Improvement of the Capacity of Wireless Networks by Optimizing Communication Distance

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***Abstract*—As the number of nodes increases, the capacity of ad-hoc wireless networks is constrained by radio interference. Especially when a source node cannot directly communicate with its destination node, every packet has to travel through one or more intermediate nodes. The throughput decreases as the number of relayed hop count increases. To effectively use the limited radio resources, we propose a scheme that a node avoids radio interference among its adjacent nodes by appropriately controlling its transmission power. In this case, the network capacity is expected to quite improve when each node sets its communication distance to physical distance to the next intermediate node. However, this may be difficult to realize in practical environments. In this paper, we examine the optimal communication distance to maximize the network capacity when all nodes take the same communication distance. Results showed that the communication distance to maximize the network capacity depended on the node density. We further showed that the network capacity was independent of the node density. In addition, the proposed scheme could improve the network capacity up to 2.1 times higher than the traditional scheme.**

***Index Terms*—wireless network, network capacity, radio interference, transmission power control**

I. Introduction

As the number of nodes increases, the capacity of ad hoc wireless networks is constrained by radio interference. Especially, when a source node cannot directly communicate with its destination node, every packet has to travel through one or more intermediate nodes. The throughput decreases as the number of relayed hop count increases. There are several ways to assure the network capacity by reducing the radio interference; decreasing relayed hop count by relaying packets to mobile nodes, restricting the number of relayed hop count, or decreasing the radio interference by suppressing node's transmission power.

Grossglauser and Tse [1] have proposed the scheme that the network capacity becomes constant independently of the number of nodes by using mobility of nodes and restraining the number of relayed hop count. A node can communicate with its nearest neighboring node only when they are getting close. However, the successful probability of communication between two adjacent nodes is at most 14% due to the radio interference among other nodes. In this paper, we try to increase the network capacity by appropriately controlling node's transmission power. ALOHA [2][3] and CSMA/CA [4] also target efficient utilization of wireless network resources by the means of media access control that adjust the transmission timing in accordance with the network condition. By combining our proposed scheme with them, we expect that the network capacity further improves because the radio interference among nodes is reduced.

When each node can set its communication distance to physical distance to the next intermediate node, the network capacity is expected to quite improve because the effects of radio interference are minimized. GPS [5] is a well known scheme to estimate node locations. However, GPS cannot work in a building because it receives the radio waves from satellites. In addition, GPS is expensive and requires a measurable amount of electric power consumption. To estimate the location information at a low cost, Shen and Wang [6] and Patwari and Hero [7] have proposed schemes based on received signal strength (RSS). However, RSS is not accurate due to fading and shadowing effects. Experimental results have shown that the degree of errors became 4.3 m when 49 nodes were randomly deployed over a 50×50 m^2 area [8].

In this paper, we investigate the optimal communication distance to maximize the network capacity when all nodes take the same communication distance instead of physical distance to their next intermediate nodes. First, we assume that the node can transmit packets to its nearest neighbor when there is only its nearest neighbor in the area where the radio wave of the node impacts. Under this assumption, through analyses and simulation experiments, we examine the optimal communication distance to maximize the network capacity.

The remainder of this paper is organized as follows. In Section II, we describe the related work about the communication on ad hoc wireless networks. In addition, we introduce the model for radio interference among nodes. In Section III, we analyze the optimal communication distance to maximize the network capacity. Then we verify the accuracy of our analysis and show the effectiveness of our proposal through simulation experiments. Finally Section IV gives conclusions of this paper.

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II. RELATED WORK

In this section, we describe the scheme that uses mobility of nodes for improvement of the network capacity. Then, we introduce the model for radio interference among nodes.

A. Improvement of the network capacity

To effectively use the limited radio resources, Grossglauser and Tse [1] have proposed the scheme that uses mobility of nodes. First, They assume that N nodes move randomly and have infinite buffers to store data. Nodes transmit their data under the following policy π,

- Each node tries to transmit its own or forwarding data to its nearest node.
- A data transmission is only conducted between three kinds of node pairs: source-destination, source-intermediate, or intermediate-destination.
- The data transmission successes only when there is no radio interference defined by the signal-to-interference (SIR) model [9] described in Subsection II-B1.

Consequently, routes between two arbitrary nodes are one direct route and $N-2$ two-hop routes which go through one intermediate node. In addition, the following facts are fulfilled.

- The probability that two arbitrary nodes can communicate following the policy π is $\Theta\left(\frac{1}{N}\right)$.
- The probability is equal to the long-term throughput between any two nodes.

Thus, the throughput between two arbitrary nodes is $\Theta\left(\frac{1}{N}\right)$. By accumulating throughput of all the $N-1$ routes, the total average throughput becomes $\Theta(1)$. This communication model implicitly assumes that applications are tolerant about transmission delay because nodes may wait for a long time to satisfy the policy π.

We also assume this type of multihop communication. Moreover, we try to improve the network capacity by appropriately controlling node's transmission power.

B. Radio interference models

In general, a radio wave is attenuated in inverse proportion to αth power of distance. Suppose that node X_i emits a radio wave with transmission power P_i. Then, the power that node X_i receives from X_0 is expressed as

$$\frac{P_0}{\mid X_i - X_0 \mid^{\alpha}} \tag{1}$$

We introduce the signal-to-interference (SIR) model [9] and the occupation zone model [10] as models of radio interference based on this attenuation characteristic in wireless networks.

1) SIR model: SIR model is the model that determines whether a node can receive data based on the intensity of signal perceived on it. X_i can correctly receive data from X_0 if the following condition is satisfied.

$$\frac{\dfrac{P_0}{\mid X_i - X_0 \mid^{\alpha}}}{N_0 + \displaystyle\sum_{k \neq 0} \frac{P_k}{\mid X_i - X_k \mid^{\alpha}}} \geq \beta \tag{2}$$

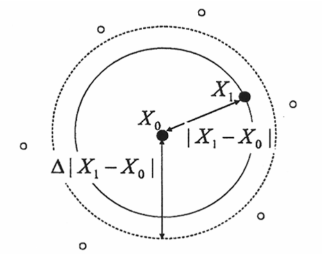

Fig. 1. success of communication in occupation zone model

Here, β is the signal-to-interference ratio (SIR) required for successful communication. N_0 is the background noise power.

Equation (2) indicates that X_i can receive data when the ratio of the signal power received from X_0 to the sum of other signals and noise is not less than β.

2) Occupation zone model: Since the analysis based on SIR model is difficult because of the complicated expression, we also introduce the occupation zone model [10]. Node X_0 can transmit data to node X_i if the following condition is hold.

$$\mid X_j - X_0 \mid \geq \Delta \mid X_i - X_0 \mid \; (i \neq j) \tag{3}$$

Here, Δ is the occupation ratio and X_0 occupies a circular zone, that is the occupation zone, whose radius is $\Delta \mid X_i - X_0 \mid$ during its transmission. When a source node transmits data to its nearest neighbor, its radio wave also impacts communication of nodes in the occupation zone. As shown in Fig. 1, Eq. (3) indicates that a source node can transmit when there is only its nearest neighboring node in the occupation zone. In the analyses given in Section III, we use this model because of its simplicity.

We note here the relation between SIR and occupation zone models. On our investigation, the probability that a receiver node fulfills Eq. (2) when the corresponding sender node satisfies Eq. (3) depends on the parameters in Eqs. (3) and (2). For example, it becomes 99.2% in the case of $\alpha = 4$, $\beta = 6$, $N_0 = 0$, $N = 1000$ and $\Delta = 1.4$. Thus, if a sender node fulfills Eq. (3), it is highly possible that the corresponding receiver node fulfills Eq. (2). Although we consider this effect in the following evaluations, we plan to study on the detail of the validity of the occupation zone model as future work.

III. DERIVATION OF THE OPTIMAL COMMUNICATION DISTANCE TO MAXIMIZE THE NETWORK CAPACITY

In this section, we derive the optimal communication distance to maximize the network capacity when all nodes take the same communication distance. We assume that a node can transmit data when it fulfills Eq. (3) with its nearest neighbor. We define the network capacity as successful probability P of communication between these two nodes. In what follows, we analyze the optimal communication distance to maximize P. Then, we verify the accuracy of our analysis and show the effectiveness of our proposal by simulation experiments.

A. Analysis

Suppose that the number of nodes is N. We assume that the area is a circle with radius R_{eq}, a node x exists at the center, and other $N-1$ nodes are uniformly located in the area.

Because x can transmit data to its nearest neighbor within the distance of r only when other $N-2$ nodes don't exist within Δr, P is expressed as follows.

$$P = {}_{N-1}\mathrm{C}_1 P_r(1) P_{\Delta r}(0)^{N-2} \quad (4)$$

Here, $P_r(1)$ is the probability that a node exists within r from x and $P_{\Delta r}(0)$ is the probability that a node don't exist within Δr from x. These are expressd as follows.

$$P_r(1) = \int_0^{2\pi} \int_0^{r} f_{r,\theta} dr d\theta$$

$$P_{\Delta r}(0) = 1 - \int_0^{2\pi} \int_0^{\Delta r} f_{r,\theta} dr d\theta$$

Here, we regard the area as a polar coordinate system in which node x is located at the center. $f_{r,\theta}$ is the probability that a node is on (r,θ) (See the details of the derivation of $f_{r,\theta}$ in Section A). By substituting Eq. (13) , $P_r(1)$ and $P_{\Delta r}(0)$ becomes as follows.

$$P_r(1) = \left(\frac{r}{R_{eq}}\right)^2 \quad (5)$$

$$P_{\Delta r}(0) = 1 - \left(\frac{\Delta r}{R_{eq}}\right)^2 \quad (6)$$

Hence, P is expressed as follows.

$$P = {}_{N-1}\mathrm{C}_1 \left(\frac{r}{R_{eq}}\right)^2 \left\{1 - \left(\frac{\Delta r}{R_{eq}}\right)^2\right\}^{N-2} \quad (7)$$

According to Section A, the expectation of physical distance between two adjacent nodes is proportional to $\frac{1}{\sqrt{N}}$. Therefore, we replace r by $\frac{\alpha}{\sqrt{N}}$ (α is a constant number). We further define β as $\left(\frac{\Delta r}{R_{eq}}\right)^2 = \frac{\Delta^2 \alpha^2}{R_{eq}^2 N}$. Consequently, Eq. (7) is expressed as follows.

$$P = \frac{1}{\Delta^2} {}_{N-1}\mathrm{C}_1 \beta \{1-\beta\}^{N-2} \quad (8)$$

Since $0 < \beta < 1$, β decreases with the growth of N, and $\lim_{N\to\infty} \beta N$ becomes constant, the binomial distribution in Eq. (8) is approximated by the following poisson distribution

$$P = k e^{-\Delta^2 k} \quad (9)$$

where $k = \frac{\alpha^2}{R_{eq}^2}$. From Eq. (9), the maximum of P and the corresponding α are expressed as follows

$$P_{opt} = \frac{1}{\Delta^2 e} \quad (10)$$

$$\alpha_{opt} = \frac{R_{eq}}{\Delta} \quad (11)$$

From $\alpha = r\sqrt{N}$, the distance to maximize P is expressed as follows

$$r_{opt} = \frac{R_{eq}}{\Delta\sqrt{N}} \quad (12)$$

Results shows that P_{opt} depends on only the occupation ratio Δ. Therefore, if a node takes the optimal communication distance, P_{opt} is independent of N. In addition, P_{opt} is inversely proportional to the square of Δ.

Here, we define the node density as $d = \frac{N}{\pi R_{eq}^2}$. Since r_{opt} is expressed to $\frac{1}{\Delta\sqrt{\pi d}}$, r_{opt} depends on d. Since it is difficult for a node to obtain the information on the whole area, it has to estimate d based on locally obtained information. If all nodes are uniformly distributed in the area, the node density throughout the area equals to that in a part of the area. In this case, we expect that a node can estimate d. However, in realistic situations, the node distribution is more complex than the uniform one. By combining with the clustering method, e.g., LEACH [11], we expect that the clusterhead can calculate the node density in its cluster and notify its cluster members. Compared to calculation of the distance between two nodes, that of the number of nodes in a certain range is considered relatively easy. We would like to study on the detail of the mechanism as future work.

Someone may predict that r_{opt} is the same as the average distance r_{nr} between two arbitrary nodes. We derive r_{nr} as $\frac{2\sqrt{2}}{3\sqrt{N}} R_{eq}$ (the derivation process is described in Section A. In fact, $r_{opt} = \frac{3\sqrt{2}}{4\Delta} r_{nr}$ that is nearly equal to $\frac{1}{\Delta} r_{nr}$.

Finally, we examine the differences between Eqs. (8) and (9) to verify the accuracy of the approximate expression Eq. (9). We found that the differences were at most 1% when N was over 50 and the approximation was valid.

B. Simulation experiments

To verify the accuracy of our analysis in Subsection III-A and to show the effectiveness of our proposal, we simulate the successful probability P of communication between two adjacent nodes when each node takes the communication distance r.

We briefly give the simulation steps as follows.

1) Distribute N nodes randomly in the circular area with radius R_{eq}.
2) Check the achievement of Eq. (3) for each node.
3) Obtain P by calculating the ratio of nodes that fulfill Eq. (3) to N.

Through simulation experiments, we investigate the optimal communication distance r_{opt} by showing the transitions of P according to N, Δ and r. In the following results, R_{eq} is set to 0.5 and we show the average of 100 simulations.

1) Accuracy of analysis: We verify the accuracy of our analysis by comparing with simulation results. Figure 2 illustrates how P varies according to r in the case of $\Delta = 1.1$ and $N = 10, 100$. Since Eq. (9) is the approximate expression based on the assumption of quite large N, analytical results and simulation results are different in the case of $N = 10$. On the other hand, analytical results and simulation results are approximately consistent in the case of $N = 100$. In addition, when N is small, P is drawn a gentle trajectory in both analytical and simulation results. Furthermore, we find

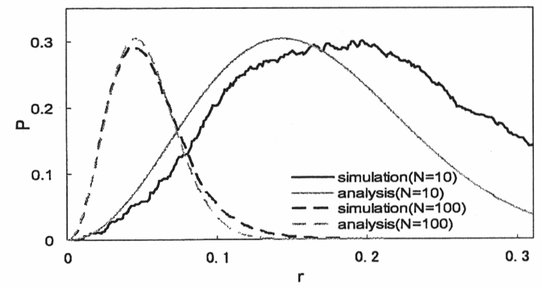

Fig. 2. relation between P and N, r ($\Delta = 1.1$)

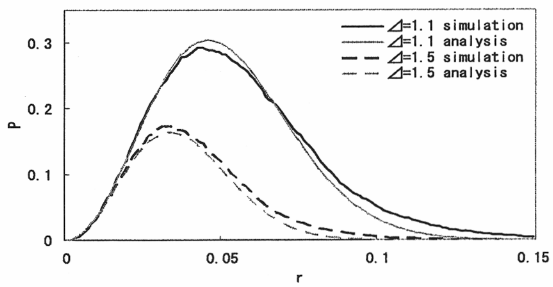

Fig. 3. relation between P and Δ, r ($N = 100$)

the wide range of r attains near P_{opt} in the case of simulation results. We expect that this characteristic is attractive in practical situations since it encourages the insensitivity of parameter settings in our proposal. Furthermore, graphs are asymmetry because the term affecting P changes from β to $\{1-\beta\}^{N-2}$ in Eq. (8) with the growth of r. Figure 3 illustrates how P varies according to r in the case of $N = 100$ and $\Delta = 1.1, 1.5$. We also find that the analyses are valid independently of Δ.

Next, we focus on P_{opt} that is the maximum of P. Figure 4 illustrates how P_{opt} and r_{opt} vary according to N in the case of $\Delta = 1.1$. We first find that analytically derived P_{opt} is slightly smaller than simulation-based P_{opt}. The analysis does not suppose a situation where a receiver node simultaneously fulfills Eq. (3) with multiple sender nodes as shown in Fig. 6, In such a situation, it is natural that only one of them can transmit its data to the receiver to avoid radio interference. We consider this assumption in the simulation experiments. However, since the differences between analytical results and simulation results are at most 4%, the analyses are sufficiently useful. On the other hand, the differences of r_{opt} between analytical and simulation results are less than 1% when N becomes over 100. Figure 5 illustrates how P_{opt} and r_{opt} change according to Δ in the case of $N = 100$. Irrespective of Δ, the error degrees of P_{opt} and r_{opt} are 4% and 3% in average.

From above discussion, our analyses are valid in the case of $N \geq 100$. On the other hand, in terms of usefulness, since the trajectory is sharp when N increases as shown in Fig. 2, we guess that controlling r_{opt} is difficult in such a situation. As a practical value of N, for example, LEACH [11] that is one of famous clustering methods assumes practicality $15 \sim 20$ nodes

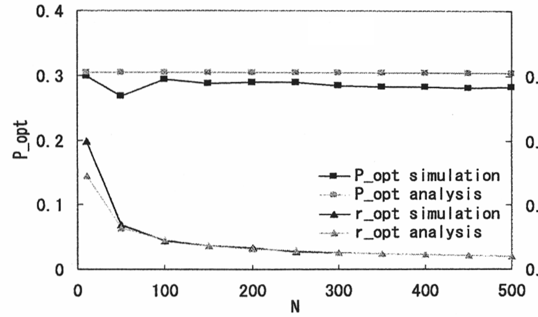

Fig. 4. relation between P_{opt} and N and between r_{opt} and N

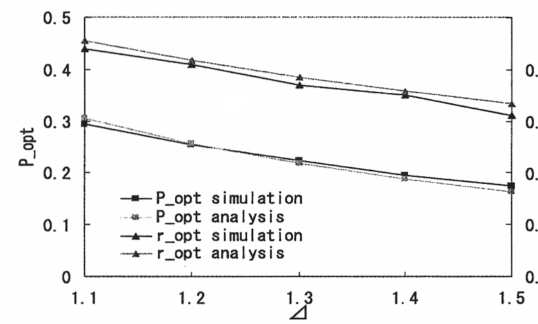

Fig. 5. relation between P_{opt} and Δ and between r_{opt} and Δ

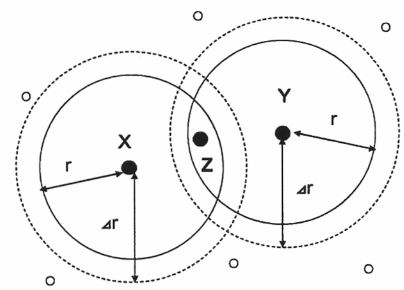

Fig. 6. situation where multiple nodes simultaneously satisfy Eq. (3) with the same node

TABLE I

P_{rv} ($\beta = 6$, $N_0 = 0$, $N = 1000$)

α \ Δ	1	1.1	1.2	1.3	1.4	1.5
3	0.636	0.783	0.863	0.920	0.955	0.969
4	0.869	0.934	0.963	0.981	0.992	0.996

exist in a cluster. We plan to evaluate the practicality of our proposal by implementing it on a real system and conducting several experiments.

2) Comparison with the traditional scheme: We demonstrate the effectiveness of our proposal in terms of the network capacity by comparing with the traditional scheme [1]. In the traditional scheme, the condition of successful communication depends on the value of SIR at the receiver node. For the comparison purpose, based on SIR model, we first derive the probability P_{rv} that a node can receive data when the corresponding sender node fulfills Eq. (3).

Table I indicates how P_{rv} varies in accordance with α and Δ. To conform to [1], we set $\beta = 6$, the background noise power $N_0 = 0$ and $N = 1000$. As shown in Tab. I, P_{rv} becomes higher as α increases. Since α defines the degree of

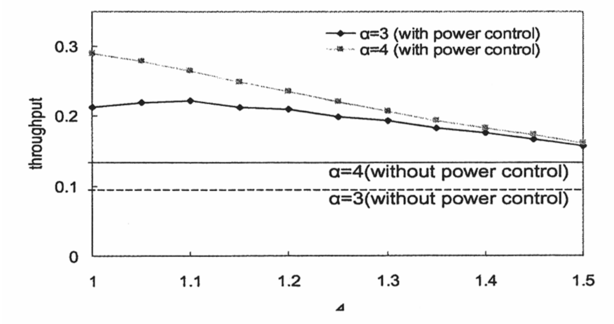

Fig. 7. proposal vs. traditional scheme ($\beta = 6,\ N = 1000$)

signal power decay, a large value of α encourages a node to satisfy Eq. (2). We also find that P_{rv} increases with the growth of Δ. This is because the occupation zone spreads in response to Δ.

Since the product of P_{rv} and P_{opt} is the successful probability of communication that considers both the sender node and the receiver node, it is equal to the long-term throughput of the source node. Figure 7 illustrates the throughput of the proposed scheme and the maximum throughput of the traditional scheme in the case of $\alpha = 3, 4$. Here, we use the simulation results in Ref. [1] as the throughput of the traditional scheme. In the case of $\alpha = 3$, the throughput of the proposed scheme is maximized at $\Delta = 1.1$. On the other hand, that decreases monotonically when $\Delta = 1$. We can conclude that the proposed scheme improves the network capacity up to 2.1 times higher than the traditional scheme by appropriately controlling the transmission power.

IV. Conclusions and Future Works

In this paper, we tried to improve the network capacity by the scheme that a node avoids radio interference among its adjacent nodes by appropriately controlling its transmission power. For that purpose, through analyses and simulation experiments, we derived the optimal communication distance to maximize the network capacity when all nodes take the same communication distance. Results showed that the communication distance to maximize the network capacity depended on the node density. We further showed that the network capacity was independent of the node density. In addition, the proposed scheme could improve the network capacity up to 2.1 times higher than the traditional scheme.

As future works, we plan to combine the proposed scheme with a clustering method, e.g., LEACH and propose an estimation method of the node density in a cluster.

A. Analysis on Expectation of Physical Distance between Two Adjacent Nodes

We give analysis on expectation of physical distance between two adjacent nodes. Suppose that N nodes are uniformly located in a circle with radius R_{eq}. The probability $f_{r,\theta}$ that a node exists in radius r and angle θ from a center becomes $f_r f_\theta$ where f_r is the probability that a node exists in radius r and f_θ is the probability that a node exists in angle θ. f_r is expressed as $f_r = cr$ using the constant number of c, and f_θ is expressed as $f_\theta = \frac{1}{2\pi}$. Since c is derived from $\int_0^{R_{eq}} f_r dr = 1$, we can obtain $f_r = \frac{2r}{R_{eq}^2}$. As a result, $f_{r,\theta}$ is obtained as follows.

$$f_{r,\theta} = \frac{r}{\pi R_{eq}^2} \tag{13}$$

Assume a minute circle with radius x in which two nodes can exist. This can be described as follows.

$$N \int_0^{2\pi} \int_0^{x} \frac{r}{\pi R_{eq}^2} dr d\theta = 2$$

Hence, we derive the following equation.

$$x = R_{eq}\sqrt{\frac{2}{N}} \tag{14}$$

We further obtain the average distance R between the center and an arbitrary node.

$$\begin{aligned} R &= \int_0^{2\pi} \int_0^{x} r \frac{r}{\pi x^2} dr d\theta \\ &= \frac{2}{3}x \end{aligned} \tag{15}$$

Since R equals the average distance r_{nr} between two arbitrary nodes in a minute circle, r_{nr} is expressed as follows.

$$r_{nr} = \frac{2\sqrt{2}}{3\sqrt{N}} R_{eq} \tag{16}$$

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