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Effect of Radio Wave Obstruction by Obstacles on Performance of IEEE 802.16j Wireless Multi-Hop Relay Networks

Go Hasegawa*, Yuuki Ise†, Yoshiaki Taniguchi*, and Hirotaka Nakano*
*Cybermedia Center, Osaka University,
1–32, Machikaneyama, Toyonaka, Osaka, Japan
Email: {hasegawa, y-tanigu, nakano}@cmc.osaka-u.ac.jp
†Graduate School of Information Science and Technology, Osaka University,
1–5, Yamadaoka, Suita, Osaka, Japan
Email: y-ise@ist.osaka-u.ac.jp

***Abstract*—In IEEE 802.16j networks, radio wave interference between wireless links must be taken into account when radio resources are assigned to network links. The protocol model, which defines the transmission and interference ranges as circles, is well-known as one of the major radio interference models. Although a lot of related studies on IEEE 802.16j networks use the protocol model, they do not consider the presence of obstacles. In this paper, we first investigate the performance of IEEE 802.16j networks considering the effect of obstacles. For that purpose, we define an obstacle model and extended protocol model for accommodating obstacles, where radio waves propagation is obstructed by obstacles. Next, the performance of IEEE 802.16j networks is evaluated through simulation experiments using the obstacle model and the extended protocol model. Additionally, we present a method for estimating the performance of IEEE 802.16j networks with obstacles. Then, we use multiple regression analysis based on simulation results and construct regression equations for network service ratio and power-to-throughput ratio. By evaluating the accuracy of the developed equations based on real-world environment, we confirm that the service ratio can be estimated with a high degree of accuracy when the distribution density of obstacle is small.**

***Keywords*-IEEE 802.16j, wireless multi-hop networks, relay network, obstacles, radio wave blocking**

I. Introduction

With the rapid progress of networking technologies, the demands for broadband access network environment is growing at various places such as home, office, and public areas. Wireless communication technologies are important to accommodate such services and users' demands. IEEE 802.16j [1][2] has attracted much attention to satisfy such demands, providing wider-area broadband wireless access environment. The IEEE 802.16j protocol utilizes multi-hop wireless networks for extending the network service area [3][4][5].

Generally, IEEE 802.16j wireless multi-hop relay networks (hereinafter, relay networks) consist of two types of nodes: gateway and relay nodes. As shown in Figure 1, there is a wired connection between the gateway node and an external network, while relay nodes communicate with the gateway node through wireless links. These nodes construct a tree topology where the root is the gateway node and there is a wireless multi-hop transmission path from any relay node to the gateway node [6][7][8]. A client terminal can access the external network by connecting to one of these nodes whose service area covers the client terminal [9]. One advantage of relay networks is that it is possible to extend the network service area by adding relay nodes without additional wired network facilities. In other words, the relay networks can provide wireless access environment by using multi-hop relaying to the area to which the radio waves cannot be directly reached from the gateway node. Therefore, the relay network is considered as possible networking technologies especially for thinly-populated regions and the area where the radio wave of gateway node is hard to reach due to underground and shades of buildings.

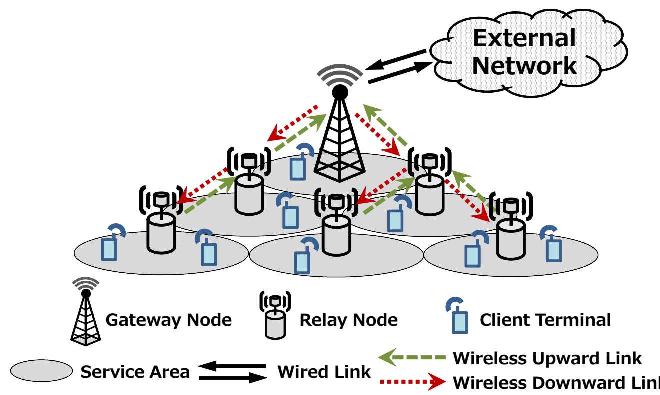


Figure 1. IEEE 802.16j multi-hop relay networks

In relay networks, obstacles, which refer in this paper to physical objects such as residential, office and commercial buildings, largely affect the connectivity between relay nodes and radio wave interference among wireless links. For example, even when two nodes exist in the transmission range of each other, the obstacles can prevent the nodes from communicating with each other. Furthermore, obstacles can reduce the size of the service area. On the other hand, the obstacles can increase network performance by reducing the occurrence of radio wave interference since the interference range is limited by the obstacles. Therefore, since the obstacles have both advantage and disadvantage on the network performance, it is important to consider the presence of obstacles and their influence on radio wave propagation for assessing the network performance.

In wireless networks, there is a general problem related to radio wave interference. Specifically, multiple nodes that exist in the interference range of each other cannot successfully transmit the radio waves at the same time [10][11]. To avoid this problem, relay networks use an Orthogonal Frequency Division Multiple Access (OFDMA) protocol [12], which gives radio resources to network links as transmission opportunities [13]. Previous studies on relay networks have focused on preventing radio wave interference by introducing concepts such as link scheduling [14][15][16] and power control [17][18][19].

The protocol model [20], which defines the transmission and interference ranges as circles, is well-known as one of the major radio interference models. In the protocol model, whether a transmission succeeds or encounters interference depends on only the distance between nodes, which are obtained through comparison with the transmission and interference ranges of other nodes. Therefore, the connectivity between relay nodes and radio wave interference among network links can be easily determined. Although a lot of studies on relay networks use the protocol model [21][22][23][24][25], they did not consider the presence of obstacles.

In this paper, extending the paper [1], we investigate the performance of IEEE 802.16j networks considering the effect of obstacles. First, we define an obstacle model which determines location and size of obstacle in the network. Then, we extend the function of the protocol model for accommodating obstacles. Specifically, radio waves propagation is obstructed by the obstacles in the extended protocol model. Next, we consider both positive and negative aspects for the relay network due to radio wave obstruction. Using the obstacle model and the extended protocol model, the performance of relay networks is evaluated through simulation experiments in terms of network service ratio and power-to-throughput ratio.

Furthermore, we propose a method for estimating the performance of relay networks. In the network construction process, it is helpful to estimate the network performance before the network is actually constructed. For example, the performance estimation enables the number of nodes deployed in the network or the transmission range of the nodes to be adjusted in order to achieve pre-determined performance goals such as service ratio, network throughput,

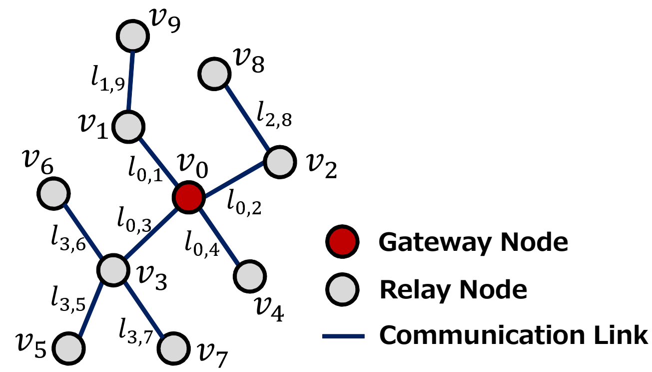


Figure 2. Network topology

and power consumption. For this purpose, by using multiple regression (polynomial regression) analysis of numerical results of simulation experiments, the regression equations are derived to estimate the performance of relay networks. We confirm the effectiveness of the estimation method by evaluating the accuracy of regression equations. Specifically, we conduct simulation experiments based on the real-world environment to assess the estimation accuracy of the proposed method.

The rest of this paper is organized as follows. In Section II, we introduce the network model of the relay networks. Section III introduces the obstacle model and the extended protocol model. The simulation results based on the proposed models are given in Section IV. Then in Section V, we present a method for estimating the performance of relay networks and evaluate the effectiveness of method. Finally, Section VI concludes this paper and describes future work.

II. System model

This section describes the network model, the radio interference model, and time slot assignment mechanism utilized in this paper.

A. Network model

The network is assumed to consist of N nodes, where v_i $(0 \leq i \leq (N-1))$ denotes both the i-th node and the point of the node's location in a field. One node in the network, denoted as v_0, serves as the gateway node, and the remaining nodes function as relay nodes, constructing a network topology that describes the communication between all nodes in the form of a directed graph. In relay networks, the gateway node is connected to an external network, and the relay nodes communicate with the gateway node either directly or via other relay nodes along the path between the relay node and the gateway node. There are two kinds of communications: upward communication and downward communication. In upward communication, data is transferred from relay nodes toward the gateway

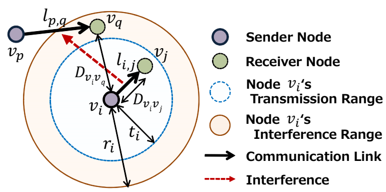


Figure 3. Radio interference based on the protocol model

node. Conversely, data is transferred from the gateway node toward relay nodes in downward communication. The path is determined by a routing algorithm, and the directed graph is constructed as a tree structure whose root is the gateway node v_0. Note that we do not consider the user clients which connect to the relay node.

Figure 2 shows an example of a network topology where a gateway node and nine relay nodes are deployed. In the figure the link between nodes means two directed links. In the figure, the red circle indicates the gateway node, gray circles indicate relay nodes, and solid lines indicate communication links respectively. Here, a communication link from node v_i to node v_j is denoted as $l_{i,j}$.

B. Radio interference model

In this paper, the propagation and interference of radio waves are modelled by the protocol model [20]. The transmission and interference range of node v_i is defined as the following sets of points.

$$\mathcal{T}_i = \{p \mid D_{v_i p} \le t_i\} \quad (1)$$

$$\mathcal{R}_i = \{p \mid D_{v_i p} \le r_i\} \quad (2)$$

Here, D_{ab} is the the distance between a and b. In addition, t_i and r_i represent the transmission range and the interference range of node v_i, respectively. In general, $r_i > t_i$, and the ratio of the interference range to the transmission range for node v_i is set to be between around 2 and 4 depending on the environment [26].

Based on the protocol model, the conditions to determine the success of transmission and the occurrence of the interference are as follows. Node v_j can receive a transmission from node v_i when $v_j \in \mathcal{T}_i$ is satisfied. Figure 3 shows an example of radio interference between communication links. In this figure, there are four nodes maintaining two communication links $l_{i,j}$ and $l_{p,q}$. The protocol model defines the radio interference between $l_{i,j}$ and $l_{p,q}$ based on the distances between the four vertices v_i, v_j, v_p, and v_q. When $v_q \in \mathcal{R}_i$ is satisfied, link $l_{i,j}$ interferes with link $l_{p,q}$.

C. Time slot assignment mechanism

The IEEE 802.16j protocol uses the OFDMA mechanism to control the ability of nodes to transmit by assigning radio resources for transmission. In the OFDMA mechanism, radio resources are divided along both frequency and time dimensions. For simplicity, in this paper, each divided radio resource is regarded as a time slot. In the relay networks, time slots are assigned to wireless links as transmission opportunities. Then, different time slots are assigned to wireless links that interfere with each other in order to prevent radio wave interference. On the other hand, multiple links can communicate simultaneously within the same time slot as long as the time slot is assigned to the links that do not interfere with each other. This mechanism is known as spatial reuse of wireless resource [27][28].

The performance of relay networks can be improved by spatial reuse with concurrent transmissions since such an approach reduces the total number of time slots assigned to all communication links in the network. The time slot assignment problem with consideration of spatial reuse is regarded as a vertex coloring problem [29] of the conflict graph [30]. In the conflict graph, a vertex represents a link in the network and an edge between two vertices is constructed when the corresponding links interfere with each other, and time slots can be assigned to links in the network by allocating different colors to adjacent vertices in the conflict graph. However, since the vertex coloring problem is known to be NP-hard [31][32], heuristic algorithms have been proposed for solving the problem [33][34][35][36]. In this paper, we use the method proposed in [35] to assign time slots to links for performance evaluation.

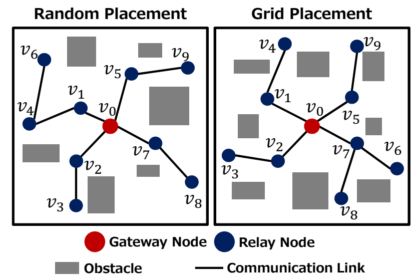


Figure 4. Obstacle model

III. PROPOSED MODELS

This section introduces an obstacle model utilized in this paper, followed by the extension of the protocol model for accommodating the effect of the obstacles on radio wave propagation. Finally, using the obstacle model and extended protocol model, the influence of obstacles on network performance is discussed.

A. Obstacle model

Figure 4 depicts the obstacle model, where rectangular obstacles are deployed in the field. In the model, two placement patterns are considered. In random placement, the obstacles are deployed at random in the field. In grid placement, on the other hand, the obstacles are deployed

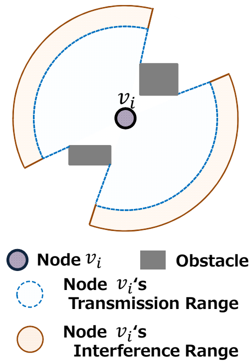


Figure 5. Extended protocol model

in a grid pattern. In both placements, the obstacles are not deployed at the center of the field, where the gateway node is located. The side lengths of the obstacles are chosen at random from within a certain range, and the obstacles are placed parallel to the field. The relay nodes cannot be deployed at locations occupied by obstacles. The height of the obstacles is ignored since the network model is constructed in a plane. Here, the following function $O(k)$ is defined whether or not a point k in the field is occupied by obstacles.

$$O(k) = \begin{cases} 1 & \text{point } k \text{ is occupied by obstacles} \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

B. Extended protocol model

In general, the effects of obstacles on radio waves include obstruction, reflection, and diffraction. We consider only radio wave obstruction in this paper since it has great effects on relay network performance.

For evaluating the effects of obstacles, we extend the protocol model considering radio wave obstruction by obstacles. The modified model is crefered to as extended protocol model. In this model, the transmission and interference range of node v_i are also defined as sets of points. The sets $\mathcal{T}_i'$ and $\mathcal{R}_i'$ are described as follows.

$$\mathcal{T}_i' = \{p' \mid p' \in \mathcal{T}_i \text{ and } C(v_i, p') = 0\} \quad (4)$$

$$\mathcal{R}_i' = \{p' \mid p' \in \mathcal{R}_i \text{ and } C(v_i, p') = 0\} \quad (5)$$

Here, $C(a, b)$ is the following function that determines the presence of obstacles between two points a and b.

$$C(a, b) = \begin{cases} 1 & \exists k(D_{ak} + D_{bk} = D_{ab} \text{ and } O(k) = 1) \\ 0 & \text{otherwise} \end{cases} \quad (6)$$

where D_{ak}, D_{bk}, and D_{ab}, means the distance between points a and b.

Figure 5 shows an example of the extended protocol model. The limitation of the transmission and interference range of node v_i by obstacles is confirmed in this figure.

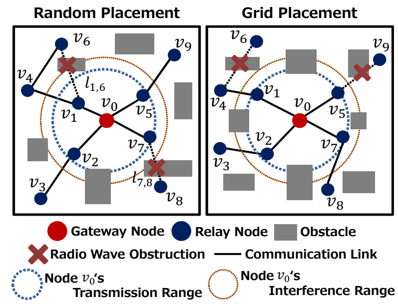


Figure 6. Combined image of the obstacle model and the extended protocol model

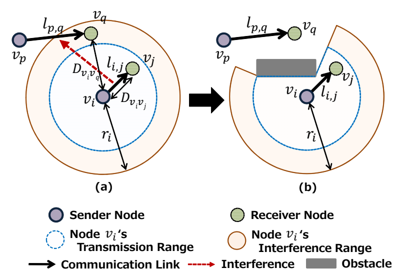


Figure 7. The influence of obstacles on radio wave interference

C. Effect of obstacles on relay network performance

Figure 6 shows the combined image of the obstacle model and the extended protocol model. The effect of obstacles on the connectivity between relay nodes is represented in this figure. For example, in the left panel of Figure 6, $l_{1,6}$ and $l_{7,8}$ become disconnected due to radio wave obstruction by obstacles. In this case, v_6 can connect to the network via v_4. On the other hand, v_8 is completely disconnected from the network by another obstacle. This is a negative aspect of obstacles in relay networks, owing to the increased number of isolated nodes and the higher average hop count between relay nodes and the gateway node.

On the other hand, Figure 7 shows an example of a beneficial effect of radio wave obstruction. Although in Figure 7(a) $l_{i,j}$ and $l_{p,q}$ interfere with each other, by adding obstacles as shown in Figure 7(b), the interference range of v_i is limited and v_q is not affected by the interference from v_i. As a result, the addition of an obstacle allows these two links to transmit simultaneously, which is a positive aspect of obstacles.

As described above, obstacles entail both advantages and disadvantages in terms of network performance. Therefore, it is important to consider the presence of obstacles and their influence on radio wave propagation for assessing the network performance.

IV. Performance evaluation and discussions

In this section, we evaluate the influence of obstacles on the performance of relay networks through simulation experiments by using the obstacle model and the extended protocol model proposed in the previous section. We utilized the simulator built in our labortory since there is no existing simulator which can simulate thedetailed behavior of IEEE 802.16j networks with obstacles.

A. Evaluation settings

In the simulation experiments, one gateway node was placed at the center of a 1×1 square area, and 99 relay nodes were distributed at random locations in the field. The transmission range was set to 0.15, 0.20, 0.25, 0.30, or 0.35, where all relay and gateway nodes utilize the same value for each experiment. The ratio of the interference range to the transmission range was set to 2.0 for all nodes. Note that we have confirmed the setting of this ratio does not change the overall tendency of the following results. A network topology was constructed such that the hop count between the gateway node and each relay node was minimized. The number of obstacles was set to be from 0 to 250 at intervals of 25 in the case of random placement. For the grid placement, we choose one the following placement patterns: 3×3 (8 obstacles), 5×5 (24 obstacles), and 7×7 (48 obstacles). The length of the sides of each obstacle was set to a random value between 0.004 and 0.04, assuming that the obstacles are placed in 2000m$\times$2000m area of real-world environment. We determine the traffic demand from relay nodes to the gateway nodes according to the Voronoi diagram for each relay node, where we assume the user clients are distributed uniformly in the area and they generate the same amount of traffic to the gateway node.

We observed the *service ratio* and the *power-to-throughput ratio* as network performance metrics. The service ratio is the ratio of the area where the relay network can provide service to the overall field area, excepting the area of the obstacles. The power-to-throughput ratio is the value of the total power consumption of the nodes divided by the gateway throughput. Here, the total power consumption is simply defined as the sum of the squares of the transmission ranges of all connected nodes, and the gateway throughput is defined as the ratio of the number of time slots assigned to links directly connected to the gateway node against the number of slots assigned to all communication links in the network. We focused only on the downward communication and conducted 100,000 iterations of the simulation experiments for each set of parameter settings and the all results were divided according to the number of connected nodes excluding isolated nodes, and the average values were used for performance evaluation.

B. Effect of the number of obstacles

Figure 8 depicts the service ratio and the power-to-throughput ratio in the random placement pattern as a function of the number of connected nodes when the transmission range is set to 0.20. The x-axis of graph means the number of connected nodes. Note that the x-axis value of less than 100 means that there are some nodes disconnected from the network due to radio wave obstruction by obstacles.

As shown in Figure 8, both metrics increase as the number of connected nodes increases, but there are differences in their increase tendency. The service ratio in Figure 8(a) decreases as the number of obstacles increases regardless of the number of connected nodes since radio wave propagation is obstructed by obstacles. On the other hand, the power-to-throughput ratio in Figure 8(b) does not show such a simple trend. When the number of obstacles increases from 0 to 150, the power-to-throughput ratio decreases, whereas in the case of the increase in the number of obstacles from 150 to 250, the power-to-throughput ratio increases together with the number of obstacles. The reason for this is as follows.

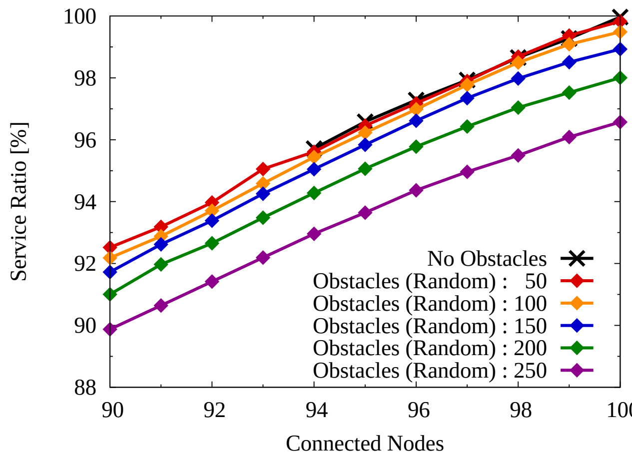
When the number of obstacles increases from 0 to 150, multiple wireless links in the network come to be able to transmit simultaneously due to the limitation of the interference range by obstacles. As a result, the network throughput is improved. On the other hand, as the number of obstacles increases further, the links between nodes are likely to become disconnected due to the radio wave obstruction by obstacles. It leads to the decrease in the network throughput.

C. Effect of the obstacle placement pattern

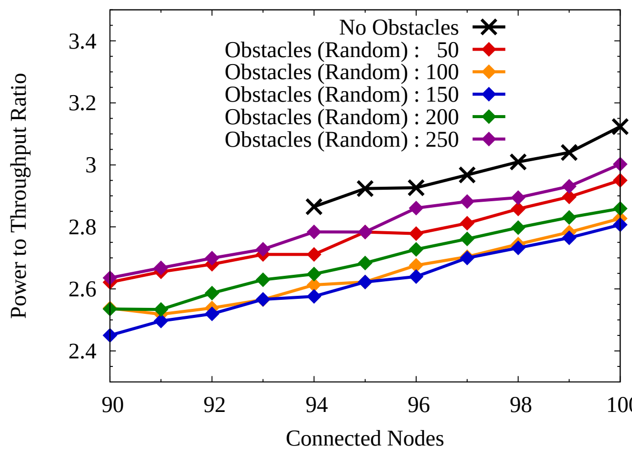
Figure 9 represents the effects of obstacle placement pattern on the network performance where the results of random and grid placement patterns with similar number of obstacles. In terms of service ratio, the obstacle placement pattern and the number of obstacles have little impact as shown in Figure 9(a). This is because the number of obstacles is small as compared with Figure 8, and the service ratio is mainly dependent on the number of connected nodes. On the other hand, Figure 9(b) shows that the decrease trend of the power-to-throughput ratio as the number of obstacles increases is different in the two placement patterns, and when comparing the same number of obstacles in both patterns, the grid placement pattern shows lower power-to-throughput ratio. This is because in the grid placement pattern the number of connected nodes is barely affected since the obstacles are regularly spaced. As a result, the network throughput is improved and the power-to-throughput ratio decreases since the interference is reduced effectively due to the presence of obstacles.

D. Effect of the transmission range

Figure 10 shows the relationship between the service ratio and the power-to-throughput ratio when the transmission range of the nodes is set to 0.15, 0.20, 0.25, 0.30, and

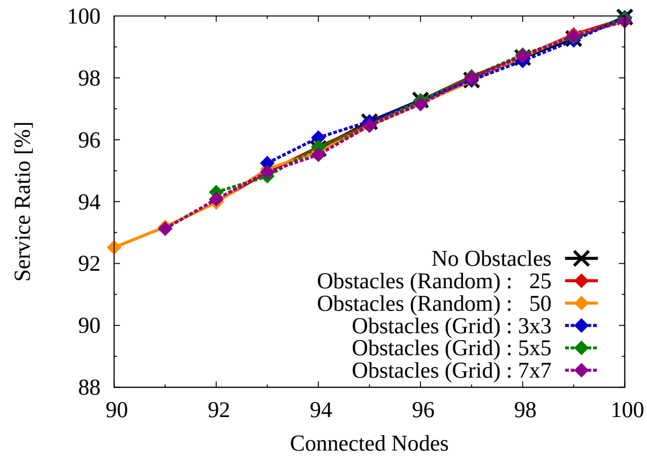


(a) Service ratio

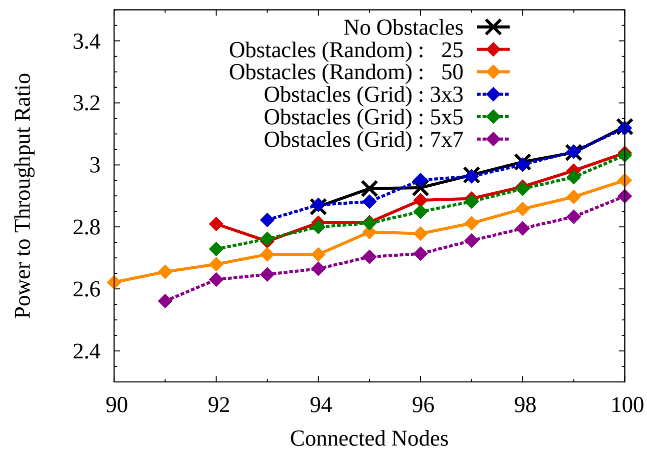


(b) Power-to-throughput ratio

Figure 8. Effect of the number of obstacles with random placement pattern



(a) Service ratio



(b) Power-to-throughput ratio

Figure 9. Effect of the obstacle placement pattern

0.35. In this case, 200 obstacles are placed with random placement pattern. In the graph, the number of connected nodes is indicated for each plot, where it increases from left to right and the rightmost point indicates the average value when the number of connected nodes is 100.

We focused on the plots denoted with squares in the figure when the number of connected nodes is 95. Here, there are two methods for improving the service ratio. One involves increasing the transmission range of each node, and the other involves deploying additional nodes in the network. As shown in Figure 10, when the transmission range becomes large, the power-to-throughput ratio increases rapidly while the service ratio increases. On the other hand, by deploying additional nodes in the field, the service ratio can be enhanced with a small increase of the power-to-throughput ratio. Also, we can see from this figure that the power-to-throughput ratio does not so increased as transmission power increases, compared with the case of no obstacles where the power is proportional to the square of the transmission range. This is because of the another effect of the obstacles. However, we conclude that the deployment of additional nodes can improve the service ratio more effectively than the increase in the transmission range of nodes.

V. Estimation of Network Performance

As described in Section IV, the performance of relay networks is largely affected by the various network parameters such as the number of connected nodes, a transmission range of each node, and distribution density of obstacles. In this section, we propose a method for estimating the performance of relay networks on the basis of the regression analysis of the simulation results. The accuracy of the analysis is then evaluated using both obstacle model and the real-world environment.

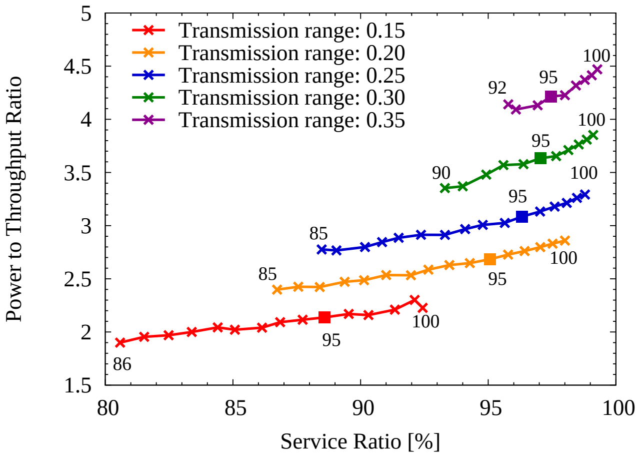


Figure 10. Effect of transmission range on network performance

A. Regression analysis of simulation results

As a method for estimating network performance, regression equations are derived based on the simulation results presented in the previous section. Specifically, the equations for the service ratio and the power-to-throughput ratio are denoted as $S(n, t, d)$ and $P(n, t, d)$, where n, t, and d represent the number of connected nodes in the network, the transmission range of the nodes, and the distribution density of obstacles, respectively. We take there three parameters since they affect the performance of the relay network considered in this paper. The distribution density of obstacles is defined as the ratio of the area of obstacles to the overall area. All parameters are normalized to fall within the range between 0 and 1 based on the maximum values in the simulation experiments. By using these network parameters and the network performance as explanatory variables and objective variables, respectively, multiple regression analysis is conducted.

We conducted Microsoft Excel for regression analysis. As the result, we obtain the following equations to estimate the service ratio and the power-to-throughput ratio.

$$S(n, t, d) = 7.78 + 92.54n + 34.95t^2 - 27.9d \quad (7)$$
$$P(n, t, d) = -1.21 + 2.42n + 9.25t - 2.14d \quad (8)$$

B. Accuracy of the regression equations

In order to examine the accuracy of the regression equations, the estimation values from the equations are compared with the simulation results. In detail, for each experiment, the obstacle placement pattern is first determined based on the obstacle model or the real-world environment. Next, on the basis of each obstacle placement pattern, simulation experiments are conducted, where the number of nodes is 100, and the transmission range of each node is set from 0.15 to 0.35. As a result, the service ratio and the power-to-throughput ratio are obtained as simulation results. Moreover, by using the regression equations in Equations (7) and (8), the estimation values are calculated based on each parameter setting utilized in the simulation experiments. Finally, the estimation accuracy of the regression equations is evaluated through comparison with the simulation results and estimation values. Here, as a metric of the accuracy, the relative error E_r in Equation (9) is utilized, where V_r and V_s indicate the simulation result and the estimation value, respectively.

$$E_r = \frac{|V_r - V_s|}{V_s} \quad (9)$$

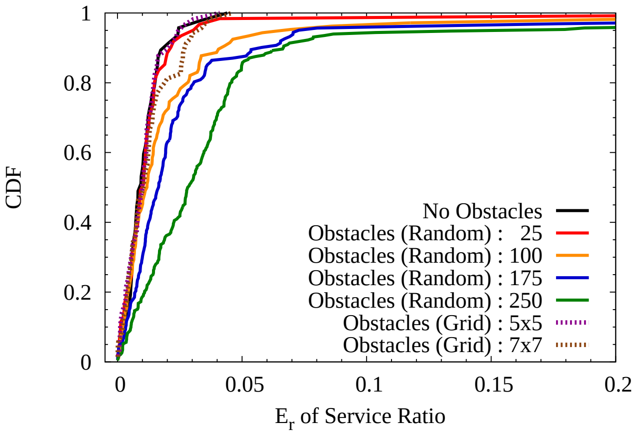
1) Evaluation results based on the obstacle model: Figures 11(a) and 11(b) depict the distributions of the relative error for the service ratio and the power-to-throughput ratio, respectively, with several values for the number of obstacles in the case of both placement patterns. From the figures, it is observed that the accuracy of the equations is high regardless of the obstacle placement pattern. However, the figures also represent that the increase in the number of obstacles leads to deterioration of the accuracy in both metrics. This is because when the number of obstacles is large, the obstacles have greater impact on these network performance than expected.

Therefore, these results show that the proposed methods can provide accurate estimates of network performance without simulation experiments when the number of obstacles is small.

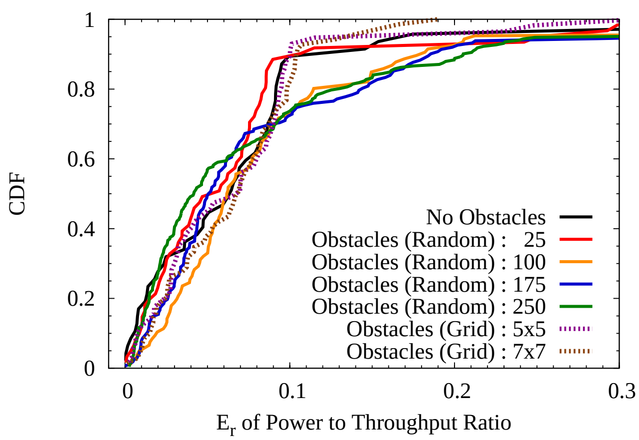
2) Evaluation results based on the real-world environment: Next, the accuracy of the equations is evaluated based on the real-world environment. For this purpose, we obtained obstacle placement patterns from maps in the real world by using Google Maps API [37]. In detail, 2000m×2000m square areas are randomly chosen from the field, ranging from Osaka Prefecture to Mie Prefecture in Japan, which satisfies the conditions that the latitude ranges from 34.5 to 35.5 degrees north and the longitude ranges from 135.5 to 136.5 degrees east, which corresponds to the residential area of the north part of Osaka, Japan. The fields whose distribution density of obstacles is from 1% to 25% are utilized for evaluation.

Figure 12 shows the distribution of relative error of the service ratio and the power-to-throughput ratio, where each plot represents the average of the results when the number of connected nodes is more than 30 in the simulation experiments. Although, in terms of the service ratio, the relative error is within 0.1 when the distribution density of obstacle is small, it becomes large as the distribution density of obstacle increases due to the biased tendency of distribution of obstacles. As a result, when the distribution density of obstacles is small, the service ratio can be estimated with a high degree of accuracy using the proposed method in real-world environment.

On the other hand, the relative error for the power-to-throughput ratio varies as shown in Figure 12(b) even when

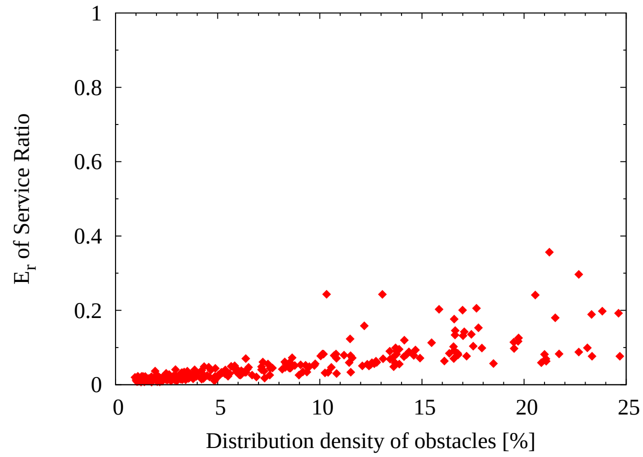


(a) Service ratio

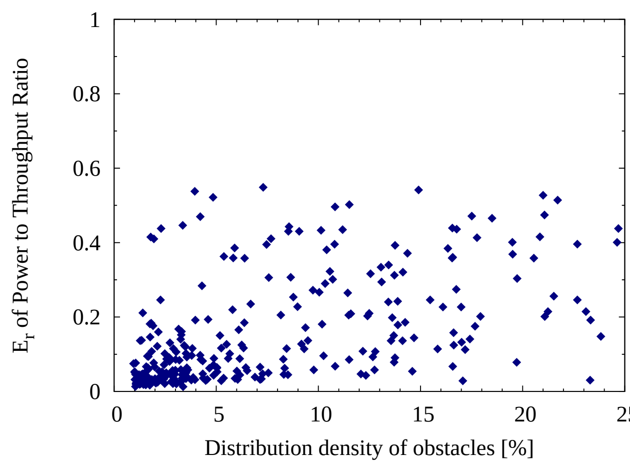


(b) Power-to-throughput ratio

Figure 11. Distribution of relative error for the obstacle model



(a) Service ratio



(b) Power-to-throughput ratio

Figure 12. Distribution of relative error for the real-world environment

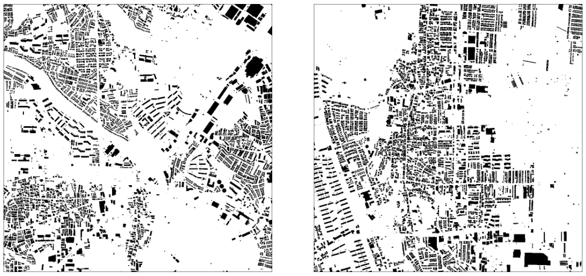
the distribution density of obstacles is small. The possible reason is as follows. In the field where there is a lot of obstacles concentrating around the gateway node, the link directly connected to the gateway node is likely to become disconnected due to the radio wave obstruction by obstacles. Although the regression equations are constructed based on simulation results including such situations, the decrease in the number of links of the gateway node has a great impact on the throughput beyond the expectation especially when the distribution density of obstacles is large. Therefore, the accuracy of the proposed method becomes worse in terms of the power-to-throughput ratio.

Figure 13 represents the examples of this case, where black part means the obstacles. 1Although the distribution density of obstacles in both cases is around 17%, the estimation accuracy is different. In Figure13(a), the relative error is 0.0285, while it is 0.471 for Figure 13(b), where many obstacles located at the center area of the field.

VI. Conclusions

In this paper, the performance of IEEE 802.16j multi-hop networks was investigated by considering the presence of obstacles. We first defined the obstacle model which determines location and size of each obstacle in the network, and extended the protocol model for determining the connectivity and interference relationships considering radio wave obstruction by obstacles. Simulation experiments using the proposed models revealed that the deployment of additional relay nodes improves the service ratio more effectively than an increase in the radio transmission range of each relay node. We also revealed the effects of the network parameters, such as the number of connected nodes, a transmission range of each node, and distribution density of obstacles, on the performance of IEEE 802.16j networks.

In addition, a method for estimating the performance of relay networks on the basis of regression analysis was also



(a) Lower estimation error (E_r = 0.0285) (b) Larger estimation error (E_r = 0.471)

Figure 13. Examples of the real-world environment

proposed. By comparing between the simulation results and the estimation values derived from the regression equations, we confirmed that the equations can yield an accurate estimation of network performance when the number of obstacles is small. This results help us estimate the performance of relay networks with obstacles in designing step. However, the accuracy of the proposed equations was deteriorated in terms of the power-to-throughput ratio using the real-world environment even when the number of obstacles is small, since the links directly connected to the gateway node are likely to become disconnected due to the radio wave obstruction by obstacles.

Future work will be directed toward applying more precise radio interference models, including signal-to-interference-plus-noise ratio (SINR) model in order to consider other effects of obstacles, such as reflection and diffraction of radio waves. We need to evaluate the validity of the regression model and to consider more detailed obstract model which accommodate the reflection and diffraction of radio waves. We also plan to evaluate of the proposed model with packet-level performance metric such as packet delivery delay and packet loss ratio. Furthermore, we need to apply the proposed scheme to multi-carrier OFDMA system, whereas in this paper we implicitly assume the single-carrier OFDMA where the radio resources are only time slots. Node replacement for obtaining better performance based on the proposed regression model is another interesting topic.

References

[1] Y. Ise, G. Hasegawa, Y. Taniguchi, and H. Nakano, "Evaluation of IEEE 802.16j relay network performance considering obstruction of radio waves propagation by obstacles," in *Proceedings of ICNS 2012*, Mar. 2012.

[2] IEEE Std 802.16j, *IEEE standard for local and metropolitan area networks, Part 16: Air interface for fixed broadband wireless access systems, Amendment 1: Multihop relay specification*, June 2009.

[3] S. W. Peters and R. W. H. Jr, "The future of WiMAX: Multihop relaying with IEEE 802.16j," *IEEE Communications Magazine*, vol. 1, pp. 104–111, Jan. 2009.

[4] V. Genc, S. Murphy, Y. Yu, and J. Murphy, "IEEE 802.16j relay-based wireless access net- works: An overview," *IEEE Wireless Communications*, vol. 15, no. 5, pp. 56—–63, Oct. 2008.

[5] D. Kumar and N. Nagarajan, "Technical issues in IEEE 802.16j mobile multi-hop relay (mmr) networks," *European Journal of Scientific Research*, vol. 65, no. 4, pp. 507–—533, Dec. 2011.

[6] M. Okuda, C. Zhu, and D. Viorel, "Multihop relay extension for WiMAX networks - Overview and benefits of IEEE 802.16j standard," *Fujitsu Scientific and Technical Journal*, vol. 44, no. 3, pp. 292–302, Jan. 2008.

[7] F. E. Ismael, S. K. S. Yusof, and N. Fisal, "An efficient bandwidth demand estimation for delay reduction in IEEE 802.16j MMR WiMAX networks," *International Journal of Engineering*, vol. 3, no. 6, pp. 554–564, Jan. 2010.

[8] B. Lin, P. Ho, L. Xie, and X. Shen, "Optimal relay station placement in IEEE 802.16j networks," in *Proceedings of IWCMC 2007*, Aug. 2007.

[9] D. Niyato, E. Hossain, D. I. Kim, and Z. Han, "Joint optimization of placement and bandwidth reservation for relays in IEEE 802.16j mobile multihop networks," in *Proceedings of IEEE ICC 2009*, pp. 4843–4847, Jun. 2009.

[10] G. Zhou, T. He, J. A. Stankovic, and T. Abdelzaher, "RID: Radio interference detection in wireless sensor networks," in *Proceedings of INFOCOM 2005*, pp. 891–901, Mar. 2005.

[11] A. P. Subramanian, M. M. Buddhikot, and S. Miller, "Interference aware routing in multi-radio wireless mesh networks," in *Proceedings of WiMesh 2006*, pp. 55–63, Sep. 2006.

[12] S. Chieochan and E. Hossain, "Adaptive radio resource allocation in OFDMA systems: A survey of the state-of-the-art approaches," *Wireless Communications and Mobile Computing*, vol. 9, no. 4, pp. 513—–527, Apr. 2009.

[13] D. Ghosh, A. Gupta, and P. Mohapatra, "Scheduling in multihop WiMAX networks," *ACM SIGMOBILE Mobile Computing and Communication Review*, vol. 12, pp. 1–11, Apr. 2008.

[14] C.-Y. Hong and A.-C. Pang, "3-approximation algorithm for joint routing and link scheduling in wireless relay networks," *IEEE Transactions on Wireless Communications*, vol. 8, no. 2, pp. 856–861, Feb. 2009.

[15] D. Ghosh, A. Gupta, and P. Mohapatra, "Adaptive scheduling of prioritized traffic in IEEE 802.16j wireless networks," in *Proceedings of WiMob 2009*, pp. 307–313, Oct. 2009.

[16] S. Yang, C. Kao, W. Kan, and T. Shih, "Handoff minimization through a relay station grouping algorithm with efficient radio-resource scheduling policies for IEEE 802.16j multihop relay networks," *IEEE Transactions on Vehicular Technology*, vol. 59, no. 5, pp. 2185—–2197, Jun. 2010.

[17] V. Genc, S. Murphy, and J. Murphy, "Analysis of transparent mode IEEE 802.16j system performance with varying numbers of relays and associated transmit power," *IEEE Wireless Communications & Networking Conference*, pp. –, Apr. 2009.

[18] A. Singh and V. Potdar, “Torpid mode: Hybrid of sleep and idle mode as power saving mechanism for IEEE 802.16j,” in *Proceedings of IEEE WAINA 2010*, Apr. 2010.

[19] J. Liang, Y. Wang, J. Chen, J. Liu, and Y. Tseng, “Energy-efficient uplink resource allocation for IEEE 802.16j transparent-relay networks,” *Computer Networks*, vol. 55, no. 16, pp. 3705—–3720, Jun. 2011.

[20] P. Gupta and P. R. Kumar, “The capacity of wireless networks,” *IEEE Transactions on Information Theory*, vol. 46, pp. 388–404, Mar. 2000.

[21] X. Meng, K. Tan, and Q. Zhang, “Joint routing and channel assignment in multi-radio wireless mesh networks,” in *Proceedings of ICC 2006*, Jun. 2006.

[22] H. Venkataraman, A. Krishnamurthy, P. Kalyampudi, J. McManis, and G.-M. Muntean, “Clustered architecture for adaptive multimedia streaming in WiMAX-based cellular networks,” in *Proceedings of the World Congress on Engineering and Computer Science*, vol. 2, pp. 753–758, Oct. 2009.

[23] P. Thulasiraman and X. Shen, “Interference aware subcarrier assignment for throughput maximization in OFDMA wireless relay mesh networks,” in *Proceedings of ICC 2009*, pp. 14–18, June. 2009.

[24] C. Cicconetti, I. F. Akyildiz, and L. Lenzini, “Bandwidth balancing in multi-channel IEEE 802.16 wireless mesh networks,” in *Proceedings of INFOCOM 2007*, vol. 5, pp. 6–12, May. 2007.

[25] Y. Lu and G. Zhang, “Maintaining routing tree in IEEE 802.16 centralized scheduling mesh networks,” in *Proceedings of 16th International Conference on Computer Communications and Networks 2007*, pp. 240–245, Aug. 2007.

[26] W. Wang, Y. Wang, X. Y. Li, W. Z. Song, and O. Frieder, “Efficient interference-aware TDMA link scheduling for static wireless networks,” in *Proceedings of the 12th Annual International Conference on Mobile Computing and Networking*, pp. 262–273, Sep. 2006.

[27] L. Kleinrock and J. Silvester, “Spatial reuse in multihop packet radio networks,” *Proceedings of the IEEE*, vol. 75, no. 1, pp. 156–167, Jan. 1987.

[28] L.-W. Chen, Y.-C. Tseng, D.-W. Wang, and J.-J. Wu, “Exploiting spectral reuse in routing, resource allocation, and scheduling for IEEE 802.16 mesh networks,” *IEEE Transactions on Vehicular Technology*, vol. 58, pp. 301–313, Jan. 2009.

[29] M. V. Marathe, H. Breu, H. B. Hunt, S. S. Ravi, and D. J. Rosenkrantz, “Simple heuristics for unit disk graph,” *Networks*, vol. 25, pp. 59–68, Sep. 1995.

[30] K. Jain, J. Padhye, V. Padmanabhan, and L. Qiu, “Impact of interference on multi-hop wireless network performance,” *Wireless Networks*, vol. 11, pp. 471–487, Jul. 2005.

[31] S. Khanna, N. Linial, and S. Safra, “On the hardness of approximating the chromatic number,” *Combinatorica*, vol. 20, no. 3, pp. 393–415, Mar. 2000.

[32] B. N. Clark, C. J. Colbourn, and D. S. Johnson, “Unit disk graphs,” *Discrete mathmatics*, vol. 86, no. 1–3, pp. 165–177, Dec. 1990.

[33] W. Klotz, “Graph coloring algorithms,” *Mathematical report TU-Clausthal*, vol. 5, pp. 1–9, May. 2002.

[34] V. A. Kumar, M. V. Marathey, S. Parthasarathyz, and A. Srinivasan, “Algorithmic aspects of capacity in wireless networks,” *ACM SIGMETRICS Performance Evaluation Review*, vol. 33, pp. 133–144, Jan. 2005.

[35] R. Ishii, G. Hasegawa, Y. Taniguchi, and H. Nakano, “Time slot assignment algorithms in IEEE 802.16 multi-hop relay networks,” in *Proceedings of ICNS 2010*, pp. 265–270, Mar. 2010.

[36] J. Tang, G. Xue, C. Chandler, and W. Zhang, “Link scheduling with power control for throughput enhancement in multihop wireless networks,” *IEEE Transactions on Vehicular Technology*, vol. 55, no. 3, pp. 733–742, May 2006.

[37] Google Maps API, available at http://code.google.com/apis/maps, accessed on 22nd May 2013.