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Effect of a New Channel Assignment Strategy on Multihop Wireless Networks

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SUMMARY Recently, the mulitihop wireless network system attracts the interest of many people as a communication network system of the next generation. The multihop wireless network has unique features in which neither base stations nor wired backbone networks are required and a terminal can communicate with the other terminal beyond the transmission range by multihopping. In this network, a communication link between two terminals which can communicate directly is required a channel. Since cochannel interference may occur, we need to assign channels to communication links carefully. In this paper, we describe a channel assignment strategy which takes the degree of cochannel interference into consideration, and we evaluate an effectiveness of this strategy by computer simulations. We show that this strategy is more effective than a strategy which does not take the degree of cochannel interference into consideration. And we also consider a few channel assignment algorithms briefly.

key words: *multihop wireless network, channel assignment, CIR-edge coloring, strong edge coloring, graph theory*

1. Introduction

The mulitihop wireless network system attracts the interest of many people as a communication network system of the next generation [1]–[9]. This network only consists of terminals with personal communication devices. Each terminal can receive a message from a terminal and send to another terminal. If a terminal cannot communicate with an other terminal directly, some intermediate terminals relay the messages. Therefore, the multihop wireless network needs neither base stations which are needed in the current cellular phone system nor wired backbone networks. And the multihop wireless network can construct a network inexpensively and easily. We expect this network system to be applied in various areas, for example, a mobile communication network system [3], a sensor network system [4], a wireless metropolitan area network (wireless MAN) or a wireless mesh network (WMN) [5]–[8], and so on.

Recently, the demand for the use of the multimedia contents on the mobile communication system has increased, and many researchers are studying about the system to be realized this demand [15]. In this system, it is hoped to guarantee to deliver a large amount of data without the delay. But it is not easy to guarantee this. Because the usable resources on the wireless network, such as channels, are limited, so it is not easy to transmit a large amount of data. To use the network resources effectively, we consider the channel assignment problem on multihop wireless networks.

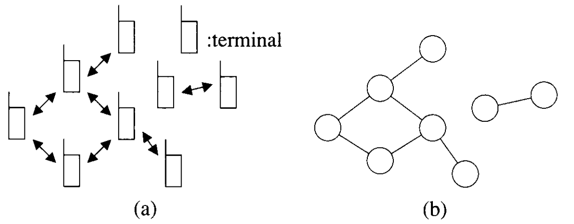

Fig. 1 An example of the multihop wireless network and its graph expression.

In the multihop wireless network, each terminal communicates to the other terminals using a channel which is the one such as a time slot of the Time Division Multiple Access (TDMA), a carrier of the Frequency Division Multiple Access (FDMA), a code of the Code Division Multiple Access (CDMA), and so on. Since cochannel interference may occur, we cannot assign channels randomly. Here, we construct a graph from the network as follows. Each vertex represents a terminal and each edge represents a link which can communicate directly. We need to assign channels efficiently to achieve high spectral efficiency in the network in Fig. 1(a). A channel assignment to terminal pairs in Fig. 1(a) corresponds to an edge coloring in Fig. 1(b). Strong edge coloring [10] is related to this channel assignment problem of multihop wireless networks. Strong edge coloring is a strategy in worst cases of cochannel interference and does not take the degree of interference into consideration. Therefore, in [9] we define a new edge coloring strategy which takes the degree of interference into consideration and discuss its computational complexity. In this paper, we evaluate the effectiveness of the strategy by computer simulations.

2. Preliminaries

2.1 Precondition of the Wireless Network Environment

In this paper, we assume that the multihop wireless network

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environment is satisfied the following conditions.

- There is no obstacle between terminals which can communicate directly. In short, we assume line-of-sight links.
- Any multipath does not occur.
- Each terminal has a non-directive antenna.
- All terminals output by the same transmission power.
- Each terminal has a position measurement system such as the GPS.

2.2 Definitions

In this paper, we represent a multihop wireless network by a graph. Each terminal is represented as a vertex. If two terminals communicate to each other, we join the vertices corresponding the two terminals by an edge. In this paper, we call this edge "communication edge." If two terminals do not communicate directly and if cochannel interference may occur between two terminals, we join the vertices corresponding the two terminals by an edge. In this paper, we call this edge "interference edge."

Let $G = (V(G), E(G))$ be an undirected graph such that $V(G) = \{v_1, v_2, \cdots, v_n\}$ is the vertex set, $E(G)$ is the edge set. Let $N = (G, w_N)$ be an undirected network such that w_N is the edge weight function assigning a positive real number $w_N(e)$ to each edge e of N.

3. Channel Assignment Strategies

In this section, we discuss a channel assignment problem on the multihop wireless network. The channel assignment problem is a problem which assigns channels to all communication links on the network so that cochannel interference may not occur. When a multihop wireless network is represented as a graph, a channel assignment problem on the multihop wireless network can be regarded as an edge coloring problem of graph & network theory. In the following, we consider the edge coloring problem as a channel assignment problem on the multihop wireless network.

3.1 Strong Edge Coloring [10]

A strong edge coloring of an undirected graph G is an assignment of colors to communication edges of G such that every two edges of distance at most two receive different colors. Two edges are of distance at most two if and only if the edges are adjacent to each other or there is an edge between the edges.

Figure 2 is an example of a strong edge coloring of a graph. The attached letter on each edge in Fig. 2 represents the color. In Fig. 2, we assign five colors. There is not a strong edge coloring with four colors or less since we must assign different colors to edges in the cycle C_5. For the results of the strong edge coloring, please see [10].

The strong edge coloing only to communication edges is equivalent to the channel assignment problem with worst

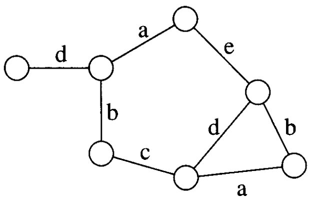


Fig. 2 An example of a strong edge coloring.

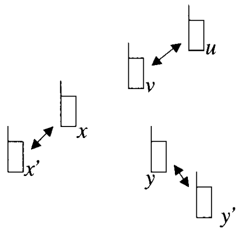


Fig. 3 Cochannel edges.

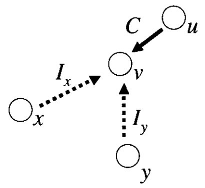


Fig. 4 An explanation of cochannel interference.

cases of cochannel interference on the multihop wireless network. So, it is important to find a strong edge coloring with the minimum number of colors. It is known that the problem of finding a strong edge coloring with the minimum number of colors for general graphs is NP-complete. But it is also known that this problem for a tree is solved in polynomial time.

3.2 Edge Coloring Based on the Degree of Interference

On the strong edge coloring, the degree of interference is not taken into consideration. So, we discuss an edge coloring problem taking the degree of interference into consideration in this section.

When we assign a channel to a terminal pair, we must consider cochannel interference. In Fig. 3, the terminal x communicates to the terminal x' with channel A, and the terminal y also communicates to the terminal y' with channel A. Now, the terminal v tries to communicate to the terminal u. In this case, can the terminal v use the channel A or not?

Here, we must consider the cochannel interference from terminal x and y. For simplicity, we neglect the cochannel interference from terminal x' and y'. In Fig. 4, a carrier C is from the terminal u and interference I_x and I_y are from the terminal x and y, respectively. It is necessary for good communication that a carrier-to-interference ratio (hereafter, we simply call it CIR.) is not less than a desired value α. For example, in the case of FM, 30 kHz channel bandwidth and analog telephone system, it is reported

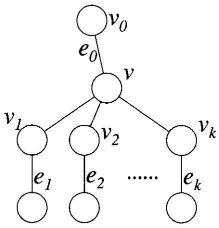


Fig. 5 An explanation of CIR-edge coloring.

$\alpha = 18$ dB [11], and in case of a wireless LAN system, it is reported $\alpha = 18.5$ dB [12]. In this paper, we assume that if a channel assignment in a multihop wireless network realizes the CIR that is not less than α for each terminal, good communication in the system is guaranteed. And we assume that the total cochannel interference received by a terminal is determined by the sum of each cochannel interference. Therefore, in the case of Fig. 4, if the following equation is satisfied, the terminal v can use channel A for communication to terminal u.

$$\frac{C}{I_x + I_y} \geq \alpha \tag{1}$$

The channel assignment problem which takes the degree of interference into consideration is represented as follows.

Definition 1: Let N be an undirected network. And α be a positive real number. If an edge weight function f satisfies the following condition, f is called CIR-edge coloring.

1. f is a function from edges to colors.
2. If edge e is adjacent to edge e', $f(e) \neq f(e')$.
3. Let v be a vertex on edge $e_0 = (v, v_0)$. Let $v_i (i = 1, 2, \cdots, k)$ be a vertex which is adjacent to v and is incident to an edge e_i whose color is $f(e_0)$ (see Fig. 5). Then,

$$\frac{w(e_0)}{w(v, v_1) + w(v, v_2) + \cdots + w(v, v_k)} \geq \alpha. \tag{2}$$

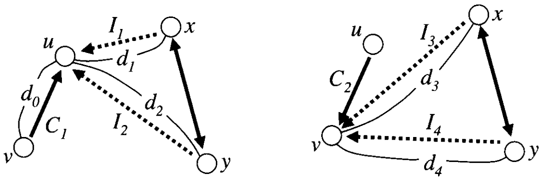
The minimum number of colors for all CIR-colorings of N is called CIR-edge coloring number of N. It is known that the problem of finding the CIR-edge coloring number of N is NP-complete, even if N is a tree [9].

4. Interference Models

In this section, we consider about cochannel interference. To simplify cochannel interference model, we neglect interference of multipath in the following explanation.

4.1 Interference from Surrounding Communication Edges

First, we consider how interference occur when there are only two communication pairs with a same channel. Figure 6 shows the relation between a carrier and interference in this situation. In Fig. 6, the terminal u and v communicate to each other with channel A, and the terminal x and y communicate to each other with channel A. In this situation, there are the following four interference patterns.



(a) (b)

Fig. 6 Four cochannel interference patterns between 2 edges with a same channel.

a) When u receives messages from v, u receives the interference I_1 from x.
b) When u receives messages from v, u receives the interference I_2 from y.
c) When v receives messages from u, v receives the interference I_3 from x.
d) When v receives messages from u, v receives the interference I_4 from y.

These four interference patterns do not occur simultaneously, because u and v as well as x and y do not send the messages to each other at the same time.

Here, we assume the 40 dB/dec mobile radio propagation path loss rule [11] (in propagation path loss, radio signal strength drops proportionate to distance). Then, the CIR of the pattern a) is

$$CIR = \frac{C_1}{I_1} = \frac{d_0^{-4}}{d_1^{-4}}. \tag{3}$$

Here, d_0 represents the distance between u and v and d_1 represents the distance between u and x. Similarly, the CIR of the pattern b), c) and d) are respectively $C_1/I_2 = d_0^{-4}/d_2^{-4}$, $C_2/I_3 = d_0^{-4}/d_3^{-4}$ and $C_2/I_4 = d_0^{-4}/d_4^{-4}$, when d_2, d_3 and d_4 represent respectively the distance between u and y, the distance between v and x and the distance between v and y. If C_1/I_1 is not less than the α (e.g. $\alpha = 18$ dB), the terminal u and v can always communicate to each other correctly. Because, in Fig. 6, d_1 is the smallest in d_1, d_2, d_3 and d_4, the C_1/I_1 is the smallest value in the CIRs of four interference patterns. In the following, we regard the edge whose distance is the smallest in the edges corresponding the four interference patterns as the interference edge between two terminal pairs, and we neglect other three interference patterns.

Next, we consider the CIR when there are many communication edges with a same channel. For example, in Fig. 5, we assume that the edge e_0 and the edges e_i $(i = 1, 2, \cdots, k)$ use a same channel. Now, the distance of a communication edge e_0 is represented by d_0, and the distance between v and v_i $(i = 1, 2, \cdots, k)$ is represented by d_i. We assume that the total cochannel interference received by a terminal is the sum of each cochannel interference. Then, in Fig. 5, the CIR when v_0 receives messages from v is

$$CIR = \frac{d_0^{-4}}{d_1^{-4} + d_2^{-4} + \cdots + d_k^{-4}}. \tag{4}$$

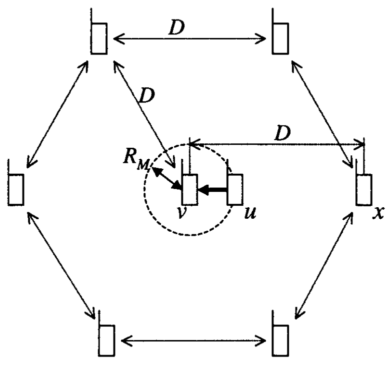


Fig. 7 The worst case of which the strength of cochannel interference is maximum.

When this CIR is not less than the α (e.g. $\alpha = 18\,\mathrm{dB}$), the terminal v and v_0 can communicate to each other using the same channel of the communication edge e_i ($i = 1, 2, \cdots, k$) correctly.

The channel assignment problem which is based on above-mentioned interference model is equivalent to the CIR-edge coloring problem. Henceforth, we call this above-mentioned interference model "strict interference model."

4.2 Conversion Strong Edge Coloring from CIR Edge Coloring

In this section, we consider a simple interference model which does not take the degree of interference into consideration. In the following, let R_M be the maximum distance where a terminal pair can communicate to each other regardless of the cochannel interference. This parameter R_M is decided by the output power and the required received power.

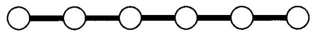
Since CIR is determined by the distance between terminals, we assume that there is the minimum distance D to which two terminal pairs should be away when these pairs use a same channel. And we also assume that we can neglect the interference from far terminals of which the distance are more than D. When we consider about the worst case of which the strength of cochannel interference is maximum, it is necessary to consider the cochannel interference from six terminals which use a same channel in surroundings. This idea is similar to the channel assignment on the cellular phone system [16]. Figure 7 shows this situation. When the terminal v receives data from u,

$$CIR = R_M^{-4}/6D^{-4} \geq 18\,\mathrm{dB}. \tag{5}$$

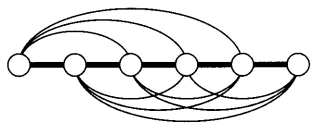
Then,

$$D/R_M \geq 4.4. \tag{6}$$

If the distance between two terminals is less than $4.4R_M$ and if these two terminals do not communicate to each other, we join the vertices by an interference edge. Figure 8 is an example which explains to add interference edges. In Fig. 8, we assume that each terminal is on a straight line and adjacent terminals communicate to each other, where the distance of each adjacent terminals is one. And let $R_M = 1$. Figure 8(b) is a graph adding interference edges. In Fig. 8(a), the distance between the leftmost terminal and the rightmost terminal is $5R_M$, so there is no interference edge between them in Fig. 8(b). And there are many interference edges between the other terminal pairs in Fig. 8(b) because their distances are less than $4.4R_M$.



(a) A graph of only communication edges



(b) A graph adding interference edges

Fig. 8 An explanation of the transformation into strong edge coloring.

The problem which assigns channels to only communication edges in a graph constructed like the above-mentioned explanation is equivalent to a strong edge coloring problem. Henceforth, we call this above-mentioned interference model "simple interference model."

5. Simulations and Considerations

In the previous sections, we showed that it is hard to obtain the channel assignment with the minimum number of channels on both of the interference models. Therefore, we propose a simple heuristic algorithm to evaluate the interference models and show the results of computer simulations for the purpose of comparing interference models. In the following simulations, we consider about applying to a wireless mesh network (WMN). And we assume that the terminals do not move, so that the network topology is a static connected graph.

5.1 Algorithm and Parameters

The outline of a channel assignment algorithm is as follows.

1) For all communication edges, let the channel of each edge be not assigned.
2) The following three steps are repeated while there are edges whose channels are not assigned.
3) Select an edge e from among the edges whose channels are not assigned.
4) Let a channel ch be the channel which satisfies a desired condition and is found first during the channel search.
5) Assign the channel ch to the edge e.

Moreover, let $\alpha = 18$ (dB) in the following simulations.

5.2 Simulations to a Virtual Mesh Network

In this section, we show the results of simulations to a virtual WMN which is made by a computer. In the following simulations, we select the edge randomly at the Step 3) of above-mentioned algorithm.

5.2.1 Simulations to a Simple Mesh Network

First, we consider about a simple mesh network of which the topology is a square lattice. Namely, we consider the case that the distances of all communication edges are the same of the communicable maximum distance R_M.

Figure 9 shows the result of simulations when the number of terminals varies from 10 × 10 to 30 × 30. In Fig. 9, a vertical axis represents the ratio r_{asgn} which is calculated by

$$r_{asgn} = \frac{\text{(the number of assigned channels)}}{\text{(the number of communication edges)}}. \quad (7)$$

The ratio r_{asgn} means the efficiency of a channel assignment. If r_{asgn} is small, then the channel assignment at that time is effective.

In Fig. 9, the r_{asgn} of the strict interference model is less than the r_{asgn} of the simple interference model when the number of terminals is small. But, the difference between the r_{asgn} of the strict interference model and the r_{asgn} of the simple interference model becomes small as the number of terminals increases. And the r_{asgn} of the strict interference model and the r_{asgn} of the simple interference model are almost the same when the number of terminals is 900. Thus, the strict interference model is not necessarily effective when the distance of each edge is almost the same value.

5.2.2 Simulations to a General Mesh Network

Next, we consider about a general mesh network where the distance of each communication edge is not the same value. In the following simulations, we use networks based on Delaunay network, which has been studied extensively in computational geometry [13] and has been applied in many areas of science and engineering. This Dealunay network is the same as Delaunay triangulation graph with the defining property that for each circumscribing circle of a triangle formed by three vertices, no other vertex is in the interior of the circle. We used Delaunay network in order to make the connected graph easily.

In this simulations, we assume that the position of each terminal is random position within the communicable range R_M of some terminals, and the mesh network data is a network where the incommunicable edges are removed from Delaunay network. Figure 10 is an example of the mesh network for following simulations.

Figure 11 shows the result of simulations when the communicable range R_M is 100 (m) and the number of terminals varies from 100 to 300. In Fig. 11, a vertical axis means the average value of the r_{asgn} in the 100 network data and the ratio of the r_{asgn} of the strict interference model to the r_{asgn} of the simple interference model.

In Fig. 11, the r_{asgn} of the strict interference model has decreased about from 59% to 76% compared with that of the simple interference model. Figure 11 shows that the strict interference model is effective for general mesh networks.

Now, we consider why the difference between Fig. 9 and Fig. 11 occurs. When each terminal is located at a uniform interval, the strength of cochannel interference received by each terminal is the same. So, the CIR of the each edge becomes the same, then it is impossible that a terminal using the same channel exists within a certain range. Namely, for the mesh network where each terminal is located at a uniform interval, the CIR edge coloring is essentially as same as the strong edge coloring. In the other hand, when each terminal is not located at a uniform interval and the distance of each communication edge is not the same value, the CIR of each edge will become the different value. Because the CIR of a short edge will become the large value in particular, we may assign the same channel to the edge if some terminals using the same channel exist within the

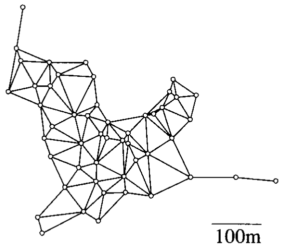


Fig. 10 An example of a mesh network based on Delaunay network (50 terminals).

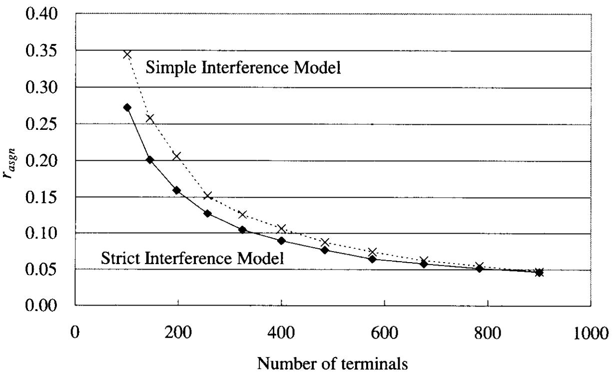


Fig. 9 The comparison between interference models for square lattice network when the number of terminals varies.

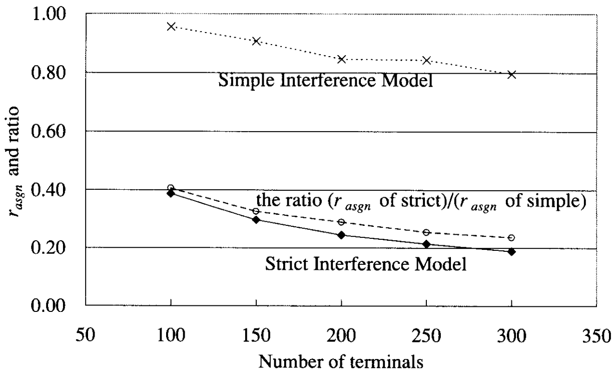


Fig. 11 The comparison between interference models for mesh networks based on Delaunay network.

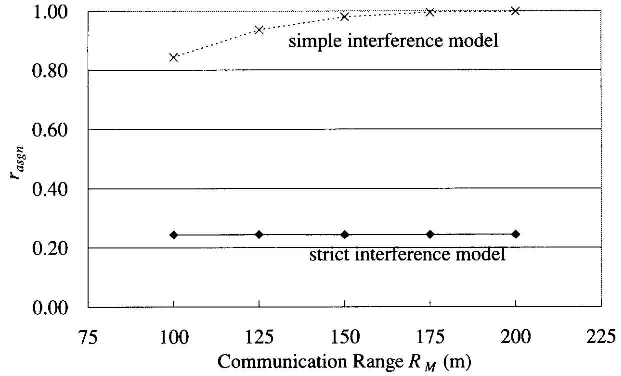


Fig. 12 The comparison between interference models when the communication range R_M varied for one mesh network.

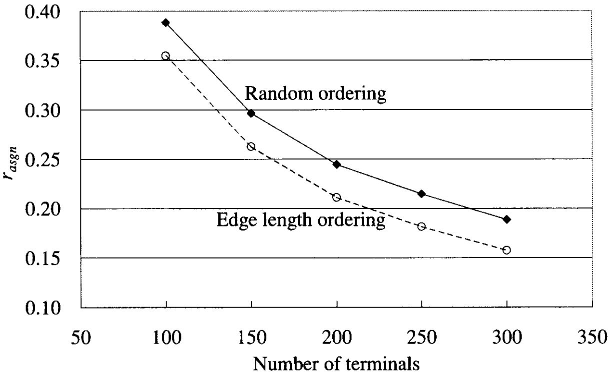


Fig. 13 The comparison of two ordering methods for mesh networks.

Table 1 Average of the number of assigned channels on WMN.

Strategy	Number of terminals				
	100	150	200	250	300
Simple & Random	253.5	371.6	469.6	593.7	677.1
Strict & Random	103.0	121.5	135.6	151.0	160.3
Strict & Edge len.	94.0	107.5	117.1	127.7	133.7

Table 2 The number of channels which can be theoretically prepared for delivering multimedia contents.

Bit rate of contents (bps)	128k	256k	512k	1024k	2048k
Allocatable ch.	1263	630	316	156	78

circle range of $4.4R_M$ radius. So, in Fig. 11, the difference between the CIR edge coloring and the strong edge coloring occurs.

In addition, we consider the channel assignment when we change the communicable range R_M. Figure 12 shows the result of the simulations to the mesh network of which the number of terminals is 200 in the case that we change the communication range R_M from 100 to 200 (m). In Fig. 12, a vertical axis means the average value of the r_{asgn} in the 100 network data.

It is clearly that the r_{asgn} of the strict interference model is almost the same in Fig. 12 if we change the R_M. Because the CIR depend on the distance of communication edge and the distances from surrounding edges which use the same channel, and does not depend on the communicable range R_M. However, the r_{asgn} of the simple interference model increase when the communication range R_M becomes large because the area where the terminal using a same channel cannot exist spreads as the communicable range R_M increases. When the channel of each communication edge is assigned by strict interference model, it is possible to reuse the same channel on each edge if we change the transmission power of each terminal. We think that this is one of the advantage of the strict interference model.

5.3 Consideration of the Channel Assignment Algorithms

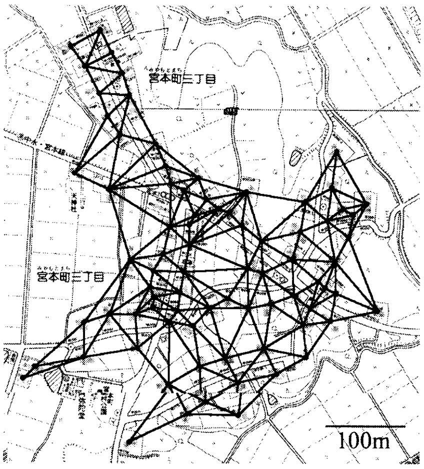
In this section, we consider the channel assignment algorithm briefly. Especially, we consider how to select an edge to assign a channel. Here, we compared two methods of selecting an edge. One is a method which selects an edge randomly. We call this method "Random ordering." The other one is a method which selects an edge with minimum length from among the edges whose channels are not assigned. We call this method "Edge length ordering."

Figure 13 shows the result that is compared these two methods. In these simulations, we use general mesh networks. In Fig. 13, a vertical axis means the average value of the r_{asgn} in the 100 network data. When we compare these two methods, the r_{asgn} of the edge length ordering method has decreased about from 9% to 17% compared with that of the random ordering. In the viewpoint of re-assignment of a same channel, this result shows that the edge length ordering method is more efficient than the random ordering method. This is because the degree of the interference from surrounding communication pairs is a little if the communication edge is short, and the same channel which is used on the short communication edge can be assigned to many edges.

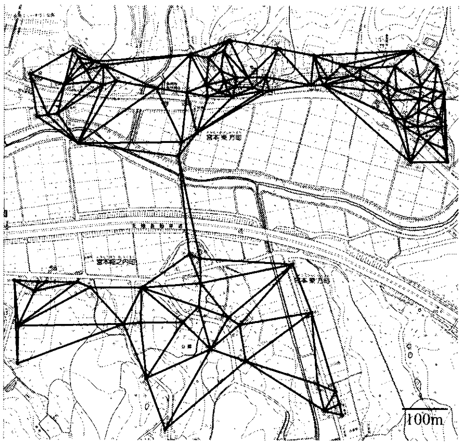
5.4 Consideration of the Number of Channels

It is hard that he current wireless communication system, such as a wireless LAN, has a lot of channels. But we expect that future wireless communication system may have more channels by fusing a modulation with a multiple access (e.g. fusing OFDM with CDMA) [17]. In this section, we consider the comparison between the number of allocatable channels and the number of necessary channels on WMN under an assumption that the wireless communication system has a lot of channels. In the following consideration, we assume that the number of channels increases by combining IEEE 802.11g wireless LAN (54 Mbps/channel and 3 channels) with CDMA.

Table 1 shows the average of the number of assigned channels by the results which are shown in Sect. 5.2.2 and Sect. 5.3. And Table 2 shows the number of allocatable channels which is inferred when multimedia data are delivered. When the channels are assigned by the simple interference model, the terminals can deliver the multimedia



(a) The network in one village (80 terminals and 206 edges).



(b) The network which connects two villages (101 terminals and 261 edges).

Fig. 14 The network which assumes applying on an actual environment. (The bold line is the network which consists communication edges and background picture is the residential quarter chart. Copyright of the residential quarter chart: Copyright(c)1998 ZENRIN Co.,LTD. Z03A-685)

data of the low bit rate such as 128 kbps and 256 kbps. On the other hand, when the channels are assigned by strict interference model, the terminals can deliver multimedia data of the 1 Mbps.

5.5 Simulations to an Actual Environment

In this section, we consider the channel assignment on an actual environment. We assume that the communication devices are attached on rooftop of each house in villages and each communication device communicates to its neighbours. Let the network data for this simulation be a network which removes incommunicable edges from Delaunay network such as Fig. 10. Figure 14 shows the networks for this simulation. In order that the network becomes a connected graph, we assumed that the communicable ranges are $R_M = 100\,(\mathrm{m})$ for the network (a) and $R_M = 250\,(\mathrm{m})$ for the network (b), respectively.

Table 3 and Table 4 show the results of this simulation on the network (a) and (b), respectively. In these results, the number of channels by the strict interference model has decreased about from 60% to 70% compared with than that by the simple interference model. These results also show that the strategy with the edge length ordering method is only a little better than the strategy with the random ordering method. Thus, we find that the strategy by the strict interference model with the edge length ordering method is effective on the actual environment.

Table 3 The result on the network (a).

Assignment Strategy	number of ch.	r_{asgn}
Simple Interference Model & Random ordering	200	0.971
Strict Interference Model & Random ordering	80	0.388
Strict Interference Model & Edge length ordering	79	0.383

Table 4 The result on the network (b).

Assignment Strategy	number of ch.	r_{asgn}
Simple Interference Model & Random ordering	261	1.000
Strict Interference Model & Random ordering	80	0.307
Strict Interference Model & Edge length ordering	75	0.287

6. Conclusion

In this paper, we evaluated the effect of a channel assignment strategy by CIR-edge coloring with strict interference model on the multihop wireless network. First, we showed the effectiveness of the CIR-edge coloring on virtual networks by computer simulations. In this result, the effectiveness of the CIR-edge coloring is the same as that of the strong edge coloring for a simple mesh network. But we found that the CIR-edge coloring is more effective than the strong edge coloring for a general mesh network. Next, we consider the channel assignment algorithm briefly. We also showed that the number of channels by the edge length ordering method is less than that of the random ordering method slightly. Finally, we showed the result of the simulation to the mesh network which assumed applying on an actual environment. From this result, we confirmed that the CIR-edge coloring is more effective than the strong edge coloring on an actual environment.

In this paper, we considered the channel assignment problem for the purpose of reducing the number of channels. But we do not consider the concrete algorithm of a channel assignment for actual networks of which the topologies are changed hourly. Thus, we are planning to consider the concrete algorithm which can be applied to actual multihop wireless networks. In this paper, we assumed some preconditions in our consideration. In the future research, we are planning to consider the problem when the precondition (e.g. moving each terminal, occurring multipath, and so on) is changed. We are also planning to consider of the more effective channel assignment algorithm referring to that of a cellular phone system [14].

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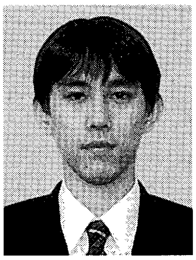

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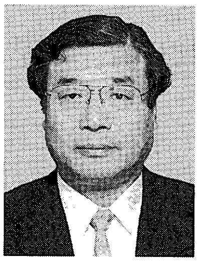

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