Evaluation of IEEE 802.16j Relay Network Performance Considering Obstruction of Radio Wave Propagation by Obstacles

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***Abstract*—In IEEE 802.16j networks using a time division multiple access protocol, radio wave interference between links must be taken into account when time slots are assigned to the links. The protocol model, which defines the transmission and interference ranges as circles, has often been utilized in related studies for determining the interference between links. However, previous studies have not considered the presence of obstacles, which can affect radio wave propagation between wireless links and consequently network performance. In this paper, we investigate the performance of IEEE 802.16j networks considering the effects of obstacles. First we define an obstacle model where radio wave propagation is obstructed by the obstacles, after which we evaluate network performance by simulation experiments based on this model. The detailed simulation results reveal that the deployment of additional nodes improves the service ratio more effectively than an increase of the transmission range of nodes. Additionally, we present a method for estimating the performance of IEEE 802.16j networks on basis of regression analysis. By evaluating the accuracy of the performed analysis, we find that the relative error in the service ratio for 95% of the results is within 0.1 and the relative error in the power-to-throughput ratio for 90% of the results is within 0.2.**

***Keywords*-IEEE 802.16j; WiMAX; relay network; obstacle; radio wave obstruction.**

I. Introduction

The IEEE 802.16j protocol [1] utilizes multi-hop wireless networks for extending the network service area [2]. 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 Fig. 1, there is a wired connection between the gateway node and an external network, while relay nodes communicate with the gateway node or with neighboring relay nodes 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. A client terminal can access the external network by connecting to one of the relay nodes whose service area covers the client terminal.

Relay networks use a time division multiple access (TDMA) protocol [3], which gives transmission opportunities for wireless links between relay nodes. Therefore, radio wave interference between links should be taken into account when time slots are assigned to the links. Previous studies on relay networks have focused on preventing radio wave interference by introducing concepts such as link scheduling and

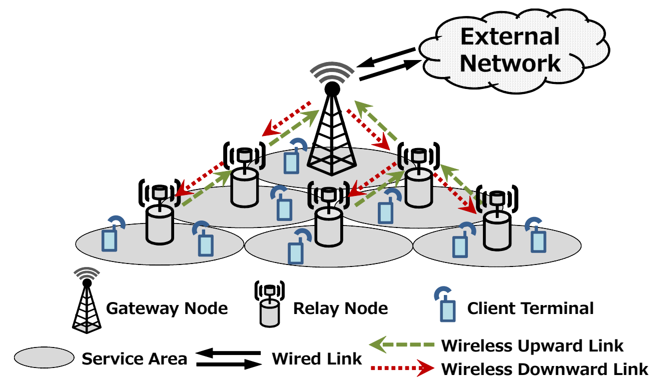

Figure 1. IEEE 802.16j wireless multi-hop relay networks

time slot assignment [4], [5]. In addition, the protocol model [6], which defines the transmission and interference ranges as circles, has often been utilized in previous works [7]–[10]. In the protocol model, whether a transmission succeeds or encounters interference depends on only the distance between the sender and receiver nodes, which are obtained through comparison with the transmission and interference ranges of other nodes. Therefore, the connectivity and the occurrence of radio wave interference in the network can be easily determined.

However, so far, the presence of obstacles in the field has not been considered. Here, obstacles refer to physical objects, such as buildings, that obstruct radio wave propagation and might substantially alter the connectivity and radio wave interference in a relay network. For example, even if a transmission between two nodes in a network is possible in the absence of obstacles, the addition of obstacles can prevent the nodes from communicating with each other. Furthermore, obstacles can obstruct radio wave propagation, thus reducing the size of the service area. On the other hand, in terms of radio wave interference, the presence of obstacles can increase network performance by reducing the occurrence of radio wave interference. Therefore, it is important to consider the presence of obstacles and their influence on radio wave propagation.

In this paper, we investigate the performance of relay networks by considering the presence of obstacles. First, we define an obstacle model based on the protocol model. In the obstacle model, rectangular obstacles are deployed in the field in various patterns. Although typically obstacles

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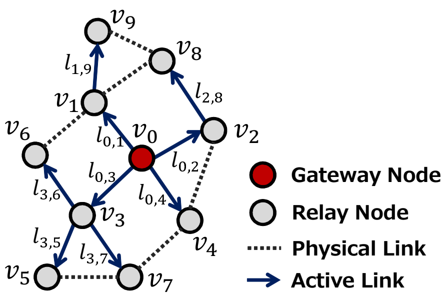

Figure 2. Network topology

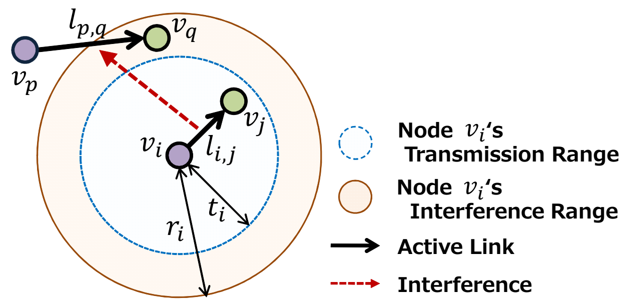

Figure 3. Radio interference based on the protocol model

have several effects on radio waves, such as obstruction, reflection, and diffraction, the obstacle model in this work considers only obstruction since its effects on relay network performance is the most pronounced. Using the obstacle model, we evaluate the performance of relay networks through simulation experiments. We also conduct simulation experiments using actual obstacles on the Osaka University campus.

Additionally, we use multiple regression analysis based on the simulation results and construct a regression equation for estimating the performance of relay networks.

The rest of this paper is organized as follows. The relay network model is introduced in Section II, the obstacle model is described in Section III, and the simulation results are presented in Section IV. Furthermore, a method for estimating the performance of relay networks is presented in Section V. Finally, our conclusions are presented in Section VI together with a description of future research directions.

II. Network model

In this section, we briefly describe the network model and the protocol model utilized for the performance evaluation. We also explain time slot assignment mechanisms based on TDMA.

A. Network topology

The network is assumed to consist of N nodes, where v_i $(0 \leq i \leq (N-1))$ denotes the i-th node. One node in the network, denoted as v_0, serves as the gateway node, and the remaining nodes function as relay nodes, forming 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. 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. When two nodes can communicate directly with each other, the link between them is referred to as a physical link, and a link used that forms the network topology is referred to as an active link. In this paper, an active link from node v_i to node v_j is denoted as $l_{i,j}$.

Figure 2 shows an example of a network topology where a gateway node and nine relay nodes are deployed. In the figure, the red circle indicates the gateway node, gray circles indicate relay nodes, dashed lines indicate physical links, and solid arrow lines indicate active links.

B. Protocol model

In this paper, the propagation and interference of radio waves are modelled by the protocol model [6], which defines the transmission and interference ranges of a node as circles centered at the node, as shown in Fig. 3. Here, t_i and r_i represent the transmission range and the radio 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 2 and 4 depending on the environment [11].

In the protocol model, transmission and radio wave interference depend on the distance between nodes. Node v_j can receive a transmission from node v_i when $||v_i - v_j|| \leq t_i$ is satisfied, where $||v_i - v_j||$ is the distance between nodes v_i and v_j. Figure 3 also shows an example of radio interference between nodes in the protocol model. In this figure, there are four nodes maintaining two active links ($l_{i,j}$ and $l_{p,q}$). The protocol model defines the 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 $||v_i - v_q|| \leq r_i$ is satisfied, link $l_{i,j}$ interferes with link $l_{p,q}$.

C. Time slot assignment

The IEEE 802.16j protocol uses the TDMA mechanism to control the ability of nodes to transmit by assigning time slots for transmission. In the TDMA mechanism, different time slots are assigned to wireless links that interfere with each other in order to prevent radio wave interference. In other words, multiple links can communicate simultaneously within the same time slot as long as the time slot is assigned to multiple links that do not interfere with each other. This mechanism is known as spatial reuse [12]. The throughput of relay networks can be substantially improved by spatial reuse with concurrent transmissions since such an approach reduces the total number of time slots assigned to all active links in the network, which is referred to as *frame length* in this paper. The time slot assignment problem with consideration of spatial reuse is regarded as a vertex coloring problem [13] of the conflict graph [14]. 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

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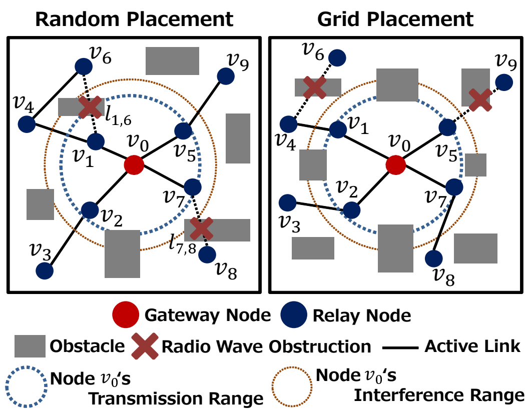


Figure 4. Obstacle model

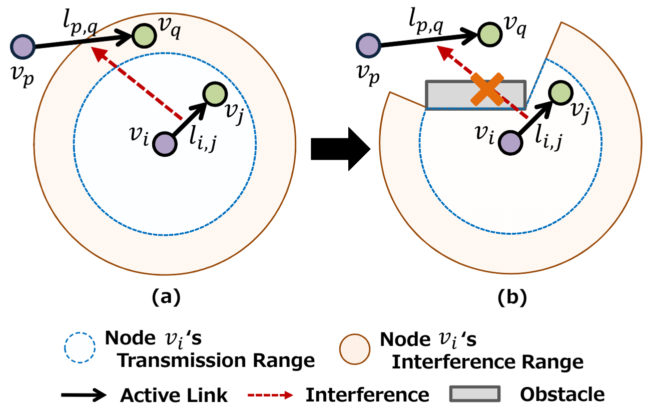


Figure 5. The influence of obstacles on radio wave interference

coloring problem is known to be NP-hard [15], heuristic algorithms have been proposed for solving the problem [11], [13], [16]. In this paper, we use the method proposed in [11] to assign time slots to links for performance evaluation.

III. Obstacle model

In this section, we introduce an obstacle model in which obstacles are deployed in the network described in Section II. We also examine the influence of obstacles on network performance.

A. Obstacle model characteristics

Figure 4 shows the obstacle model, where rectangular obstacles are deployed in the field following two placement patterns. In random placement, the obstacles are deployed at random in the field. In grid placement, on the other hand, the obstacles are deployed in a grid pattern, with the exception of 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 of values, and the obstacles are placed parallel to the field. The gateway node and the relay nodes cannot be deployed at locations occupied by obstacles. Although the influence of obstacles on radio waves includes obstruction, reflection, and diffraction, in this paper we consider only the obstruction of radio waves since its effects on the performance of relay networks is the most pronounced. We also ignore the height of the obstacles since the network model is constructed in a plane.

B. Effects of obstacles in relay networks

The obstacle model in this work considers only the effects of radio wave obstruction, which are described in this subsection. When the propagation of radio waves is obstructed by obstacles, the connectivity and radio interference in the network can change, either improving or degrading the performance of the relay network. For example, in the left panel of Fig. 4, $l_{1,6}$ and $l_{7,8}$ become disconnected due to radio wave obstruction by an obstacle. 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, Fig. 5 shows an example of a beneficial effect of radio wave obstruction. Although in Fig. 5(a) $l_{i,j}$ and $l_{p,q}$ interfere with each other, by adding obstacles as shown in Fig. 5(b), the interference range of v_i is limited and v_q is not affected by 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, deploying obstacles entails both advantages and disadvantages in terms of network performance. Therefore, it is important to evaluate the performance of relay networks in the presence of obstacles.

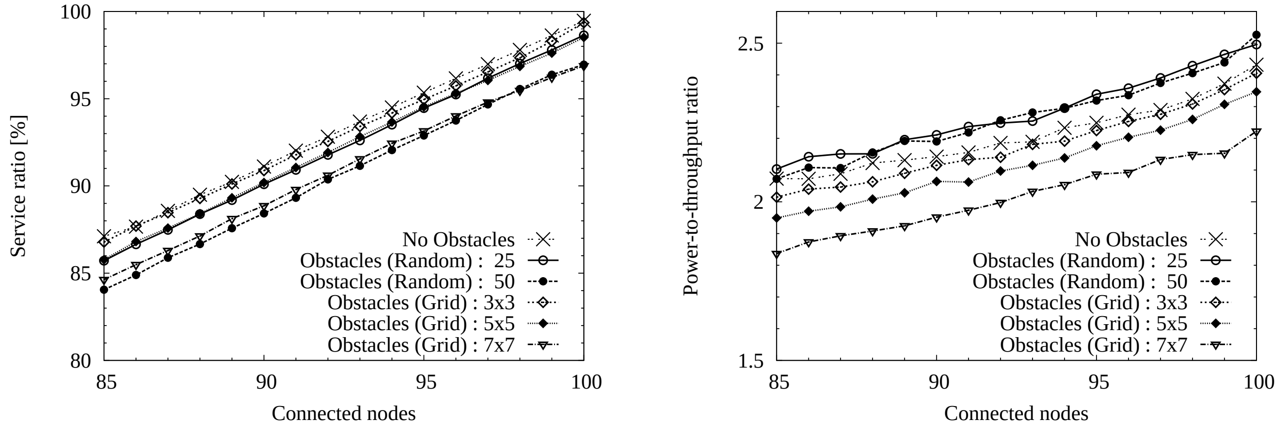
IV. Performance evaluation

In this section, we evaluate the influence of obstacles on relay network performance by using the obstacle model described in Section III.

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. Based on the protocol model, the transmission range for all nodes was set to 0.15, 0.20, 0.25, 0.30, or 0.35 in consecutive experiments. The ratio of the interference range to the transmission range was set to 2 for all nodes. A directed transmission graph (Fig. 2) was constructed with a tree topology rooted at the gateway node such that the hop count between the gateway node and each relay node was minimized. The number of obstacles was set to 0, 25, or 50 in the case of random placement. For the grid placement, we chose 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 0.01 and 0.1. The transmission range of a node and the length of the sides of each obstacle are relative value based on the size of simulation area. In the simulation, the detail of distribution function is not taken into account.

We monitored the *service ratio* and the *power-to-throughput ratio* as measures of network performance. The service ratio is the ratio of the area where the relay network can provide service to the overall field area, excepting the



(a) Service ratio (b) Power-to-throughput ratio

Figure 6. Effect of connected nodes on network performance

area of the obstacles, and 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 defined as the sum of the squares of the transmission ranges of all connected nodes. In addition, the gateway throughput is defined as the ratio between the number of time slots assigned to all links to the gateway node and the frame length. We conducted 100,000 iterations of the simulation experiments for each set of parameter settings, where all results were divided according to the number of connected nodes, and the average values were used for performance evaluation.

B. Impact of obstacle placement pattern

Figure 6 shows the service ratio and the power-to-throughput ratio as a function of the number of connected nodes when the transmission range of the nodes is set to 0.15. The x-axis of both graphs means the number of connected nodes. Not that the value of less than 100 means that there are some nodes disconnected from the network due to radio wave obstruction by obstacles. The figure shows that both measures increase as the number of connected nodes increase, but there are differences between the two plots. The service ratio in Fig. 6(a) decreases as the number of obstacles increases, regardless of the placement pattern, since radio wave propagation is obstructed by obstacles. On the other hand, the power-to-throughput ratio in Fig. 6(b) does not display such a simple trend. In the case of grid placement, the power-to-throughput ratio decreases as the number of obstacles increases, whereas in the case of random placement, the ratio increases together with the number of obstacles. The reason for this is as follows.

In random placement, the obstacles are deployed at random in the field, and therefore a link to the gateway node is likely to become disconnected due to the radio wave obstruction by obstacles. Therefore, the number of nodes connected to the gateway node decreases, which results in a decreased gateway throughput. On the other hand, in grid placement, since the obstacles are regularly spaced, the number of nodes connected to the gateway node is barely affected. As a result, the gateway throughput is improved

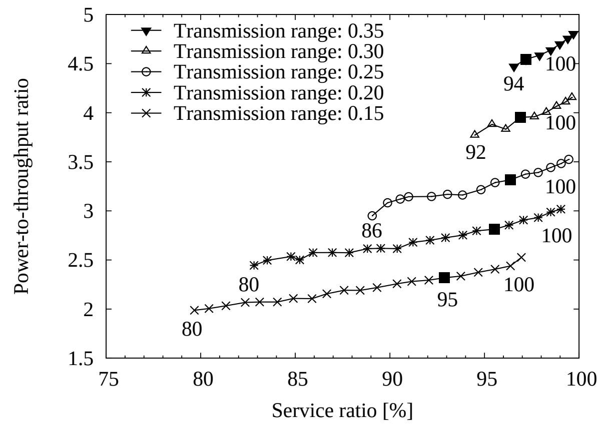


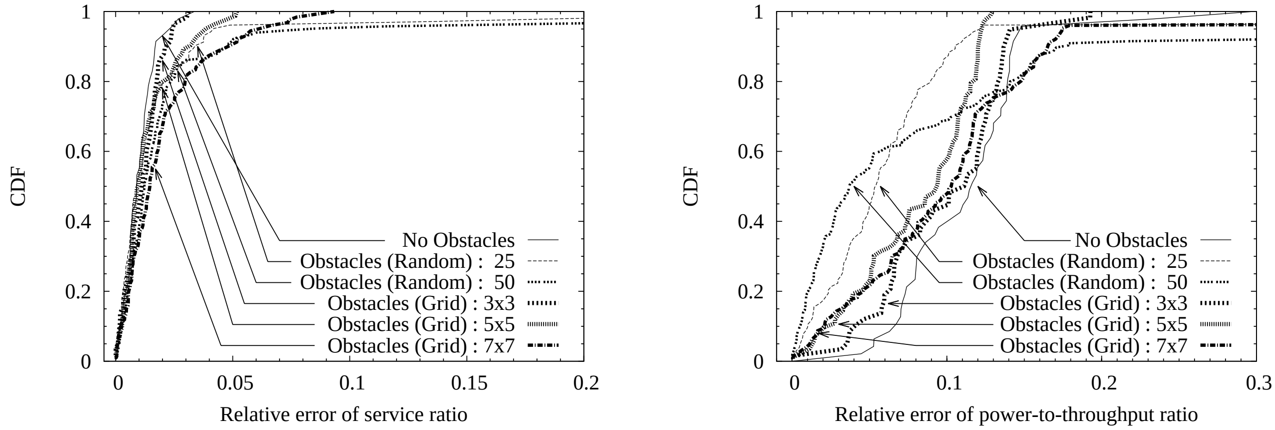
Figure 7. Effect of transmission range on network performance

since the interference is reduced effectively due to the presence of obstacles. Therefore, we find that the service ratio is unaffected by the placement pattern of obstacles, but the power-to-throughput ratio is sensitive to the obstacle placement pattern.

C. Effect of the transmission range

Figure 7 shows the relation 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 0.35. In this case, 50 obstacles are placed at random. In the graph, the number of connected nodes is indicated for each plot, where the number of connected nodes increases from left to right and the rightmost point indicates the average value when the number of connected nodes is 100.

We focus on the plots denoted with squares in the figure when the number of connected nodes is 95. Here, we consider two methods for improving the service ratio. One involves increasing the transmission range of the nodes, and the other involves deploying additional nodes in the network. As shown in Fig. 7, when the transmission range of the nodes is increased, the power-to-throughput ratio increases rapidly as the service ratio increases. On the other hand, by deploying additional nodes in the field, the service ratio



(a) Service ratio

(b) Power-to-throughput ratio

Figure 8. Relative error between regression equation results and simulation results

can be enhanced with a small increase of the power-to-throughput ratio. Therefore, the deployment of additional nodes improves the service ratio more effectively than an increase of the transmission range of the nodes.

V. Method for estimating network performance

In this section, we present a method for estimating the performance of relay networks on the basis of simulation results and regression analysis.

A. *Regression equations*

In the process of constructing a network, the ability to estimate network performance before the network is actually constructed is highly valuable. For example, such 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, and power consumption. Therefore, as a method for estimating network performance, we derived regression equations 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. 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. The following regression equations can be derived from the simulation results. The details of the regression analysis are omitted due to space limitations.

$$S(n,t,d) = 92.8n + 22.8t^2 - 14.3d + 7.87 \quad (1)$$
$$P(n,t,d) = 2.34n + 11.3t - 2.28d - 1.30 \quad (2)$$

The performance of relay networks can be estimated by using the above equations. In order to examine the accuracy of the equations, the estimation values from the equations are compared with the simulation results in the following subsections, where the relative error is used as a measure of accuracy.

B. *Evaluation of the regression equation accuracy*

Figure 8 shows the respective distributions of the relative error for the service ratio and the power-to-throughput ratio with several values for the number of obstacles in the case of both placement patterns. The accuracy of the equations is clearly high regardless of the obstacle placement pattern and the number of obstacles in the network. In particular, for the service ratio (Fig. 8(a)), the relative error for 95% of the results is within 0.1. For the power-to-throughput ratio in Fig. 8(b), the relative error for about 90% of results is within 0.2. These results show that Eqs. (1) and (2) can provide accurate estimates of network performance without simulation experiments.

C. *Campus model*

Finally, to evaluate the accuracy of the equations in a more realistic situation, simulation experiments and performance estimation with Eqs. (1) and (2) were conducted with respect to actual obstacles on the Osaka University campus, as shown in Fig. 9.

Figure 10 shows a comparison between the estimation and simulation results for different transmission ranges. In the graph, lines without plotted points represent the estimation results, and ones with plotted points represent the simulation results. When the number of connected nodes is between 75 and 85, the results of estimation and simulation are close; however, as the number of connected nodes increases further, the error between the two results becomes large, because in the campus model, radio wave propagation is obstructed more frequently as a result of the large number of obstacles and the difference in shape and size of each obstacle in the field as compared with those in the obstacle model with random and grid placement. Therefore, although the service ratio is difficult to improve, the number of connected nodes increases. The another reason is the heterogeneous distribution of obstacles in the field as shown in Fig. 9, while both obstacle placement patterns in this paper assume the homogeneous distribution.

Figure 9. Campus model

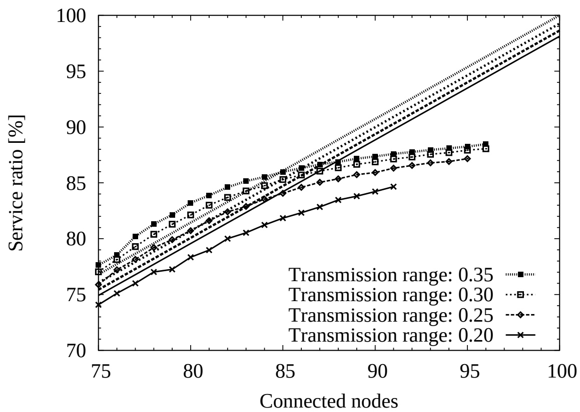


Figure 10. Comparison between estimation and simulation results

VI. Conclusions and Future Work

In this paper, the performance of IEEE 802.16j multi-hop networks was investigated by considering the presence of obstacles, where the obstacle model was defined as an extension of the protocol model. Simulation experiments based on using the obstacle model revealed that the obstacle placement pattern does not affect the service ratio, but does greatly affect the power-to-throughput ratio. A method for estimating the performance of relay networks on the basis of regression analysis was also provided in this study, and a comparison between the simulation results and the estimation results derived from the regression equations confirmed that the equations can yield an accurate estimation of network performance. However, in testing the model with respect to a real-world environment (a university campus), the accuracy of the equations was found to be lower than in the case of random and grid placement due to differences in the characteristics of the obstacles, such as shape and size, and the distribution characteristics of obstacles.

Future work will be directed toward applying other radio interference models using signal-to-interference-plus-noise ratio in order to consider other effects of obstacles, such as reflection and diffraction of radio waves. Moreover, additional research will be conducted with the aim to increase the accuracy of the regression equations, especially with respect to real-world networks.

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