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# アドホックネットワークにおける送信電力制御を用いた省電力ルート構築法

萬代 雅希 †　中山 悟志 ‡　渡辺 尚 †
† 静岡大学情報学部情報科学科　‡ 日本電気株式会社

抄録: 本研究では，アドホックネットワークにおける送信電力制御を用いた省電力ルート構築法 PERFECT (Power-efficient routing based on the Function of Energy Computing Time) を提案する．PERFECT では，ルート構築時に RREQ(Route REQest) を転送する際，RREQ を転送するまでの時間を RREQ の受信電力を用いて算出するルーチング方式である．PERFECT は，位置等の制御情報が不要で，異なるアンテナ特性のノードが混在する環境下でも動作可能である．本研究ではさらに，離散的な送信電力制御環境下において，省電力ルート構築可能な拡張方式 D-PERFECT (Discrete-PERFECT) を提案する．理論解析および計算機シミュレーションにより PERFECT および D-PERFECT の有効性を示す．

# Energy-efficient Route Construction Scheme with Transmission Power Control in Wireless Ad Hoc Networks

Masaki BANDAI†,　Satoshi NAKAYAMA‡,　Takashi WATANABE†
†Dept. of Computer Science, Shizuoka Univ.　‡ NEC Corp.

*Abstract—In this paper, we propose a novel routing algorithm constructing a power efficient route called PERFECT (Power-efficient routing based on the Function of Energy Computing Time) in ad hoc networks. In PERFECT, the standby time to forward RREQ (Route REQest) is calculated by the received power of RREQ. PERFECT does not need additional control packets such as position information etc.. Even if some nodes equipped with different characteristic antenna exist together, PERFECT can construct a power efficient route. In addition, we also propose the extended version of PERFECT called D-PERFECT (Discrete-PERFECT) for discrete power control environment. Theoretical and Simulated results show the effectiveness of PERFECT and D-PERFECT.*

## 1 Introduction

The rapid progress in sensor devices and wireless technologies enables ad hoc sensor networks to be realized. They have an advantage that they need no specific predefined infrastructure, so that they are expected to be applicable to a wide variety of fields, e.g. agriculture, environment assessment, civil engineering, disaster mitigation, animal tracking, and so forth. For such applications ad hoc sensor networks are required to provide an effective ways for small nodes to communicate with significant restriction on batteries. Several protocols and methods have been proposed in MAC layer, routing layer, application layer to extend network lifetime and to achieve high power-efficiency [1].

Among them are routing algorithms proposed in [2]-[6]. [2] constructs a route which contains nodes so as to level off residue of batteries of all nodes. However it does not decrease the total battery consumption. Moreover, if a specific path is always used to meet application requirements, these methods fail to level off the batteries. The Friis transmission equation and its extensions indicate that transmission power is in proportion to the n-th (n varies from 2 through 4.) power of the distance between a transmitter and a receiver. That means that shorter distance of a hop greatly decreases transmission power. According to this simple observation, some routing algorithms for constructing a power-efficient route have been also proposed in [3]-[6]. These methods request that a node choose a nearest node as a next hop, which reduces not only transmission power but also exposed nodes along the route from sources to destinations to achieve better throughput because of spatial reuse over time. However, these routing methods require much control traffic to obtain information of neighbor nodes. For example, methods in [4][5] exchange neighbor node's location. Wireless channel condition suffers from multi-path fading, noise, absorption, diffraction, scattering, etc as well as the distance between nodes. Therefore, location information is not sufficient to derive the optimally power-efficient route. Additionally, the proposed methods can not construct the accurate power-efficient route, if nodes have different types of antennas.

In this paper, we propose a novel routing algorithm constructing a power efficient route called PERFECT (Power-efficient routing based on the Function of Energy Computing Time) in ad hoc networks. In PERFECT, the standby time to forward RREQ (Route REQest) is calculated by the received power of RREQ. PERFECT does not need additional control packets such as position information etc.. Even if some nodes equipped with different characteristic antenna exist together, PERFECT can construct a power efficient route. The simulation results show PERFECT can construct more power-efficient route than a mostly related method, i.e. DPER. Moreover, this paper proposes an extended version of PERFECT called D-PERFECT (Discrete PERFECT) for a discrete power control environment, where the network interface can control transmission power not continuously but in a step-wise manner. Theoretical and simulation results show D-PERFECT can construct more power-efficient route than PERFECT in a discrete power control environment.

## 2 Related Works

In order to extend network lifetime, [2] constructs a route which contains nodes so as to level off residue of batteries of all nodes. Especially, a new power-cost metric based on the combination of both node's lifetime and distance based power metrics is defined. In the proposed routing algorithm, nodes make routing decisions solely on the basis of location of their neighbors and destination. However, these routing algorithms cannot decrease the total battery consumption.

According to the Friis transmission equation, it is known that shorter distance of a hop greatly decreases transmission power. There are some power efficient route construction methods [3]-[6]. PARO (Power-Aware Routing Optimization) is proposed in order to minimize the transmission power between source and destination [3]. In PARO, one or more intermediate nodes called "redirectors" is elected to forward packets even when the source and destination can communicate directly. However, since the intermediate nodes are selected locally, the route between source and destination may become longer.

DPER (Directionality-based Power Efficient Routing) [4] is a routing protocol which constructs a power efficient route by selecting a node locating close to the destination as the next hop. In the route building phase, DPER divides the area into some round areas in which it centers on the destination. The source node selects a node which can communicate with the lowest power, located in the adjoining area for the next hop. In DPER, each sender can select the intermediate node through which the overall route is gradually approached to the destination. However, since DPER needs location information of other nodes, much control traffic is generated. Moreover, the location based routing has a problem which does not reflect the real radio channel condition.

CONSET (CONnectivity SET) [5] is a cross-layer solution to construct a power efficient route. CONSET maintains the CS (Connectivity Set). CS is the most energy efficient set of nodes that guarantee the node's connectivity to the network. When receiving RTS (Request to send), CTS (Clear to send), or Hello, CONSET estimates distance and angle of arrival of the sender node. The node is added into CS if the node is detected first and can communicate with the lowest power directly. CONSET constructs a power efficient route by transmitting RREQ with power which reaches the farthest node in CS. CONSET needs much traffic to estimate the location of neighbor nodes. Moreover, CONSET has a problem of not operating normally in the environment which has nodes equipped with different characteristic antenna.

It is required a simple power efficient routing algorithm reflecting the channel condition and operating with different characteristic antennas, without using position information.

## 3 Proposed PERFECT

In PERFECT, the standby time to forward RREQ is calculated by the received power of RREQ. PERFECT corresponds to the route building phase in DSR (Dynamic State Routing).

### 3.1 PERFECT Algorithm

In PERFECT, there are two phases, route building phase and data transmission phase. The route building phase is shown in Table 1. In

Table 1: PERFECT algorithm

```
When a RREQ reception event occurs:
if (SeqNumTable.isNewest(RREQ) & CalcStnbyTime(RREQ.RxPower) < WaitTimeTable[RREQ]) ||
WaitTimeTable[RREQ] = NULL
    WaitTimeTable[RREQ] = CalcStandbyTime(RREQ.RxPower);

When a timer expiration event occurs:
if RREQ.Destination= this.Address       // If the destination of the RREQ is others
    Broadcast(RREQ);
else                                    // If the destination of the RREQ is itself
    Accept(RREQ);
SeqNumTable.Renew(RREQ);
WaitTimeTableRemove(RREQ);
```

route building phase, when a node receives a RREQ, it calculates the standby time inversely proportional to the received power of the RREQ. The node relays the RREQ with full power when the standby time expires, so that the node with less standby time relays earlier than other nodes receiving the same RREQ, which means that a node with the strongest receiving power dominates in relaying the RREQ in order to create the least power consumption route in data transmission phase. When the destination receives the RREQ, it sends back RREP (Route REPly) to the source along the route. After receiving RREP, nodes are into data transmission phase. In the data transmission phase, the source and intermediate nodes transmit packets with minimum transmission power by power control MAC (Medium Access Control) protocol such as [7].

In PERFECT, additional control traffic to DSR is not generated. PERFECT can construct a power efficient route corresponding to wireless channel condition. If a node equipped with high gain antenna exists, the node is specially handled.

## 3.2 Standby Time

PERFECT calculates the standby time according to the received power of the RREQ. Each node transmits the RREQ after the time expiration. A node calculates smaller standby time when it has received a RREQ with stronger power. Because, the link the RREQ with stronger power passed has possibility that reduces transmission power. The standby time is calculated as follows.

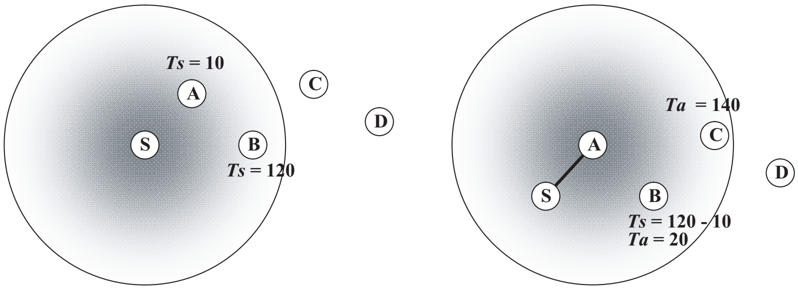
$$T = a\left(\frac{1}{P_r}\right)^b \tag{1}$$

where $P_r$ is the received power of the RREQ, $a$ is a parameter which adjusts the scale of the standby time, and $b$ is a parameter which adjusts the priority of short hop. If the standby time calculated by (1) is smaller than back-off time of the MAC protocol, it may happen to unintended change of the order of RREQ forwarding. We use $a$ to cope with this problem. The large $a$ avoids the influence the back-off time of the MAC protocol and so on. However, too large $a$ causes increasing time of route construction. $b$ adjusts the priority of short hop. A large $b$ reduces the standby time calculated when a strong received power is observed.

## 3.3 An Example Operation

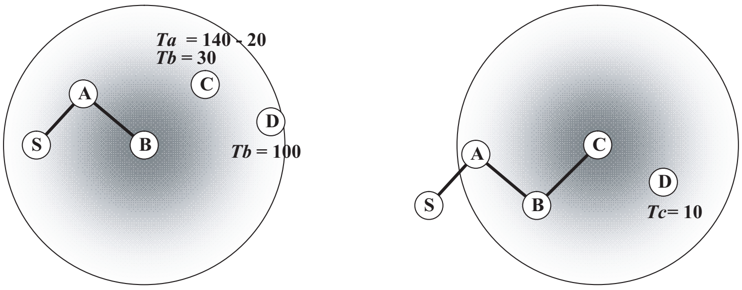
We assume a topology which has five nodes of the same characteristic antenna shown in Fig. 1(a). We assume that the route construction request to node D is generated in node S. Node S broadcasts the RREQ, and nodes A and B receive the RREQ. Nodes A and B calculate $T_s$, the standby time until re-broadcasting the RREQ from node S, according to the received power of the RREQ. Since node A observes a stronger power than node B, node A calculates smaller $T_s$ than node B's $T_s$. We assume node A's $T_s = 10$ and node B's $T_s = 120$.

At $T = 10$, node A expires standby time first, and the RREQ is broadcasted. The RREQ from node A is received by nodes S, B, C as shown in Fig. 1(b). Each node checks the sequence number of the received RREQ. Node S judges the RREQ which was already transmitted by checking the same sequence number, and it cancels the RREQ. Nodes B and C calculate $T_a$, the standby time until re-broadcasting the RREQ from node



(a) Node S broadcasts RREQ.

(b) Node A broadcasts RREQ (T = 10).



(c) Node B broadcasts RREQ (*T* = 30).

(d) Node C broadcasts RREQ (*T* = 60).

Figure 1: An example operation of PERFECT.

A uses the same procedure. We assume node B's $T_a = 20$ and node C's $T_a = 140$.

Then, node B receives two RREQs from node S and from node A. Node B compares the remainder of standby time, $T_s$ and $T_a$, calculated from the received power of RREQs, and the RREQ which has a longer standby time is canceled. In this example, since $T_s = 120 - 10 > T_a = 20$, the RREQ from node S is canceled. As shown in Figs. 1(c) and (d), the above procedure is repeated, and RREQ is forwarded only through the power efficient route $S \rightarrow A \rightarrow B \rightarrow C \rightarrow D$. If node D obtains the RREQ, it accepts the RREQ after the standby time expiration. The route $S \rightarrow B \rightarrow D$ is a route which is constructed by DSR on the same topology.

# 4 Performance Analysis

We analyze the transmission power consumption performance of the proposed PERFECT by means of the analytical method as shown in [8]. In [8], it is shown that the expected one hop distance $z$ depends only on the average neighborhood size $N_{avg}$ when the minimum number of hops between source and destination is selected.

$$z = 1 + e^{-N_{avg}} - \int_{-1}^{1} e^{-\frac{N_{avg}}{\pi}(arccos t - t\sqrt{1-t^2})}dt. \tag{2}$$

In PERFECT, a node which satisfies the following conditions is selected as the next hop.

- Nearest node from the source node

- Nearer node to the destination than the source

In Fig. 2, analytical model of PERFECT is shown. Node A is selected as the next hop because Node A satisfies the above two conditions. The probability that there are no nodes in the dashed area in Fig. 2. The expected one hop distance $z$ in PERFECT is expressed as the following:

$$\begin{aligned} z &= e^{-N_{avg}} \\ &\quad + \int_{0}^{1} e^{-\frac{N_{avg}}{\pi}(arccos t - t\sqrt{1-t^2})}dt \\ &\quad - \int_{-1}^{0} e^{-\frac{N_{avg}}{\pi}(arccos t - t\sqrt{1-t^2})}dt. \end{aligned} \tag{3}$$

In order to determine the expected number of hops $h$, we need to find the average distance

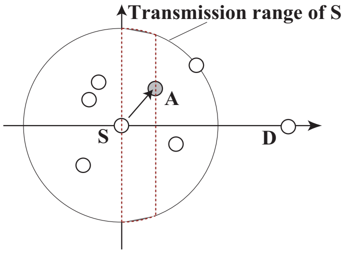


Figure 2: Analytical model of PERFECT.

between any two points in the network. When we assume that the network is situated inside a disc of radius $R$, the expected distance $d$ is shown as follows [8]:

$$d = \frac{128}{45\pi}R. \tag{4}$$

Then, the expected number of hops $h$ is:

$$h = \frac{d}{z}. \tag{5}$$

Generally, the relationship between transmission power $P_t$ and receiving power $P_r$ is shown as the following.

$$P_r = P_t k d^{-3}, \tag{6}$$

where $k$ is a constant from antenna gains $G_t$ and $G_r$ and wavelength of the radio $\lambda$.

$$k = \frac{\lambda^2 G_t G_r}{(4\pi)^2}. \tag{7}$$

Now, we consider when $P_r/k = 1$. The total transmission power $P_{total}$ is the product of the third power of one hop distance $d$ and number of hops between source and destination $h$.

$$P_{total} = d^3 h. \tag{8}$$

In Fig. 3, we show the analytical result of the total transmission power. From this figure, in a low node density, transmission power consumption of PERFECT becomes large. However, in a high node density, transmission power performance improves dramatically. It is considered that as node density becomes high, one hop distance becomes small in PERFECT. Therefore, the power consumption becomes small.

# 5 Performance Evaluation

In this section, we investigate property of PERFECT by computer simulation.

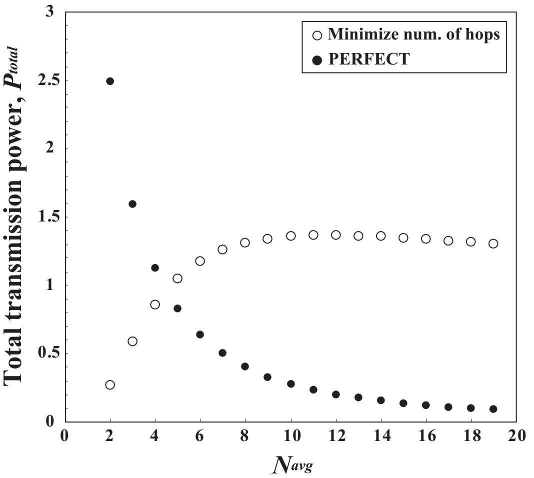


Figure 3: Analytical result of the total transmission power.

Table 2: Simulation assumptions

| | |
|---|---:|
| Attenuation const., $L$ | 3 |
| Antenna gain | 0 [dBi] |
| Max. Power | 15 [dBm] |
| Receive thresh., $Thr$ | -74 [dB] |
| Carrier sense thresh. | -95 [dB] |
| Capture threshold | 10 [dB] |
| Bit rate | 11 [Mbps] |
| Frequency | 2.4 [GHz] |
| MAC protocol | CSMA/CA |
| Space size | 80x20x4[m]x6[floors] |

## 5.1 Simulation Assumption

Simulation assumptions are shown in Table 2. We suggest the building model as simulation space model. Each node is placed on the floor. We evaluate the total transmission power, and the route construction delay. The total transmission power, $P$, is defined as,

$$P = \sum_{h=0}^{H_{max}-1} \frac{Thr_{h+1} L}{Gt_h Gr_{h+1}}, \tag{9}$$

where $Thr$ is the receive threshold, $L$ is the propagation loss of radio channel, $Gt$ and $Gr$ are transmission and reception antenna gain, respectively. $P$ means the lowest ideal total transmission power. $H_{max}$ is the maximum number of hops. The route construction delay, $D$, is defined

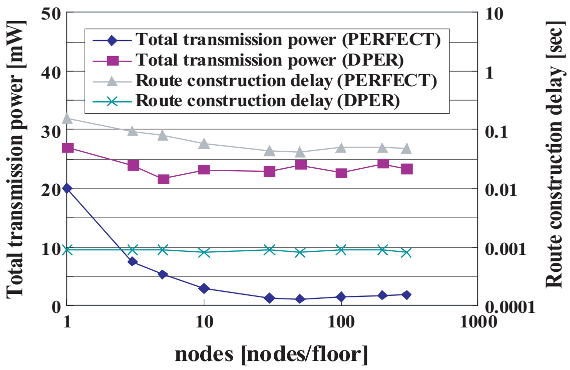


Figure 4: Total transmission power and route construction time in continuous power control environment.

as,

$$D = T_{aceptRREQ} - T_{geneRREQ}, \qquad (10)$$

where $T_{acceptRREQ}$ is the time when the destination accepts the RREQ, $T_{geneRREQ}$ is the time when the source generates the RREQ. $D$ means the delay of one way route construction. In the following simulations, we use empirical parameters: $a = 1E - 6$ and $b = 0.7$.

### 5.2 Performance Comparison

We compare the performance of PERFECT with DPER. Another related work, CONSET can not operate efficiently since RREQs collide with Hello packets, and no RREQs reach the destinations. The simulation results of total transmission power and route construction delay are shown in Fig. 4. Fig. 4 shows that PERFECT is more power efficient than DPER because PERFECT can construct power efficient route. Especially, when number of nodes is large, performance improvement becomes large. The reason is as follows. The transmission power of DPER is almost constant for all number of nodes. In DPER, it is assumed that all nodes have the position information of neighbor nodes. By using the position information, the next hop is selected in adjoining area for the next hop. Nodes calculate appropriate route and unicast RREQ. Therefore, although the number of nodes is large and the number of selectable small hops becomes large, the selected next hop does not change. As result, the transmission power performance is independent from the number of nodes. Contrary, the transmission power of PERFECT becomes small as the number of nodes increases. This is because that in PERFECT, when the number of nodes is large, smaller hops tend to be selected. On the other hand, it is also shown that PERFECT requires longer route construction delay than DPER. This is because that in PERFECT, sufficient large standby time than MAC layer backoff is set for selecting small hop. However, it is considered that this is not deadly drawback since cached information is available after first construction. Note that the standby time does not relate to communication after route construction.

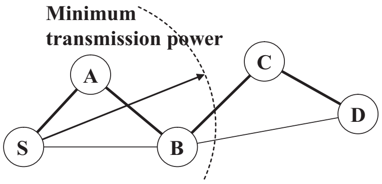


Figure 5: PERFECT in a discrete power control environment.

## 6 Extension for Discrete Power Control

### 6.1 Deterioration in Discrete Power Control Environment

PERFECT assumes the continuous power control (CPC). However, many consumer products control the transmission power discretely. For example 0, 7, 10, 13, 15 [dBm] are available as the transmission powers in Cisco Aironet 350. In such discrete power control (DPC) environment, PERFECT can not achieve high power consumption performance. PERFECT constructs a route S → A → B which contains short distance hops, as shown in thick line in Fig. 5. It is wasteful that node S transmits to node A, despite node B can be received even if node S transmits by minimum transmission power. The performance of PERFECT is deteriorated because of containing such too short hops. D-PERFECT is a method that can select appropriate route, such as S $\rightarrow B$ in Fig. 5 in discrete power control environment.

### 6.2 Discrete-PERFECT

We extend PERFECT to prevent performance deterioration in discrete power control environ-

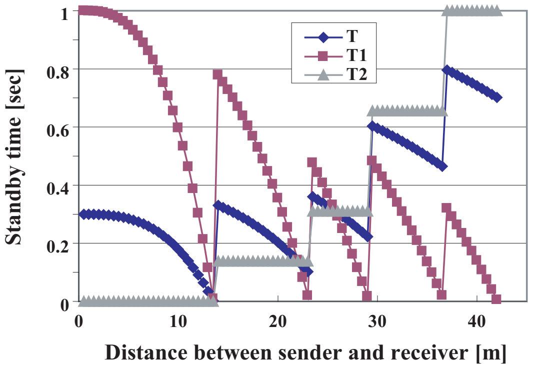


Figure 6: Standby time in discrete power control environment.

ment. We propose an extension of PERFECT called D-PERFECT. D-PERFECT is a method which changes PERFECT with only the standby time calculation. D-PERFECT's standby time calculation has two members, $T_1$ and $T_2$, which have different purposes. $T_1$ is introduced to make outside of each transmission range high priority. $T_1$ is shown in (4),

$$T_1 = T_{max}\left(1 - \frac{P_{desired}}{P_t}\right)^{\beta} \tag{11}$$

where $T_{max}$ is the maximum standby time, $\beta$ is a parameter which changes the characteristic of the equation (4), and $P_{desired}$ is minimum transmission power to communicate between transmitter and receiver. $P_{desired}$ is a function of the received power of RREQ, $P_r$. Nodes transmit RREQ with maximum power, $P_{max}$. Then, the propagation loss of radio channel $L$ is introduced as follows.

$$L = \frac{P_{max}G_rG_t}{P_r}. \tag{12}$$

Therefore, $P_{desired}$ is expressed as

$$P_{desired} = \frac{ThrL}{G_tG_r} = \frac{ThrP_{max}}{P_r}, \tag{13}$$

where $Thr$ is the received power threshold. $P_t$ is the discrete selectable transmission power. Here, we use 0, 7, 10, 13, 15 [dBm] as the discrete transmission power. $P_t$ is the minimum discrete transmission power which exceeds $P_{desired}$.

$$P_t = min\{P | P > P_{desired}\}. \tag{14}$$

$T_1$ is the discrete curve in Fig. 6.

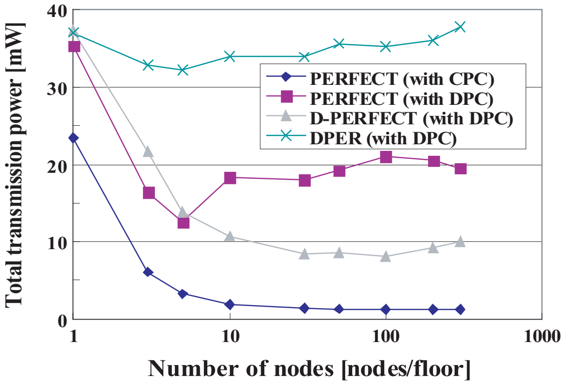


Figure 7: Total transmission power in discrete power control environment.

$T_2$'s purpose is to make near the sender high priority. $T_2$ is shown as follows.

$$T_2 = T_{max}\left(\frac{P_t - P_{min}}{P_{max} - P_{min}}\right)^{\gamma} \tag{15}$$

where $T_{max}$ and $P_t$ are equal to explanation in (4). $P_{min}$ and $P_{max}$ are maximum and minimum transmissions power, respectively. $\gamma$ is a parameter which changes the characteristic of (8). $T_2$ is the discrete curve in Fig. 6.

D-PERFECT selects the node located near the sender and outside of each transmission range to construct a power efficient route in discrete power control environment. Therefore, D-PERFECT calculates the standby time by the following,

$$T = \alpha T_1 + (1 - \alpha)T_2. \tag{16}$$

where $\alpha$ is weight of the priority outside of range. This is the standby time calculation equation in D-PERFECT. $T$ is the discrete curve in Fig. 6.

### 6.3 Performance Comparison

We compare the performance of D-PERFECT with both PERFECT and DPER in discrete power control environment. In the following simulations, we use the empirical parameters $T_{max} = 0.1$, $\alpha = 0.2$, $\beta = 1.0$, and $\gamma = 0.5$.

The simulation results of the total transmission power is shown in Fig. 7. In Fig. 7, it is shown that PERFECT with DPC degrades its performance of power efficiency than PERFECT with CPC. This means that PERFECT with CPC selects too small hops in discrete

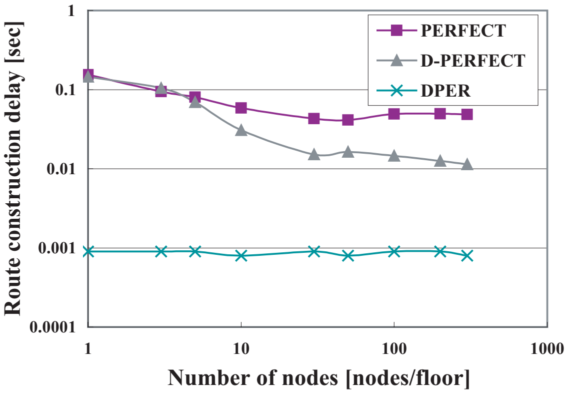


Figure 8: Route construction time in discrete power control environment.

power control environment. It is also shown that both PERFECT and D-PERFECT have better performance than DPER for all conditions of number of nodes. This is because that both PERFECT and D-PERFECT can select small hops for improve power consumption performance. It is also shown that the performance of D-PERFECT with DPC is almost same as PERFECT with DPC in case of small number of nodes, smaller than 8. This is because that number of selectable nodes is small in case of small number of nodes. Therefore, it is considered that the constructed route of both D-PERFECT and PERFECT is not much different. In case of large number of nodes, larger than 8, D-PERFECT can achieve better performance than PERFECT. Especially, the performance of PERFECT degrades as larger number of nodes. The reason is that PERFECT selects too small hops.

The simulation results of the route construction delay is shown in Fig. 8. In this figure, both PERFECT and D-PERFECT degrade their route construction delay performance than DPER. This is because that introducing the standby time makes the propagation of RREQ large in both PERFECT and D-PERFECT. However, it is considered that this is not deadly drawback since cached information is available after first construction. Note that the standby time does not relate to communication after route construction. Comparing D-PERFECT and PERFECT, the route construction delay of D-PERFECT is smaller than that of PERFECT because the number of hops of D-PERFECT is smaller than that of PERFECT.

From Figs. 7 and 8, it is shown the effectiveness of D-PERFECT under discrete power control environment because of its superior performance.

## 7 Conclusions

In this paper, we have proposed a novel routing algorithm constructing a power efficient route called PERFECT in ad hoc networks. In PERFECT, the standby time to forward RREQ is calculated by the received power of RREQ. PERFECT does not need additional control packets. Even if some nodes equipped with different characteristic antenna exist together, PERFECT can construct a power efficient route. The simulation results show PERFECT can construct power-efficient route. Moreover, this paper has proposed an extended version of PERFECT called D-PERFECT for a discrete power control environment. Theoretical and simulation results show D-PERFECT can construct more power-efficient route than PERFECT in a discrete power control environment.

## References

[1] I.F.Akyildiz, W.Su, Y.Sankarasubramaniam, E. Cayirci, “A survey on sensor networks,” IEEE Communication Magazine, pp.102-114, Aug. 2002.

[2] I.Stojmenovic and X.Lin, “Power-aware localized routing in wireless networks,” IEEE Trans. on Parallel and Distributed Systems, Vol.12, No.10, 2001.

[3] M.Krunz and A.Muqattash, S.Lee, “Transmission power control in wireless ad hoc networks: challenges, solutions, and open issues,” IEEE Network, Vol.18, No.5, 2004.

[4] J.Choi, Y.Ko, and J.Kim, “Utilizing directionality information for power-efficient routing in ad hoc networks,” Proc. of the IEEE/IEE 3rd International Conference on Networking, 2004.

[5] V.Bhuvaneshwar, M.Krunz, and A.Muqattash, “CONSET: A cross-layer power aware protocol for mobile ad hoc networks,” Proc. IEEE ICC’04, 2004.

[6] S.Narayanaswamy, V.Kawadia, R.S.Sreenivas, and P.R.Kumar, “Power control in ad-hoc networks: Theory, architecture, algorithm and implementation of the COMPOW protocol,” Proc. of European Wireless Conference, 2002.

[7] P.Ding, J.Holliday, A.Celik, “Power control MAC protocol analysis and improvement for ad hoc networks,” Proc. of SECON’04, 2004.

[8] L.Kleinrock and J.Silvester, “Optimum transmission radii for packet radio networks or why six is the magic number,” in Proc. of IEEE Nat. Telecommun. Conf., pp.4.3.1–4.3.5, Dec. 1978.