Setting Radio Transmission Range Using Target Problem to Improve Communication Reachability and Power Saving

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Abstract. Ad hoc networks can be composed entirely of mobile wireless terminals, and do not require permanent network infrastructure such as access points. They are considered a useful network configuration technology for various situations. For example, they are used to construct sensor networks in which distributed, inexpensive sensors monitor environmental conditions such as temperature and humidity. Further, ad hoc networks can be implemented after severe disasters that have disabled other network infrastructures. In general, ad hoc network terminals are battery powered. Therefore, extending network lifetime by reducing terminal power consumption is an important issue in ad hoc network management. One method for reducing power consumption involves reducing the radio transmission range of each terminal. However, reducing the radio transmission range causes degradation in the reachability of each terminal. In this paper, we propose a method to set ad hoc network radio transmission ranges using a *Target problem*, to reduce power consumption and increase each terminal's reachability. Next, we evaluate our method using various routing protocols, and define the applicability of our proposed method for each protocol. Simulation results show that the proposal improves communication reachability and power savings in ad hoc networks with normally distributed terminals, when the Destination-Sequenced Distance-Vector (DSDV) routing protocol is used.

Keywords: ad hoc network, power saving, reachability, target problem.

1 Introduction

Ad hoc networks [1] are used in many situations because they can be constructed autonomously, without network infrastructures such as access points (APs). In times of peace, for example, ad hoc networks are used to configure sensor networks [2] for environmental monitoring; they are also used in geocast communications systems [3], which distribute data among all terminals in a geographic area. Moreover, they are employed in vehicle-to-vehicle (V2V) communications [4] to

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deliver information regarding traffic congestion and accidents. In contrast to ad hoc networks, infrastructure mode networks may suffer severe damage during large-scale disasters such as tsunamis or earthquakes. In these situations, infrastructure mode networks may lose their ability to communicate. However, ad hoc networks can communicate because they are not dependent on network infrastructures [5].

In general, terminals in an ad hoc network (such as smartphones and tablets) are battery powered. Terminals in an ad hoc network send data packets and also act as packet relay nodes. Thus, compared to an infrastructure mode network, power consumption must be suppressed as much as possible. Ad hoc network terminals are unable to work rapidly if their power consumption is reduced. As a result, the network structure becomes extremely sparse, and the terminal's reachability is impeded. Therefore, extending network lifetime by reducing terminal power consumption is an important issue in ad hoc network management. As a possible solution, the power consumption of terminals can be restrained by reducing their radio transmission range; however, this solution degrades reachability. Some studies have proposed and evaluated various transmission range management methods [6,7]. If a normal terminal distribution is followed, however, these approaches may not work effectively. In this paper, we propose a method to set the radio transmission range using a *Target Problem* [8]; this method reduces power consumption and increases terminal reachability in ad hoc networks with normally distributed terminals. Moreover, we evaluate the total goodput using 2 routing protocols (Destination-Sequenced Distance-Vector: DSDV [9], Ad hoc On-demand Distance Vector: AODV [10]), and we define the applicability of our proposed method for each routing protocol. Simulation results show that when the DSDV routing protocol is used, the proposed method improves both communication reachability and power savings in ad hoc networks with normally distributed terminals. The remainder of this paper is constructed as follows: Section 2 describes related works. Section 3 provides an overview of the target problem and the method of setting the radio transmission range based on the target problem; subsequently, we evaluate our proposed method in Sect. 4. Finally, Sect. 5 summarizes our paper and discusses future studies.

2 Related Works

In this section, we provide an overview of ad hoc networks and their applications. Furthermore, we discuss the power consumption and reachability issues of ad hoc networks.

2.1 Overview of the Ad Hoc Network

There are two forms of wireless local-area networks (WLANs) based on IEEE 802.11 [11] infrastructure mode and ad hoc mode. In infrastructure mode, WLAN systems contain access points (APs) connected to outside networks via Ethernet, and a number of terminals located within the radio transmission range of the

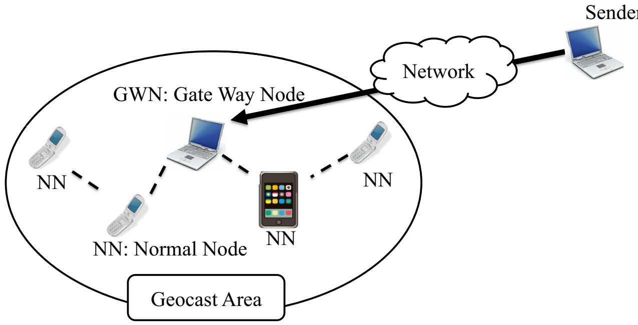

Fig. 1. Overview of geocast communication.

APs. Conversely, networks using ad hoc mode can be configured autonomously using wireless terminals such as laptops and tablets, without network infrastructure such as APs. Moreover, ad hoc mode networks can be configured rapidly and inexpensively. In this paper, we focus on ad hoc mode. In ad hoc networks, there are 2 communication methods, referred to as single-hop and multi-hop. In single-hop communication, each terminal communicates directly (1 hop). Thus, the sender must increase transmission power if the distance between the sender and receiver is relatively long. Therefore, single-hop communication is not suitable for extending ad hoc network lifetime. Conversely, in multi-hop communication, the sender and receiver are not required to communicate directly; packets can be relayed by terminals in between the sender and receiver. In other words, terminals in multi-hop communication networks can receive packets from neighboring terminals. Thus, multi-hop communication is suitable for extending the lifetime of ad hoc networks.

Geocast communications are examples of ad hoc networks. Here, we explain geocast communication, in which data is sent only to terminals in a specified area (referred to as the geocast area: GA) using the terminal's location information. Figure 1 shows components in a geocast communication system. Here, we explain the geocast communication process, using Fig. 1. First, there are 2 types of terminals in a GA gateway nodes (GWNs) and normal nodes (NNs). The GWN is a terminal that connects the GA to other networks outside of the GA. Only the GWN receives information from outside networks; the received information is delivered to the NNs in the GA by the GWN. In geocast communication, a terminal outside of the GA (Sender in Fig. 1) sends information to the GWN of the GA, in order to communicate with an NN inside the GA. The GWN sends its received information to NNs in the transmission area of the GWN, and the NN can also send its received data to other NNs.

We describe the following examples of geocast communication applications:

1. Send warning messages in the event of a disaster
2. Delivery of traffic information such as traffic congestion and accidents using V2V.
3. Delivery of information for residents in a specific area

2.2 Power Consumption and Reachability Issues of Ad Hoc Networks

In this section, we describe the power consumption and the reachability issues of ad hoc networks. Note that we assume the sending of emergency evacuation information during a disaster. In emergency situations, the information from the GWN must be received by all NNs that exist in the GA, because users are sending urgent information. That is, all NNs in the GA must be able to communicate with the GWN using single-hop or multi-hop communication. However, the transmission range of the terminals may be not sufficient if it was set haphazardly; in this case, an NN may not be able to connect to an NN that is communicating with the GWN. As a result, the NN is isolated from the GWN (isolated terminal). The isolated terminal cannot receive information from the GWN, and cannot send the information outside of the GA.

One solution for this issue is to extend the radio transmission range. Using this solution, it is possible to create an environment in which all NNs can transmit and receive information. However, terminals in the ad hoc network are, in general, battery powered. In addition to transmitting and receiving packets, terminals in an ad hoc network relay packets for other terminals. Thus, terminals consume more battery power if power consumption is not suppressed as much as possible. Terminal batteries are rapidly depleted, and network lifetime is shortened (by increasing the number of the terminals in which battery depletion is occurring). In particular, having access to the latest information is urgently required during a disaster. Therefore, sufficient network lifetime is required to obtain the latest information. To extend the network's lifetime, its power consumption must be reduced. Consequently, there is the trade-off between the creating an environment in which all terminals can transmit and receive information, and maintaining sufficient battery power. However, both *network power savings* and *communication reachability* are important goals in the management of geocast communications for ad hoc networks. In order to solve this issue, various studies have proposed transmission range management methods. For example, [6] shows the optimum transmission range in chain networks, and [7] suggests the designing method of transmission range based on the energy efficiency in simple network model. If a normal terminal distribution is followed, however, these approaches may not work effectively.

3 Setting the Radio Transmission Range Based on the Target Problem

In this section, we provide an overview of the 2 dimensional target problem [8]. Furthermore, we describe the method of setting the radio transmission range based on the target problem, to improve power savings and terminal reachability in ad hoc networks.

3.1 Overview of the 2 Dimensional Target Problem and Its Application to Single-Hop Communication

The nodes appear equivalent to the arrows that an archer shoots at a target. The hit points have a probabilistic characteristic. The 2 dimensional target problem considers the distribution of hit points. Random variables X_i $(i = 1, 2, \cdots, n)$ are independent of each other, and the normal distribution has variance σ_i^2 and average μ_i. Random variable Z is defined as Eq. (1):

$$Z = \sum_{i=1}^{n} \left(\frac{X_i - \mu_i}{\sigma_i} \right)^2 \tag{1}$$

Z has χ^2 distribution for which flexibility is n. This indicates that the sum of the squares of independent random variables that follow standard normal distribution $N(0, 1)$ has a χ^2 distribution. In other words, the distribution of the squared sums of the distances between the hit points and the origin of the space has a χ^2 distribution. In the 2 dimensional target problem, distribution of the distances is important. We consider the χ distribution as the square root distribution of the χ^2 distribution. That is, the square root of the squared sum of distances from the origin to the hit point. Thus, the distribution of the distances from the origin indicates a χ distribution if flexibility n yields each component of the Cartesian coordinates (Fig. 2). Therefore, in the 2 dimensional target problem, the arrow's hit probability takes a χ distribution if the size of the target is known and the neighboring distribution of the hit points forms a normal distribution. As an example, we assume a target with a radius of R, whose origin is the center of a 2 dimensional plane. Hit probability $F(R)$ has a χ distribution; its flexibility is 2 when the neighboring distribution of hit points follows a 2 dimensional $N(0, \sigma^2)$. In other words, it follows a Rayleigh distribution as below:

$$F(R) = 1 - \exp\left(-\frac{R^2}{2\sigma^2} \right) \tag{2}$$

Moreover, the probability that the hit point is outside of the target (miss probability) $Y(R)$ is expressed by the complementary distribution of Eq. (2) $(1 - F(R))$:

$$Y(R) = \exp\left(-\frac{R^2}{2\sigma^2} \right) \tag{3}$$

Next, we explain the application of the target problem in geocast communication systems. We assume that the GWN's transmission range is the radius of the target, and that the GWN is located at the center of a GA (origin $(0, 0)$). The probability $Y(R)$ that an NN in the GA cannot connect to the

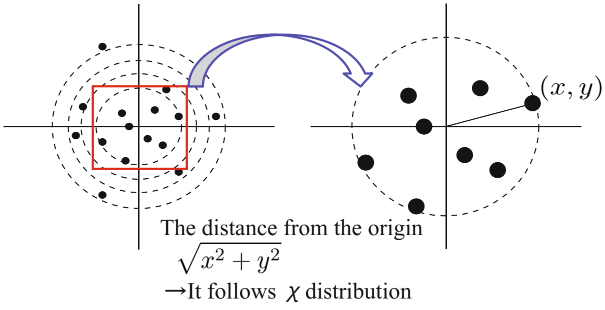

Fig. 2. Relationship between the distance from the origin and the χ distribution in the 2 dimensional target problem

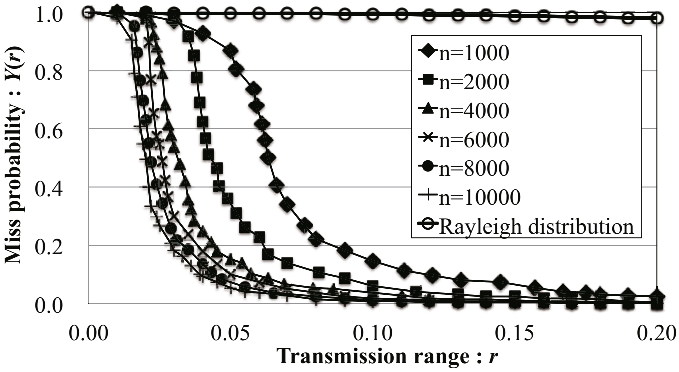

Fig. 3. Relationship between the transmission range r and miss probability for each n ($\sigma = 1.0$).

GWN with a single hop is estimated by Eq. (3). Therefore, NNs are placed according to a 2 dimensional normal distribution and the GWN is placed in the center of a geocast area, and the miss probability $Y(R)$ that the NN cannot connect to the GWN with a single hop follows the complementary distribution of a Rayleigh distribution. In the 2 dimensional normal distribution, the NNs are concentrated near the GWN (the GWN is placed where NN density is high). As a specific example, the GWN may be placed in an evacuation center when a disaster occurs. Moreover, when the GWN is placed in a location that will be used as a landmark for users, such as an aircraft [12], many users who can see the GWN move toward it. As a result, the distribution of the users follows a normal distribution.

3.2 Miss Probability Estimation Method in Multi-hop Communication

To facilitate geocast communication in an ad hoc network, it is preferable for the NNs and the GWN to be connected using multi-hop, from the viewpoint of

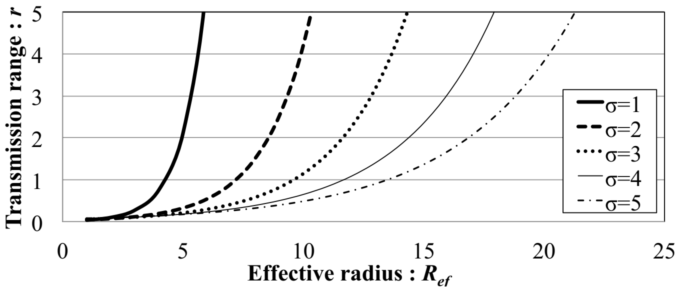

Fig. 4. Relationship between the transmission range r and effective radius R_{ef} for each σ $(n = 1,000)$.

reducing network power requirements. Based on the results from the single-hop environment in the previous section, we model the existence probability of an isolated node (miss probability) in the communication area of the GWN for a multi-hop environment. This problem is a kind of the connectivity problem [13]. Note that the network model is a unit disk graph (UDG), which is a type of intersection graph containing equal-radius circles. Moreover, the GWN is the nearest terminal from the origin.. In this section, as a preliminary experiment, we investigated the relationship between multi-hop miss probability and transmission range, for varying numbers of terminals. We assumed a 2 dimensional plane, and terminals were distributed according to 2 dimensional $N(0, \sigma)$. The numbers of terminals n were set to $(1,000,\ 2,000,\ 4,000,\ 6,000,\ 8,000,\ 10,000)$. In this paper, we shows the results of $\sigma = 1.0$ as an example. Experimental results contain the averages of 30 trials. Figure 3 shows the relationship between the transmission range of each terminal in the multi-hop environment r and the miss probability of terminal $Y(r)$, and Fig. 3 also shows the relationship between r and the complementary Rayleigh distribution. In Fig.3, the vertical axis denotes $Y(r)$ and the horizontal axis denotes r. From Fig.3, $Y(r)$ does not indicate the complementary Rayleigh distribution, regardless of the number of terminals n.

Next, we investigated the relationship between the effective radius R_{ef} and transmission range of each terminal r. R_{ef} can be obtained by adding r and the distance of the farthest terminal that the GWN can connect with using multi-hop. Moreover, it meets $R_{ef} \geq r$. The relationship between R_{ef} and r is obtained as follows. First, we established the transmission range of the GWN in the single-hop environment R as R_{ef}. Next, we compared the miss probability of r in the multi-hop environment and the miss probability of R in the single-hop environment. Then, we investigated the relationship between R_{ef} and r, to determine if the miss probability had the same value. As an example, Figure 4 shows the relationship between R_{ef} and r when n is $1,000$. Note that σ was set to (1.0, 2.0, 3.0, 4.0, and 5.0). As shown in Fig. 4, R_{ef} has an exponential relation with r as Eq. (4):

$$r = \alpha \exp(\beta R_{ef}) \tag{4}$$

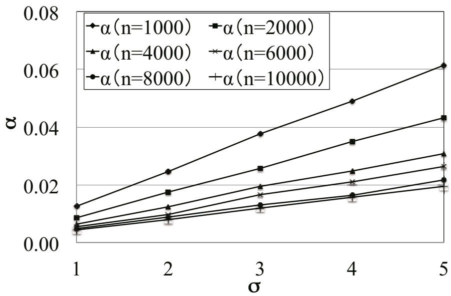

Fig. 5. Relationship betweenα and σ.

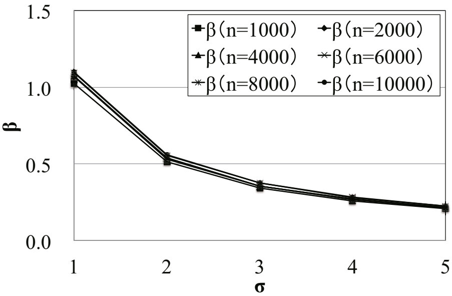

Fig. 6. Relationship between β and σ.

Table 1. Value of $\phi(n)$.

n	1,000	2,000	4,000	6,000	8,000	10,000
$\phi(n)$	0.0123	0.0087	0.0062	0.0053	0.0043	0.0039

We then investigated the relationship between α and σ. Figure 5 is the relationship between α and σ. As shown in Fig. 5, a proportionality relation exists between α and σ ($\alpha = \phi(n)\sigma$). Table 1 shows the value of $\phi(n)$. From Table 1, $\phi(n)$ is described as Eq. (5):

$$\phi(n) = 0.03786n^{0.496} \tag{5}$$

Thus, α can be presented as follows:

$$\alpha = \frac{0.03786\sigma}{\sqrt{n}} \tag{6}$$

Next, Fig. 6 shows the relationship between β and σ. As the figure shows, β is inversely proportional to the σ regardless of n. Moreover, β can be written using σ as follows:

$$\beta = \sigma^{-1} \tag{7}$$

From Eq. (6) and Eq. (7), r is presented using R_{ef} as follows:

$$r = 0.3786\frac{\sigma}{\sqrt{n}}\exp(R_{ef}\sigma^{-1}) \tag{8}$$

By substituting R_{ef}, which was obtained from Eq. (8) for Eq. (3), the existence probability of an isolated terminal (miss probability) in a multi-hop environment for each r can be obtained as follows:

$$Y(R_{ef}(r)) = \exp\left(-\frac{(\log(\sqrt{n}r\sigma^{-1}) + 1)^2}{2}\right) \tag{9}$$

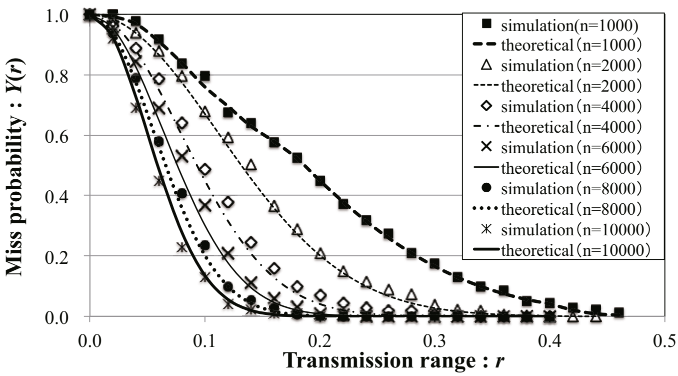

Fig. 7. Comparison of simulation values and theoretical values from Eq. (9) ($\sigma = 1.0$).

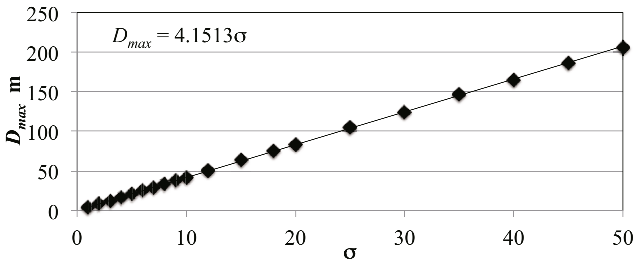

Fig. 8. Relationship between σ and the distance of the farthest node from the GWN.

In other words, the minimum transmission range that satisfies the existence probability of an isolated terminal P can be estimated by Eq. (9). Note that we refer to P as an acceptable miss probability in Sec. 4.

Subsequently, we compared the theoretical formula Eq. (9) and the simulated miss probability values in the multi-hop environment. Figure 7 shows the relationship between r and the miss probability in the multi-hop environment. Note that the values of n and σ are the same as they were in the preliminary experiment. In Fig. 7, the vertical axis shows the miss probability and the horizontal axis shows r. As shown in Fig. 7, Eq. (9) outputs almost the same miss probability as the simulation value. Therefore, Eq. (9) can estimate the miss probability in a multi-hop environment for each r. Here, Fig. 8 shows the relationship between σ and the distance D_{max} between the GWN and the node farthest from the GWN. As shown in Fig. 8, the relationship between σ and D_{max} is obtained as follows:

$$D_{max} = 4\sigma \tag{10}$$

Therefore, σ can be obtained by Eq. (10).

4 Evaluation

In this section, we describe the evaluations of our proposed method using ns2 [14]. We focused on the total goodput and total power consumption. Note that the main purpose of the evaluations was to show the effectiveness of our proposed model equation (Eq. (9)). Therefore, both the number of terminals and σ are known by terminals in our evaluations.

In our evaluation, we assumed a 2 dimensional plane. The sink node was placed at $(0, 0)$, and wireless terminals (senders) were distributed according to 2 dimensional $N(0, \sigma^2)$; the number of senders was 100. This network used an IEEE802.11b (PHY) wireless LAN environment, and UDP (User Datagram Protocol) (with a segment size of 128 byte [15]) for the transport protocol [15]. Moreover, each sender generated 60 seconds of constant bit rate (CBR) traffic (1 Kbps). The routing protocol used DSDV [9] and AODV [10]. We assumed that none of the terminals moved. In this evaluation, terminals consumed battery power when they were connected to the GWN in the multi-hop environment, and power consumption was a normalized value. In the power consumption model for our evaluation, the amount of electricity used by the terminal for the transmission range r was proportional to the square of r [16], and terminals used electricity equal to 0.001 when r was 0.01. That is, terminal power consumption was increased 4 times when r was doubled. Moreover, total power consumption was the sum of the power consumption for terminals that could communicate with the GWN, using multi-hop in one unit time. In addition, the acceptable miss probability P was 0.1% (to obtain r which satisfied P, we calculate $Y(R_{ef}(r)) = 0.001$); the simulation results contain the averages of 20 trials.

Figure 9 shows the relationship between σ and the total goodput for each r when the DSDV routing protocol was used. In Fig. 9, the vertical and horizontal axes represent the total goodput and σ, respectively. Note that "proposed" in Fig. 9 is the transmission range set by Eq. (9), and proposed meets P. As

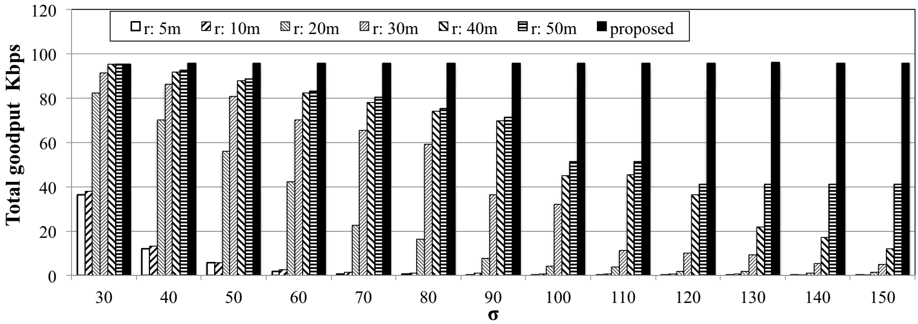

Fig. 9. Total goodput for each σ ($n = 100$, DSDV).

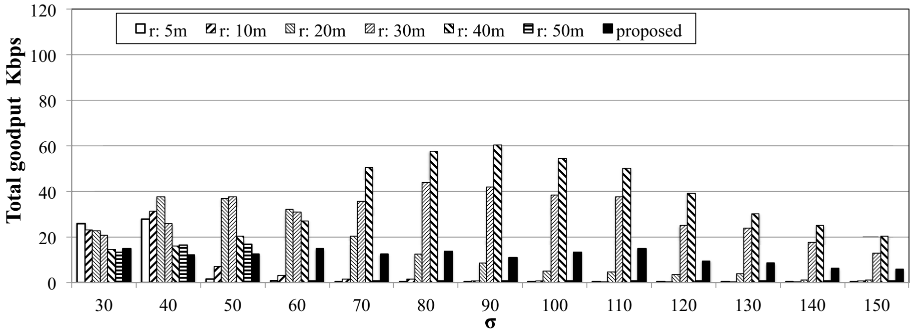

Fig. 10. Total goodput for each σ ($n = 100$, AODV).

shown in Fig. 9, when r m was fixed, the total goodput decreased if σ increased. This occurred because terminals were widely distributed across the area when σ increased. Therefore, the number of terminals that could not connect to the GWN increased if r was fixed. On the other hand, total goodput in each σ was highest when r was set to the proposed m. Our method set the transmission range for each σ in order to meet P. As a result, the proposed method improved communication reachability when DSDV was used as the routing protocol.

Figure 10 shows the relationship between σ and the total goodput for each r when AODV was used. In the figure, the vertical and horizontal axes represent total goodput and σ, respectively. Fig. 10 also represents the proposed transmission range, which was set by Eq. (9). The figure also shows that total goodput was lower than the results produced using DSDV. This decrease was caused by the placement of terminals, and the fact that AODV is a reactive protocol. In our evaluations, terminals were distributed according to a 2 dimensional $N(0, \sigma)$. That is, terminals were concentrated near the sink node. Here, a path for the sink node was generated according to the routing table, which was constructed by exchanging distance vectors with broadcasts in DSDV. Moreover, the topology near the sink node was constructed in a similar manner to a mesh network. Even if a node near the sink lost information it received from a node, it was possible to obtain that information from another neighboring node. Conversely, in AODV, a sender broadcasts a route request (RREQ) packet and receives a route reply (RREP) packet from the sink or other terminals that have already found a path to the sink during the routing path configuration process. In our evaluations, however, terminals were distributed according to a 2 dimensional $N(0, \sigma)$. Therefore, frame collisions that included AODV control packets occurred frequently near the sink. Moreover, CSMA/CA congestion frequently occurred when terminals were densely located, and a significant amount of time was required to exchange AODV control packets. As a result, goodput decreased when AODV was used for the routing protocol. For this reason, network performance decreases when the transmission range is expanded and terminals are densely distributed (similar to a normal distribution), and reactive routing protocols such as AODV are used. This is known as a type of exposed node prob-

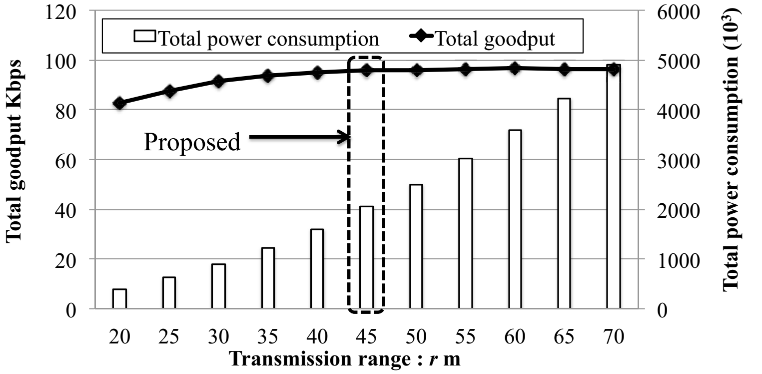

Fig. 11. Relationship between the transmission range r and both the total power consumption and total goodput ($\sigma = 30.0$, DSDV).

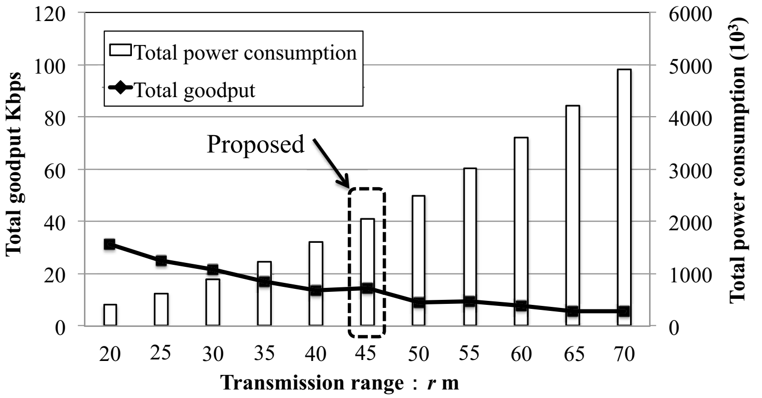

Fig. 12. Relationship between the transmission range r and both the total power consumption and total goodput ($\sigma = 30.0$, AODV).

lem [17]. Therefore, the use of AODV is unsuitable for setting the communication radius using our proposed method.

Next, Fig. 11 shows the relationship between r and both the total power consumption and total goodput when σ is set to 30 and DSDV is used. In Fig. 11, r is shown within the 25 m ranges before and after proposed (approximately 45.4 m). Total goodput was improved along with the increase in power consumption (until proposed was reached). However, total goodput was not improved to the same extent when the transmission range extended beyond proposed; only the total power consumption increased. Therefore, the transmission range that was obtained by the proposed method improved both communication reachability and terminal power savings when the DSDV routing protocol was used. Finally, Fig. 12 shows the results of a similar experiment using AODV. In this experiment, goodput was improved by using transmission ranges narrower than the proposed range. This is because the exposed node problem is restrained by reducing the number of adjacent terminals for each node, which is achieved by narrowing the communication radius. As a result, the exchange of AODV control packets is achieved easily. From the viewpoint of increasing ad hoc network uptime, setting the terminal transmission range using the target problem was very effective. Further, by using simulation experiments, we demonstrated that our method can improve communication reachability when DSDV is used for the routing protocol.

5 Conclusion

In this study, we proposed a method to set the radio transmission range using a target problem, in order to improve both the communication reachability and power savings for each terminal. We evaluated our method using ns2, from the viewpoint of both the total goodput and total power consumption. Moreover, we compared the results obtained by our proposed method and results obtained by setting a fixed value for the communication range. From the simulation results, we demonstrated that setting the communication range using our method can provide significant improvements in goodput and power savings when DSDV is used as the routing protocol. Furthermore, when AODV was used as the routing protocol, our method caused total goodput to decrease drastically. Future works will include the following evaluations.

1. Evaluations considering the joining and leaving of terminals
2. Evaluations considering more realistic power consumption model

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