Theoretical Performance for the Transmit Power in Multi-hop Wireless Networks

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***Abstract*— In the future, a very large amount of transmitted power is required to realize transmission rates such as 1Gbps. As a solution to this problem, multi-hop communications have received much attention. In this paper, we theoretically derive a closed form expression for the transmitted power in linear multi-hop networks. Moreover, we showed the validity of the proposed method by comparing the theoretical performance with computer simulations. For the parameters we used in our evaluation, we could show that 1.14 [W] less transmitted power is required to transmit the same amount of data when there are 5 relay nodes compared to direct communication. In the future, we wish to analyze the power of the whole multi-hop network including the power consumption of the terminal.**

Keywords—Multi-hop Wireless Networks; Transmit power; Shadowing; Theoretical Expression

I. INTRODUCTION

Recently, the super high speed wireless transmission technology, such as 100M-1G bps has been expected [1]. However, as the transmitted power of the terminal must be increased in proportion to the data rate, a very large transmitted power is required to realize such a 1G bps transmission rate. However, as the transmitted power of the terminal must be increased in proportion to the data rate, a very large transmitted power is required to realize such a 1Gbps transmission rate. As a solution to this problem, multi-hop communications have received much attention [2]-[4]. In figure 1, the concept of direct (single-hop) communication and multi-hop communication is shown. A multi-hop network transmits the data packets through some relay nodes. In the case of equidistant transmission, it can achieve lower transmission power than a single-hop network, because the transmission power decreases in inverse proportion to the square (or more) of the distance. It is generally known that the transmission power decreases as the number of relay nodes increases. On the other hand, the relay nodes also have their own power consumption that does not contribute to transmission. So, we focus on the fact that the total power of the whole network consists of the transmitted power and the consumed power. Our final goal is that we theoretically show the effectiveness of multi-hop networks in terms of power consumption.

In [5], a relay station (RS) transmission power control (TPC) scheme that jointly considers the routing and MAC issues are proposed and evaluated. However, the impact on the physical layer is not discussed. In [6], theoretical analyses for power consumption in multi-hop networks are shown, for the case when only pass loss is considered. However, it does not take into account the electric power attenuation due to obstacles such as buildings, which is called shadowing. Shadowing has a spatial correlation over a comparatively wide range [7]. Therefore, when service area expansion of a cellular system is done using a multi-hop connection, the relay station sometimes cannot connect as a result of shadowing. So, it is important to evaluate the performance of multi-hop networks with shadowing considerations.

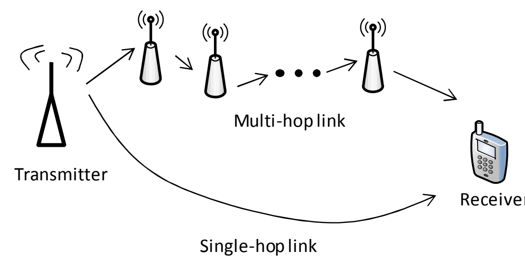

Fig.1 The concept of multi-hop communication.

In this paper, we theoretically derive a closed form expression for the transmitted power in linear multi-hop networks. Moreover, we show the validity of the proposed method by comparing the performance obtained from the derived theoretical expression with computer simulations.

The rest of our paper is organized as follows. In section 2, we derive a closed form expression for the transmitted power. In section 3, we evaluate the derived theoretical performance using computer simulations. Finally, we present our conclusions in section 4.

II. DERIVATION OF A CLOSED FORM EXPRESSION

As shown in figure 2, the wireless radio environment performance is a combination of the next three phenomena, path loss, shadowing, and multi-path fading [7]. In this study, from the previously described purpose, we consider only path loss and shadowing, which is case (B) in fig.2. So, we assume the multi-path fading is ideal.

A. ***Direct (Single-hop) communication***

When the random attenuation due to shadowing is taken into consideration, the received power at a distance *d*, $P_r(d)$ can be expressed by (1) using logarithms [7].

$$P_r(d)\ [dB] = P_t\ [dB] + K[dB] - 10\gamma\log_{10}\left(\frac{d}{d_0}\right) - \Psi \quad (1)$$

Here, P_t is the transmitted power, d_0 is the standard distance and K is propagation loss at distance d_0. The path loss coefficient γ is a value decided by the communication environment. It is shown in table 1 [7]. Here, ψ is a Gaussian distributed random variable a mean of 0 and a variance of σ^2. The shadowing deviation σ is a value decided by environment. It is shown in table 2 [7].

Well, the outage probability is a probability, $P_{out}(P_{min},d)$ which the received power in the distance d, $P_r(d)$ is smaller than a threshold value, P_{min}. It is expressed by (2).

$$P_{out} = P(P_r(d) \le P_{\min}) \quad (2)$$

The P_{out} in both a path loss and shadowing environment is expressed by (3).

$$P_{out} = 1 - Q\left[\frac{P_{\min} - \left\{P_t + 10\log_{10}K - 10\gamma\log_{10}\left(\frac{d}{d_0}\right)\right\}}{\sigma}\right] \quad (3)$$

Here, Q-function, $Q(z)$ is a probability a Gaussian distribution variable of an average 0 and distribution 1, X is larger than z. It is expressed by (4).

$$Q(z) = P(X > z) = \int_z^{\infty} \frac{1}{\sqrt{2\pi}} e^{\left(\frac{-y^2}{2}\right)} dy \quad (4)$$

Therefore, when *invQ(z)* is an inverse function of Q-function, *Q(z)*, the transmit power P_t, which is necessary to send data to the terminal at the point of the distance d is expressed by (5).

$$P_t = P_{\min} K^{-1}\left(\frac{d}{d_0}\right)^{\gamma} 10^{-\left[\frac{\text{invQ}\{(P_{out}-1)\sigma\}}{10}\right]} \quad (5)$$

B. ***Multi-hop communication***

We assume the multi-hop network whose number of relay terminals are n in alignment as shown in figure 3. As the number of times of relay is n+1 from the transmitted terminal to the received terminal, a distance of one-hop, d_{1hop} is expressed by (6).

$$d_{1\text{hop}} = \frac{d}{n+1} \quad (6)$$

From the expression (5) and (6), the transmitted power per one-hop, P_{t-1hop} is expressed by (7).

$$P_{t-1hop} = P_{\min} K^{-1}\left(\frac{d}{(n+1)d_0}\right)^{\gamma} 10^{-\left[\frac{\text{invQ}\{(P_{out}-1)\sigma\}}{10}\right]} \quad (7)$$

Therefore, transmitted power for the whole network, P_{t-all} is expressed by (8).

$$P_{t-all} = (n+1)P_{\min} K^{-1}\left(\frac{d}{(n+1)d_0}\right)^{\gamma} 10^{-\left[\frac{\text{invQ}\{(P_{out}-1)\sigma\}}{10}\right]} \quad (8)$$

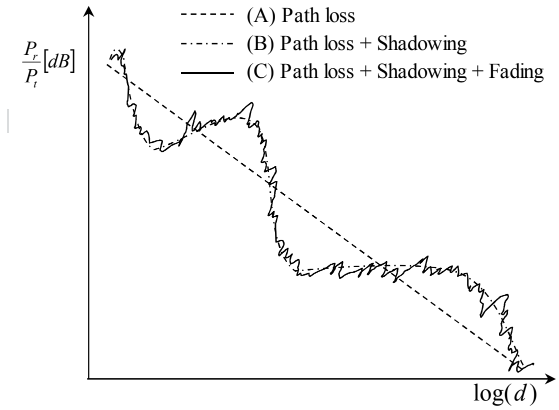

Fig.2 Wireless radio environment [7].

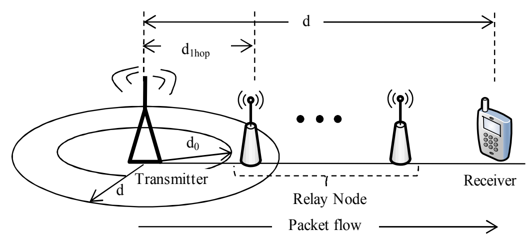

Fig.3 Simulation model.

III. PERFORMANCE EVALUATION

We assume the multi-hop network whose n relay terminals are placed at equal intervals on a straight line between the transmitter and the receiver as shown in fig. 3. Therefore, when the number of relay terminals is one, it corresponds to direct communication (single-hop). We assume the relay terminals are stationary and the environment is outdoor. We evaluate the theoretical performance given by the expression derived in section 2, expressions (5) and (8) using computer simulations with the network simulator, NS2 [8]. We show the simulation parameters in table 3.

Table 1 Path loss exponent γ.

Environment	γ
Urban macrocellular environment	3. 7~6. 5
Urban microcellular environment	2. 7~3. 5
Office building (same floor)	1. 6~3. 5
Office building (different floor)	2~6
Store building	1. 8~2. 2
Factory	1. 6~3. 3

Table 2 Shadowing deviation σ.

Environment	σ[dB]
Outdoor	4~12
Inside of an office (hard interception)	7
Inside of an office(soft interception)	9.6
Inside of an factory,straight route	3~6

*A. **Direct (Single-hop) Communication***

Using expression (5), we determine the transmitted power which is necessary to send data to a terminal at a distance d for any given parameters such as the path loss coefficient *γ* and the shadowing deviation *σ*. Note that the horizontal axis is the logarithm of the distance.

(1) Impact of the path loss coefficient *γ*

We determine the transmitted power which is necessary to send data to a terminal at a distance d by changing the value of the path loss coefficient *γ*. In figure 4, we show the transmitted power as a function of distance and the dependency on the path loss coefficient *γ*. From table 1, we evaluated the performance when the path loss coefficient γ=2.7-3.3 for an urban microcellular environment. As the theoretical value which is obtained by expression (5) and simulation results are almost equal regardless of the path loss coefficient γ, we show the validity of the proposed method. It is necessary to use larger transmitted power when the path loss coefficient γ is larger for a fixed distance d. In particular, when the path loss coefficient γ is large, the slope of the transmitted power curve increases. From this fact, it is necessary to use larger transmitted power when the path loss coefficient γ is larger.

(2) Impact of the shadowing deviation *σ*

We evaluate the transmitted power which is necessary to send data to a terminal at a distance *d* by changing the value of the shadowing deviation *σ*. In figure 5, we show the transmitted power as a function of distance and the dependency on the shadowing deviation *σ*. From table 1, we evaluated the performance when the shadowing deviation σ=5-8 for an outdoor environment. In figure 6, the result of numerical calculations of the outage probability at a distance d=200mm is shown. From fig.5, as the theoretical value which is obtained by expression (5) and simulation results are almost equal regardless of the shadowing deviation *σ*, we show the validity of the proposed method. When the shadowing deviation *σ* is large, larger transmitted power is needed for a fixed distance *d*. However, regardless of the value of the shadowing deviation *σ*, the slope of the transmitted power curve is constant. This phenomenon is different from the case of the path loss coefficient γ, i.e., fig.5. For the parameters we used in our evaluation, we can see that 1.68[W] more transmitted power is required for σ=8 compared to σ=5. From fig.6, the change in outage probability becomes slower as the shadowing deviation increases.

Table 3 Simulation parameters.

Standard	IEEE802.11
Antenna model	Non-directional
Transmit antenna gain *Gt*	1
Receive anntena gain *Gr*	1
Reference distance d_0	10 [m]
Constant *K*	-51.7 [dB]
Data rate	2 [Mbps]
Used frequency	914 [MHz]
Routing protocol	Non

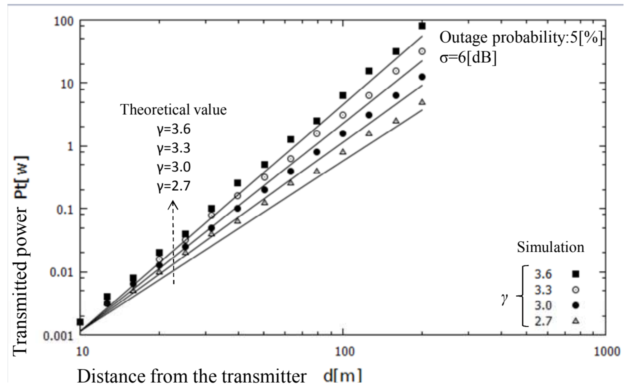

Fig.4 Relationship between distance and transmitted power. (The dependency on the path loss exponent γ)

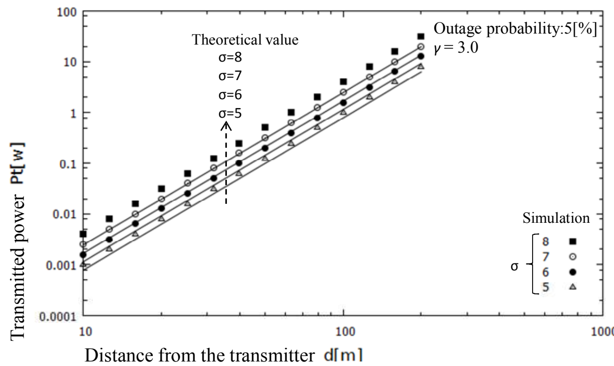

Fig.5 Relationship between distance and transmitted power. (The dependency on the shadowing deviation σ)

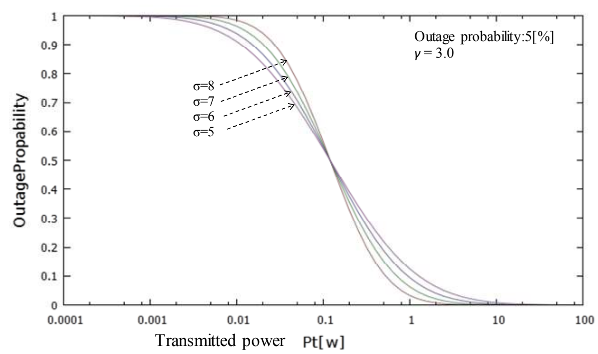

Fig.6 Results of numerical calculations of the outage probability at a distance *d*=200mm.

In other words, as the shadowing deviation *σ* increases, more transmitted power is needed for the same outage probability. This fact corresponds to the previous described fact, fig 5.

(3) Impact of the outage probability P_{out}

We evaluate the transmitted power which is necessary to send data to a terminal at a distance d by changing the value of the outage probability. In figure 7, we show the transmitted power as a function of distance and the dependency on the outage probability. From fig.7, as the theoretical value which is obtained by expression (5) and the simulation results are almost equal regardless of the outage probability, we show the validity of the proposed method. When the outage probability is larger for fixed distance d, less transmitted power is needed. This fact is reasonable from the definition of the outage probability. However, regardless of the outage probability, the slope of the transmitted power curve is constant. This phenomenon is similar to the case of the shadowing deviation σ, i.e., fig.7. For the parameters we used in our evaluation, we can see that 1.83 [W] more transmitted power is required for an outage probability of 1% compared to that of 5%.

B. Multi-hop communication

(1) Impact of the number of relay nodes

When the number of relay nodes is changed for a fixed distance d between the transmitter and receiver, we evaluate the transmitted power which is necessary to send data to a terminal at a distance *d*. In figure 8, we show the transmitted power as a function of distance and the dependency on the number of relay nodes. From fig.8, as the theoretical value which is obtained by expression (8) and the simulation results are almost equal regardless of the number of relay nodes, we show the validity of the proposed method. From fig.8 at fixed distance *d*, less transmitted power is necessary to send data to the terminal when the number of relay nodes increases. Also, regardless of the number of relay nodes, the slope of the transmitted power curve is constant. In this evaluated condition, we can see that 1.14 [W] less transmitted power is required to transmit the same amount of data when there are 5 relay nodes compared to direct communication, i.e., no relay nodes.

IV. CONCLUSION

In the future, a very large amount of transmitted power is required to realize transmission rates such as 1Gbps. As a solution to this problem, multi-hop communications have received much attention. In this paper, we theoretically derive a closed form expression for the transmitted power in linear multi-hop networks. Moreover, we showed the validity of the proposed method by comparing the theoretical performance with computer simulations. In other words, to estimate the transmitted power in multi-hop communications, we could establish a method that uses a theoretical expression. This enables us to determine the required value immediately since our method does not use time-consuming computer simulations. For the parameters we used in our evaluation, we could show that 1.14 [W] less transmitted power is required to transmit the same amount of data when there are 5 relay nodes compared to direct communication.

In the future, we wish to analyze the power of the whole multi-hop network including the power consumption of the terminal.

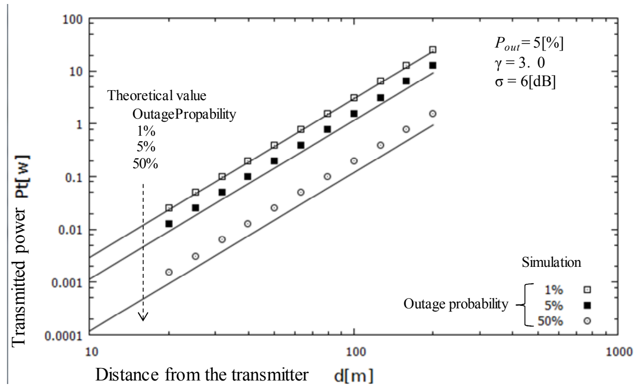

Fig.7 Relationship between distance and transmitted power. (The dependency on the outage probability)

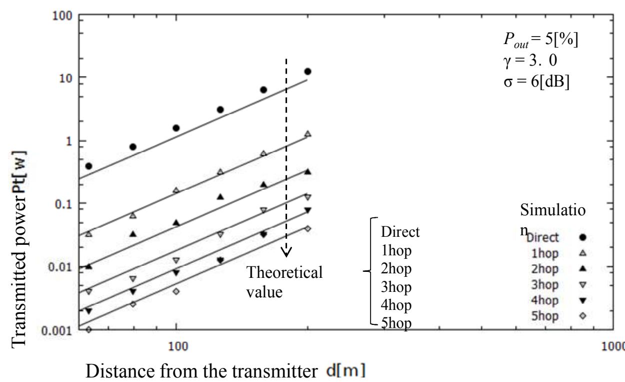

Fig.8 Relationship between distance and transmitted power. (The dependency on the number of relay nodes)

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