Channel Allocation for Averting the Exposed Terminal Problem in a Wireless Mesh Network

The wireless stations in a CSMA/CA wireless LAN access system connect directly to each other to form a wireless mesh network. To avert the exposed terminal problem that arises in such networks, we researched a channel allocation scheme. This reseach was conducted jointly with Professor Masakazu Sengoku, Faculty of Engineering, Niigata University.

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1. Introduction

Networks formed by connections of wireless station peers are called ad hoc networks or wireless mesh networks. Such networks are being widely researched as a new form of network that differs from the cellular networks that have previously been used commercially. For wireless mesh networks that adopt wireless LANs, in particular, one expectation is flexible expansion of the area in which devices connected to a wireless LAN can be used. The use of those devices, such as the N900iL and other PASSAGE DUPLE terminals, has increased greatly in the last few years. Another expectation is easy construction of tentative wireless networks when disaster strikes.

When the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) wireless LAN access system is used to construct a wireless mesh network, however, the hidden terminal problem and the exposed terminal problem may arise and greatly degrade communication quality. Two approaches to the exposed terminal problem, which is highly likely to have a particularly strong effect on communication quality, are improvement of the CSMA/CA protocol and the use of multiple channels. The former approach is being widely studied, but almost no work is being directed to the latter.

DoCoMo had shown the equivalence of the problem of channel allocation for preventing exposed terminals to the vertex coloring problem of graph theory[*1] for analyzing the number of channels required for networks in which the number of wireless stations is 10 or less [1]. Channel allocation increases in complexity with the number of wireless stations, so networks of more than 10 wireless stations require a different analytical method. We therefore investigated a channel allocation method for averting the exposed terminal problem in a wireless mesh network of more than 10 wireless stations in collaboration with Professor Masakazu Sengoku of Niigata University, who has expertise in graph theory [2][3]. In this article, we first apply an approximate analytical method that has previously been studied to the vertex coloring problem to a wireless mesh network, and describe those effects and the optimization results of that method. We then propose a method of selecting disconnect links that can reduce the effects of the exposed terminal problem while minimizing degradation of network performance when the number of channels that can be used is limited.

2. Exposed Terminal Problem in Wireless Mesh Networks

2.1 Hidden Terminal Problem and Exposed Terminal Problem

In the Institute of Electrical and Electronics Engineers (IEEE) 802.11[*2] specifications, which are widely used in wireless LANs, the wireless stations detect each other by the carrier transmitted by each based on the CSMA/CA scheme to implement station multiple access control. The control is explained briefly below.

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*1 Graph theory: A theory used extensively in research on networks and algorithm. A field that studies the various properties of 'graphs' that comprise nodes and edges (connections between nodes).

*2 IEEE 802.11: An international standard specification for wireless LAN defined by the IEEE organization in the United States.

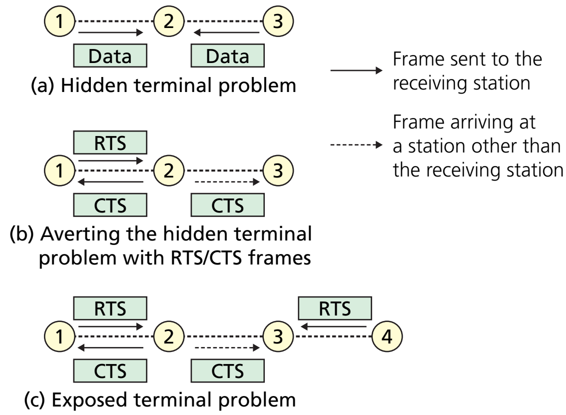

Figure 1 Hidden terminal problem and exposed terminal problem

When the packets to be transmitted by a wireless station have been generated and no carrier is detected, transmission begins immediately; if a carrier is detected, however, the wireless station stands by until no carrier is detected and then begins transmission after a randomly generated standby time passes. However, if the carrier is detected during the standby time, the standby time is not measured and nothing is transmitted until the carrier is again not detected.

This CSMA/CA scheme assumes that wireless stations can detect the carriers of other wireless stations that are in the same area. If three wireless stations are arranged along a line such that the stations at the two ends (wireless station 1 and 3 in **Figure 1**(a)) cannot detect each other's carrier, packet collision will occur at wireless station 2 in the middle. Because wireless station 1 and wireless station 3 are hidden from each other, this situation is referred to as the hidden terminal problem.

To reduce packet collision due to hidden terminals, IEEE 802.11 specifies a method in which Request To Send (RTS) and Clear To Send (CTS) frames are exchanged between the sending and receiving stations before data packets are transmitted, as shown in Fig. 1(b). While wireless station 1 is sending data packets to wireless station 2, wireless station 3 can recognize the transmission status of wireless station 1 because wireless station 3 can receive the CTS from the intermediate wireless station 2, thus preventing packet collision.

If more wireless stations are added, a different problem arises, as shown in Fig. 1(c). With four wireless stations arranged in a line, each wireless station can detect only the carriers of the adjacent wireless stations. When wireless station 1 sends packet to wireless station 2, the RTS/CTS frame exchange at the time of data packet transmission allows wireless station 3 to receive the CTS frame from wireless station 2 and enter the standby state until the communication between wireless stations 1 and 2 is finished. If wireless station 4 begins to send data to wireless station 3 while wireless station 3 is in this standby state, wireless station 3 will not be able to respond, so wireless station 4 will send the same packet repeatedly and those packets will be discarded. This is called the exposed terminal problem. It causes severe problems such as reduced TCP throughput.

2.2 Averting the Exposed Terminal Problem by Channel Allocation

The exposed terminal problem described in the previous section results in lost packets when packet transmission takes place over two wireless links (one between wireless stations 1 and 2 and one between wireless stations 3 and 4 in Fig. 1(c)) at the same time. The exposed terminal problem can be averted if, for example, channels of different frequencies are assigned to those two wireless links.

In a network that has a simple configuration as in this example, a channel allocation pattern that averts the exposed terminal problem is easily discovered, but as the network configuration becomes more complex, the channel allocation pattern also becomes more complex. We have shown that the channel allocation problem for preventing exposed terminals in a wireless mesh network is equivalent to the coloring problem in graph theory[1]. If we take the links in a wireless mesh network (**Figure 2**(a)) as the nodes of a graph, and connect the links (graph nodes) for which simultaneous communication causes an exposed terminal to generate a graph (Fig. 2(b)), the problem is changed into the vertex coloring problem, in which adjacent nodes are given different colors. Such a graph is therefore called a colored graph.

Generally, the vertex coloring problem is regarded as an Non-deterministic Polynomial (NP) complete problem, a prob-

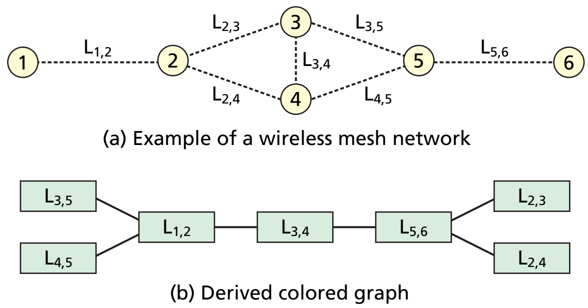

Figure 2 Colored graph for a wireless mesh network

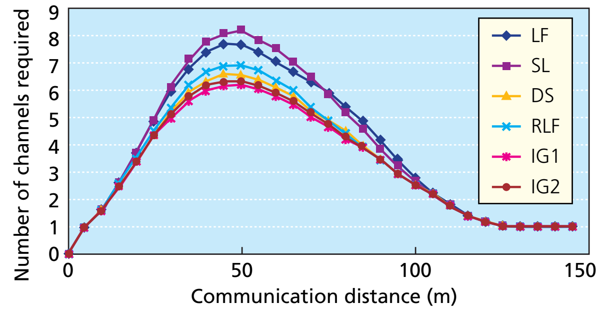

Figure 3 Number of channels required for the coloring algorithm

lem for which the optimum combination cannot be immediately derived, and there is no algorithm for efficiently discovering the least number of colors to achieve coloring. For that reason, much research is being done on approximation algorithms for solution of the vertex coloring problem. In the work reported here, we apply four algorithms of the previously proposed "fixed-order, one-time coloring" type[4], and one of the "varied-order iterated coloring" type to a wireless mesh network to verify the effects of those algorithms.

3. Approximation Algorithms for the Coloring Problem

The approximation algorithms verified in this work are listed below.

1) Largest First (LF)

Coloring begins with the highest-degree[*3] graph node and proceeds in order of descending node degree. When multiple nodes have the same degree, one is selected by an arbitrary process.

2) Smallest Last (SL)

Nodes are removed in order of the lowest node degree, and when a node is removed, coloring is done in the reverse order. When multiple nodes have the same degree, one is selected by an arbitrary process.

3) DSatur (DS)

Coloring is done in order of highest wireless station saturation. Saturation is the number of colors used by adjacent nodes. A high-degree node is taken as the initial node. When there are nodes of equal saturation, the node of highest degree among them is selected. When multiple nodes have the same degree, one is selected by an arbitrary process.

4) Recursive Largest First (RLF)

Nodes that can be given the same color are selected in order of highest node degree. The initial node is selected in the same way as for the LF algorithm, but the next node is selected from among the nodes that are not adjacent to the initial node.

5) Iterated Greedy (IG)

Once the graph is colored, the order is changed group by group (set of nodes that have the same color) and the coloring is iteratively revised. We performed many verifications for the combinations introduced in reference [5], and did detailed studies with the two low-color-count methods listed below.

a) IG 1

- Coloring is performed 5 times in order of high-node-count groups.
- Coloring is performed 2 times in order of low-node-count groups.
- Coloring is performed in random group order with a probability of 0.1.

b) IG 2

- Coloring is performed 5 times in order of high-node-count groups.
- Coloring is performed 2 times with the group order reversed.
- Coloring is performed in random group order with a probability of 0.1.

The results for a 30-wireless station network are shown in **Figure 3**. The horizontal axis in that figure represents the com-

*3 Degree: A term from graph theory that refers to the number of edges that connect to one node.

munication distance of each wireless station, the vertical axis shows the average number of colors required for the colored graph derived from the network (i.e., the number of channels required).

From Fig. 3, we can see that of the 5 algorithms that we used, the IG 1 algorithm results in the lowest number of required channels. We can also see that the number of channels required is greatest when the communication distance is near 50 m. The reason for this is that when the communication distance is small, network concatenation[*4] is difficult and the number of links is small, so the scale of the colored graph is also small; and when the communication distance is large, the network becomes concatenated and the number of links and the interference both increase, so the number of channels required is also considered to increase. Conversely, when the communication distance becomes too large, the entire network approaches a complete graph[*5], the carrier reaches all wireless stations, interference drops to zero and communication is possible with a single channel.

4. Disconnect link selection method for limited channels

If the number of channels that can be used is limited, all of the channels required for preventing exposed terminals are not necessarily allocated. In the present work, denoting the number of channels required as N and the number of channels given as M, the method described below was used to disable some of the links and, by doing so, ameliorate the exposed terminal problem.

The color (channel) numbers are represented as 1 to M. For $N > M$, the set of wireless links colored with N colors beginning from $M + 1$ is denoted as $V0$. To the wireless links of $V0$ are allocated the color from 1 to M that have low interference. Then, we denote the average edge betweenness of the $V0$ wireless links as *ave* and the standard deviation as *sd*. Assuming the shortest path will be selected in path control, the edge betweenness is synonymous with the frequency of use of each wireless link when communication between any two nodes is the same. $V0$ wireless links are disabled according to the five cases listed below, according to the edge betweenness.

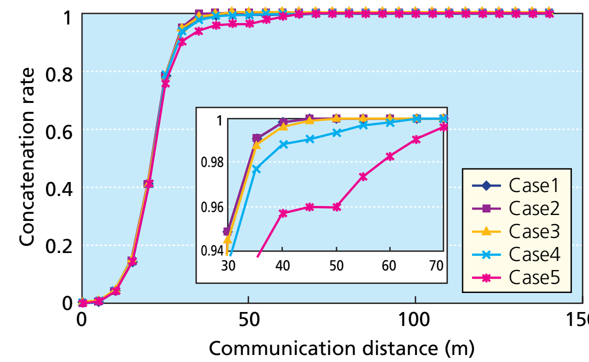

Figure 4 Network concatenation rate

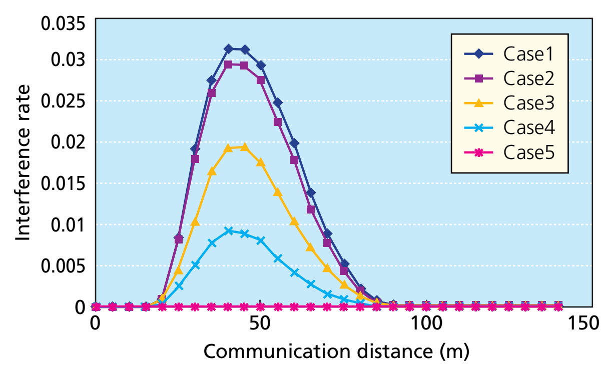

Figure 5 Interference rate

- Case 1: Do not disable links.
- Case 2: Disable links of *ave* · *sd* (product of the mean and standard deviation) or less.
- Case 3: Disable links of *ave* or less.
- Case 4: Disable links of *ave* + *sd* (sum of the mean and standard deviation) or less.
- Case 5: Disable all links.

We evaluated the above five methods by simulation. Assuming a 100×100 m area in which 30 wireless stations are randomly distributed, networks were constructed with various communication distances. The results for the concatenation rate (the proportion of network concatenation in each trial) and the interference rate for a network in which the given number of channels is four, averaged over 1,000 trials, are shown in **Figure 4** and **Figure 5**. We can see that disabling wireless links according to the selection criteria of Case 3 decreases the

*4 Concatenation: A term from graph theory that refers to the state in which a path exists between any two nodes. In this article, it refers to a single mesh network in which there are no isolated nodes.

*5 Complete graph: A term from graph theory that refers to a graph whose every node is connected to every other node.

interference rate without decreasing the concatenation rate so much. That is to say, using the edge betweenness can suppress interference while maintaining network concatenation.

5. Conclusion

We investigated channel allocation methods that adopt colored graphs from graph theory to prevent the exposed terminal problem, which degrades communication quality in a wireless mesh network. By applying conventional coloring algorithms to wireless mesh networks, we have shown that a channel allocation method based on an iterative coloring improvement algorithm can keep the required number of channels small. We also researched a method for selecting links for disconnection that can suppress the occurrence of the exposed terminal problem without decreasing network concatenation when the number of channels that can be used is limited.

References

[1] A. Fujiwara and Y. Matsumoto: “Centralized Channel Allocation Technique to Alleviate Exposed Terminal Problem in CSMA/CA-Based Mesh Networks,” IEICE TRANSACTIONS on Communications, Vol. E88-B, No. 3, pp. 958-964, 2005.

[2] K. Ishii, K. Nakano, M. Sengoku and A. Fujiwara: “A Consideration on Channel Assignment and Topology Control Using Betweenness in Mesh Networks,” Proceedings of the 2006 IEICE Society Conference, B-21-11, p.379, Sep. 2006.

[3] O. Hashimoto, K. Nakano, K. Ishii, M. Sengoku and A. Fujiwara: “A Consideration on Channel Assignment Considering the Exposed Terminal Problem in Wireless Mesh Networks,” Technical Report of Japan Society for Simulation Technology, JSST-MM2005-03, pp.13-18, Nov. 2005.

[4] P. M. Pardalos, T. Mavridou and J. Xue: “The graph coloring problem: A bibliographic survey,” in Handbook of Combinatorial Optimization, D.-Z. Du and P. M. Pardalos (Eds.) , Vol. 2, pp. 331-395, 1999.

[5] J. C. Culberson: “Iterated Greedy Graph Coloring and the Difficulty Landscape,” Technical Report TR 92-07, University of Alberta Dept of Computer Science, Edmonton, Alberta Canada T6G2H1, 1992.