Multiple Regression Analysis of IEEE 802.16j Relay Network Throughput

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***Abstract*—In IEEE 802.16j relay networks, time division multiple access (TDMA) is adopted for sharing wireless network resources while avoiding radio wave interference. Time slot assignment determines the degree of spatial reuse of wireless network resources and radio interference strength, which affects network performance. The relay network performance is also influenced by various factors, such as background noise level, path loss exponent, density of relay nodes, and transmission signal strength. In this paper, we present the results of multiple regression analysis of IEEE 802.16j relay network throughput. We first summarize the network environment parameters that affect the throughput of relay networks and conduct extensive simulation experiments with various sets of parameter values. From the simulation results, we investigate the relative effect of parameters on throughput performance by multiple regression analysis. The analysis results show that background noise level and path loss exponent are the key parameters for determining relay network throughput. We also obtain a regression equation to estimate the throughput with enough accuracy.**

***Keywords*—IEEE 802.16j, time slot assignment, SINR, throughput, multiple regression analysis**

I. Introduction

Wireless multi-hop relay networks based on IEEE 802.16j [1]–[3] (hereafter, *relay networks*) are attracting considerable attention. In general, a relay network is composed of gateway nodes, relay nodes, and user terminals (Figure 1). Gateway nodes connect to backhaul networks (e.g., the Internet) through wired links, and relay nodes relay data packets between gateway nodes and user terminals through wireless multi-hop links.

In relay networks, time division multiple access (TDMA) is adopted for sharing wireless network resources, where time slots for communication are assigned to wireless links between relay nodes [4]–[6]. Different time slots are assigned to links that interfere with each other to avoid performance degradation, whereas links that do not interfere with each other can utilize the same time slot to improve the spatial reuse of wireless network resources [7].

The performance of relay networks is strongly dependent on the communication quality of links, which is evaluated based on the signal-to-interference-plus-noise ratio (SINR). The communication quality of links also depends on the time slot assignment since the link quality in a certain time slot is affected by interfering signals from relay nodes that use the same time slot. Previous studies [8]–[11] have proposed heuristic algorithms for time slot assignment since the problem is NP-hard [12]. Furthermore, when adaptive modulation and coding (AMC) [13] is applied to data transmission, the transmission rate depends strongly on the link quality because AMC selects the most suitable modulation method depending on the SINR of the link in the assigned time slot.

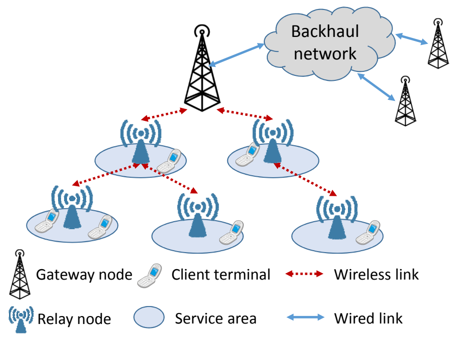


Figure 1. An IEEE 802.16j relay network

The communication quality of links is also influenced by various factors such as background noise level, path loss exponent, density of relay nodes, and transmission signal strength. Therefore, for assessing the performance of relay networks, the effect of these network environment parameters on the performance should be investigated thoroughly. This is also important for developing a suitable heuristic algorithm to solve the time slot assignment problem.

This paper presents the results of multiple regression analysis of the throughput of IEEE 802.16j relay networks, with consideration of the effects of network environment parameters. Specifically, we first summarize the network environment parameters that affect the throughput of relay networks. Next, we conduct extensive simulation experiments while varying those parameters. Since we aim to discuss the performance characteristics independent of performance degradation due to the heuristic algorithm used, in the simulation experiments we use a time slot assignment algorithm that is time-consuming but provides the configuration yielding the optimal throughput. Finally, using the simulation results, we investigate the effect of the parameters on the relay network performance by multiple regression analysis. We also obtain a regression equation for estimating the throughput. In addition, we use the analysis results to provide some insights on developing suitable heuristic algorithms for time slot assignment.

The rest of this paper is organized as follows. Section II explains the network model and assumptions in this work. Next, in Section III, we present the network environment parameters that affect the throughput of relay networks. In Section IV, the simulation results are subjected to multiple regression analysis, and the findings are summarized. Finally, we present the conclusions derived in this study and outline possible directions for future work.

II. System Model and Assumption

A. Network Model

The network consists of N nodes, where v_i $(0 \leq i \leq (N-1))$ denotes the ith node. Node v_0 serves as the gateway node, and the remaining nodes function as relay nodes. A tree network topology is constructed with v_0 as the root of the tree. Figure 2 shows an example of a network topology consisting of 10 nodes. We consider only the performance of upward transmission from the relay nodes to the gateway node since the performance characteristics of downward transmission are similar to those of upward transmission. We assume that each relay node handles a certain amount of traffic demand, which is calculated as the sum of traffic from that relay node and the traffic from those relay nodes that are its children in the tree topology.

B. Time Slot Assignment Problem

In relay networks, the radio resources are divided into time slots, which are assigned to links so as to satisfy their respective traffic demands. Here, we define the *schedule length* as the number of time slots required to satisfy the traffic demand of all links in the network. Different time slots are assigned to links that interfere with each other to avoid performance degradation, whereas links that do not interfere with each other can utilize the same time slot to increase the spatial reuse of radio resources. Increasing the spatial reuse of wireless network resources reduces the schedule length and therefore enhances the network performance because links are provided with more opportunities for transmission per unit time. Here, we define a time slot assignment problem where the objective is to assign a number of time slots to links in a way that satisfies the traffic demand while minimizing the schedule length. Previous studies [8]–[11] have proposed heuristic algorithms for time slot assignment because the problem is NP-hard [12].

C. SINR model for evaluating transmission quality

In this work, the communication quality of links at each time slot is evaluated by the SINR model [14]. The time slot used by link $l_{i,j}$ between sender node v_i and receiver node v_j is denoted as t_x. Let $V_{i,j,x}$ be a set of sender nodes that use time slot t_x. Then, the SINR of $l_{i,j}$ at t_x, denoted by $s_{i,j,x}$, is given by the following equation.

$$s_{i,j,x} = 10 \log_{10} \frac{P_{i,j}}{N + \sum_{v_k \in V_{i,j,x}} P_{k,j}}, \quad (1)$$

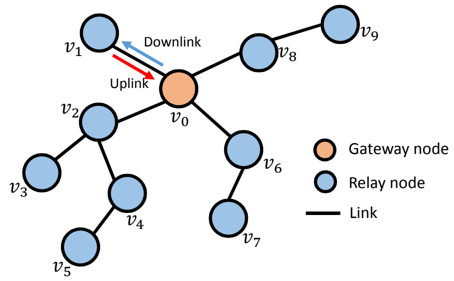


Figure 2. Network model

TABLE I
Adaptive Modulation and Coding in IEEE 802.16-2009

SINR [dB]	Modulation method	Number of bits
$s_{i,j} < 3$	-	0
$3 \leq s_{i,j,x} < 6$	BPSK	0.5
$6 \leq s_{i,j,x} < 8.5$	QPSK	1
$8.5 \leq s_{i,j,x} < 11.5$	QPSK	1.5
$11.5 \leq s_{i,j,x} < 15$	16QAM	2
$15 \leq s_{i,j,x} < 19$	16QAM	3
$19 \leq s_{i,j,x} < 21$	64QAM	4
$21 \leq s_{i,j,x}$	64QAM	4.5

where N is the background noise level. $P_{i,j}$ is the strength of the signal sent by node v_i and received by node v_j, and it is given by the following equation:

$$P_{i,j} = \left(\frac{1}{r_{i,j}}\right)^{\eta} P_i, \quad (2)$$

where η is the path loss exponent, and $r_{i,j}$ is the distance between v_i and v_j. P_i is the strength of the radio signal transmitted from node v_i.

D. AMC

In this work, we use AMC to determine the data transmission rate. AMC selects the most suitable modulation method according to SINR of the transmission link. When SINR is large, the sender node selects a modulation method that can transmit data at a high rate. Conversely, when SINR is small, the sender node selects a modulation method providing lower data transmission rate but higher robustness against degradation of the channel quality. In this paper, we assume that AMC selects the modulation method and the number of transmitted bits per time slot as shown in Table I, which follows the definition in IEEE 802.16 [2].

III. Network Environment Parameters Affecting Relay Network Performance

In this section, we summarize the parameters of the relay network that affect its throughput characteristics. Here, we define throughput as the number of bits per unit time the gateway node receives from relay nodes that are connected directly to the gateway node.

A. Background Noise Level

Background noise refers to radio waves unrelated to the transmission signal that are received by receiver nodes. It can be caused by various phenomena in the target environment. We assume that background noise is uniform in the service area. N in Equation (1) denotes the background noise level. Equation (1) indicates that when the noise level is high, SINR of the transmission is small. In that case, AMC selects a modulation method providing a low transmission rate, that increases the number of time slots required for each link in the network. Therefore, this parameter significantly affects the performance of relay networks.

B. Path Loss Exponent

The path loss exponent, denoted as η in Equation (2), is a parameter that determines the degree of radio wave attenuation as a function of the propagation distance of the waves. When η is large, the distance within which the transmission signal can be successfully received is short. This also affects the interference range for relay nodes and therefore the degree of spatial reuse of wireless network resources.

C. Density of Relay Nodes

We define the density of relay nodes as the number of relay nodes divided by the size of the target service area. When the density of relay nodes is large, the number of relay nodes within the interference range of any given relay node is also large. This limits the spatial reuse of wireless network resources, thus affecting the schedule length.

D. Transmission Signal Strength

The transmission signal strength directly affects the transmission distance. When the transmission distance is longer, relay nodes can connect to the gateway node within fewer hops. This means the network topology changes, which affects the traffic demand of each network link. Also, as in the case of the path loss exponent, the transmission signal strength affects the interference range for each relay node.

IV. Simulation Experiments and Performance Analysis

A. Simulation Settings

In the simulation experiments, multiple relay nodes are distributed randomly within a 1×1 square area, and one gateway node is located at the center of the area. The network topology is constructed according to the algorithm in [15] so that the hop count from each relay node to the gate way node is minimized. We assume that the transmission power P_i is identical for all nodes.

To determine the traffic demand of each link, we assume that user terminals are distributed uniformly throughout the area and that they connect to the nearest relay node. Furthermore, we assume that all user terminals generate the same amount of upward traffic. In this way, we can calculate the traffic demand on each link by dividing the area into Voronoi cells [16] with the corresponding relay nodes as seeds.

TABLE II
Parameter Settings

Parameter	Value
Background noise (as a ratio to signal strength)	0.00001, 0.5, 1.0
Path loss exponent	2.5, 3.0, 3.5, 4.0
Number of relay nodes	3, 5, 7
Transmission distance	0.3, 0.4, 0.5

To discuss the effect of the network environment parameters on the performance characteristics of relay networks, we use an algorithm for time slot assignment that gives the highest throughput by using the exhaust search.

We conduct the simulation experiments while changing the values of the parameters introduced in Section III. The detailed settings are summarized in Table II. We set the background noise level as a ratio to the transmission signal strength of the relay nodes. The density of relay nodes is configured by changing the number of relay nodes in the field.

B. Performance Metrics

The performance metric is taken as the throughput defined at the beginning of Section III, which is calculated by the following equation.

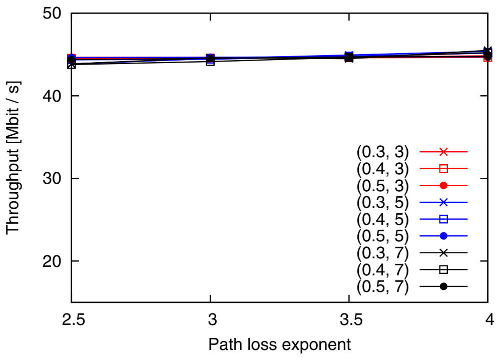
$$C_{GW} = \frac{\sum_{l_{i,j}\in L} b_{i,j}}{S\tau} \tag{3}$$

L is the set of all links in the network, and $b_{i,j}$ is the transmission quantity of link $l_{i,j}$, which is determined by AMC in Table I. S is the schedule length obtained as a result of the time slot assignment. The length of each time slot, denoted by τ, is set to $100.8\mu s$ based on [17]. For each set of parameter settings, we conduct 100 simulation runs with random distribution of the relay nodes and evaluate the average throughput over all runs.

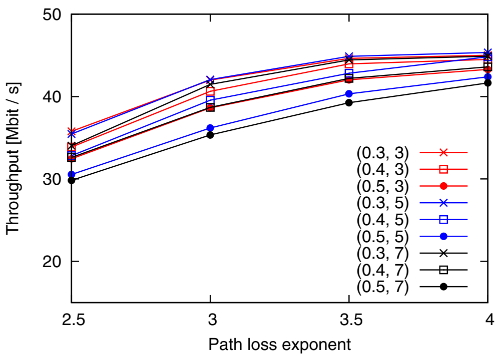
C. Simulation Results

Figure 3 presents the results of the simulation experiments, where (a), (b), and (c) correspond to background noise levels of 0.00001, 0.5, and 1.0, respectively. In each graph, the x-axis denotes the path loss exponent, and we plot the results for different combinations of transmission distance and number of relay nodes.

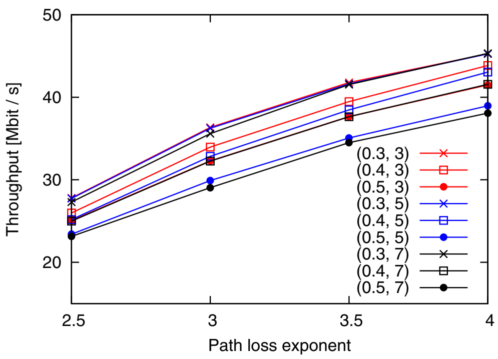
Clearly, the throughput increases with increasing the path loss exponent. This is because the received strength of radio waves emitted from relay nodes that interfere with a given receiver node is low when the path loss exponent is large. It is noteworthy that when the background noise ratio is 0.00001, the throughput is almost constant regardless of the path loss exponent because the SINR is sufficiently large to obtain the largest number of transmitted bits in AMC table (Table III), even if the path loss exponent is small. Comparing (a), (b), and (c) in Figure 3, we can see that when the background noise becomes large, the throughput degrades. The reason for this is that the SINR is small when the background noise ratio is large (Equation (1)).



(a) Background noise ratio of 0.00001



(b) Background noise ratio of 0.5



(c) Background noise ratio of 1.0

Figure 3. Simulation results

Furthermore, the throughput decreases slightly with increasing the transmission distance. This is due to the lower hop count resulting from the greater transmission distance and the greater number of relay nodes that have the same parent node. Therefore, the degree of the node increases and the required number of time slots for the relay node becomes large. Furthermore, the degree of throughput degradation is high when the number of relay nodes is large. This is because the number of relay nodes that have the same parent node is large when the overall number of relay nodes is large.

From the above results, we conclude that the effect of the number of relay nodes is small compared to that of the other parameters. The reason for this is that the total traffic demand for all relay nodes is constant, regardless of the number of relay nodes.

TABLE III
RESULT OF MULTIPLE REGRESSION ANALYSIS

Index	Value
R^2	0.774
F	3.07×10^{-33}

TABLE IV
t-VALUE AND p-VALUE RESULT

Parameter	t-value	p-value
Background noise ratio	-13.89	2.37×10^{-25}
Path loss exponent	12.46	2.76×10^{-22}
Number of relay nodes	-1.590	0.115
Transmission distance	-4.462	2.08×10^{-5}

D. Multiple Regression Analysis

Using the simulation results, we investigate the effect of the above parameters on the relay network performance by multiple regression analysis. In the analysis, we set the parameters in Table II as explanatory variables and the throughput as an explained variable.

We show the results of multiple regression analysis in Tables III and IV. Table III shows the estimation accuracy of the obtained regression model. From the results of R^2 and F-values, we can conclude that the explanatory variables in Table II can explain the throughput with enough accuracy.

Table IV shows t-value and p-value of each explanatory variables. We can observe from this table that the background noise ratio and the path loss exponent strongly affect the throughput performance, while the number of relay nodes and the transmission distance have a less pronounced effect. These results match the results of the simulation experiments in Figure 3.

We also have the regression equation as follows, estimating the throughput of the relay network from these parameters.

$$C(e, a, n, d) = -9.62e + 6.30a - 0.27n - 15.5d + 31.7 \quad (4)$$

e, a, n and d represent the background noise ratio, the path loss exponent, the number of relay nodes, and the transmission distance, respectively. From the results of p-value for each parameters, the background noise ratio and the path loss exponent are important factors to estimate the throughput of the relay networks, while the number of relay nodes and the transmission distance have less significance.

From the above results we conclude that we need to consider the effect of the background noise and the path loss exponent when constructing the heuristic algorithms for time slot assignment in the relay networks. For example, since the throughput is largely affected by the background noise level, we need to estimate the strength of the background noise before starting the time slot assignment. Similarly, the path loss exponent should be estimated, or measured in advance to obtain enough throughput by configuring time slot assignment.

V. Conclusions and Future Work

In this paper, we presented the results of multiple regression analysis of the throughput of IEEE 802.16j relay networks. The analysis results showed that the background noise level and the path loss exponent are the key parameters determining the throughput of the relay networks, while the density of rely nodes and the transmission distance have a less pronounced effect. We also obtained a regression equation to estimate the throughput and emphasized the importance of estimating or measuring both the background noise level and the path loss exponent to provide high throughput.

In future work, we plan to propose the detailed time slot assignment algorithms, with possible methods for estimating or measuring the environmental parameters that affect the relay network performance.

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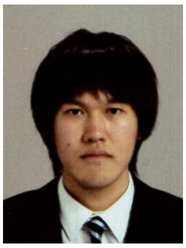

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