is 800 m, which is 55% shorter than that of a P-MP system for the same accommodation rate.

4. Conclusion

We are studying a mesh-type broadband FWA system composed of user stations and route stations connected to the wired backbone network. To assess its advantages, we evaluated its frequency utilization

Table 3. Accommodation rate of user stations in P-MP systems.

MR (m)	OMR (%)	IMR-NLOS (%)	AR (%)
500	43.96	25.12	30.92
1000	9.07	11.22	79.71
1200	4.35	8.69	86.96
1400	1.99	7.19	90.82
1600	0.97	6.76	92.27
1800	0	5.31	94.69

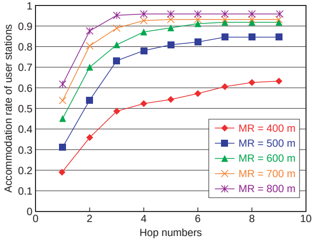


Fig. 11. Accommodation rate of user stations in mesh systems.

efficiency under optimum channel assignment in a free-space loss propagation condition and its accommodation rate of user stations in Shinjuku ward based on the real geographical conditions by computer simulation. The results show that it significantly improves frequency utilization efficiency and reduces the maximum distance needed between stations to achieve an accommodation rate of 95% compared with a P-MP FWA system. Therefore, the mesh-type FWA system is more promising than the conventional P-MP FWA system for implementing broadband services. It is also attractive as the entrance radio network for next-generation cellular systems because it will provide more bandwidth, so more base stations can be deployed.

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