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# Signal Strength Based Energy Efficient Routing for Ad Hoc Networks

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**SUMMARY**    In this paper, we propose a novel energy-efficient route-discovery scheme with transmission power control (TPC) for ad hoc networks.  The proposed scheme is very simple and improves energy efficiency without any information about neighbor nodes.  In the proposed scheme, when a node receives a route request (RREQ), the node calculates the routing-level backoff time as being inversely proportional to the received power of the RREQ. After the route discovery, source and intermediate nodes transmit packets by the power-controlled medium access control (MAC) protocol.  In addition, we propose an extended version of the proposed scheme for discrete power control devices.  Simulation results demonstrate the proposed schemes can discover more energy efficient routes than the conventional schemes.
*key words:  ad hoc networks, routing, transmission power control (TPC), power efficiency*

## 1. Introduction

The rapid progress in sensor devices and wireless technologies enables ad hoc networks to be developed. Ad hoc networks have an advantage in that they need no specific pre-defined infrastructure, so they are expected to be applicable to a wide variety of fields, e.g. agriculture, environmental assessment, civil engineering, disaster mitigation, and animal tracking. For such applications, ad hoc networks are required to provide an effective way for small nodes to communicate with significant restriction on batteries. Several protocols and methods have been proposed for the medium access control (MAC) layer, routing layer, and application layer to extend network lifetime and to achieve high energy efficiency [1]. The Friis transmission equation and its extensions indicate that transmission power is proportional to the $n$-th ($n$ varies from 2 through 4.)  power of the distance between a transmitter and a receiver. That means that a shorter hop distance significantly decreases transmission power. According to this simple observation, some routing algorithms for discovering an energy-efficient route with transmission power control (TPC) devices have also been proposed in [2]–[5], [7]–[9].

Simple energy-aware routing schemes introducing energy-related routing metrics are presented in [2]–[5]. In [2], minimum total transmission power routing (MTPR) is presented to minimize the total transmission energy of the

discovered route. In [3], min-max battery cost routing (MM-BCR), which considers the residual battery energy of nodes, is presented. Also in [4], a source node selects a route that equalizes residual battery energy of all nodes. Conditional max-min battery capacity routing (CMMBCR) considers both total transmission energy and residual battery energy [5]. These schemes are based on the conventional on-demand routing using route request (RREQ) and route reply (RREP), so the optimal route is not always discovered [6]. This is an inherent characteristic of on-demand routing protocols, which cannot be overcome by introducing energy-related routing metrics.

Schemes presented in [7]–[9] request that a node chooses a node as a next hop, which reduces transmission power and exposed nodes along the route from sources to destinations to achieve better throughput. However, these routing schemes require much control traffic to obtain information about neighbor nodes. Location information is not sufficient to derive the optimally energy-efficient route. In addition, conventional methods cannot accurately discover energy-efficient routes, if nodes have different types of antennas.

In this paper, we propose novel energy-efficient route discovery with TPC in ad hoc networks. The proposed routing scheme is very simple and improves energy efficiency without any information about neighbor nodes. In the proposed scheme, when a node receives a RREQ, the node calculates the routing level backoff time, which is inversely proportional to the received power of the RREQ. After route discovery, source and intermediate nodes transmit packets by the power-controlled MAC protocol. In addition, we propose an extended version of the proposed scheme for discrete power control devices. Simulation results demonstrate the proposed schemes can discover routes that are more energy efficient than conventional schemes.

## 2. Related Work

There are many energy-saving schemes in ad hoc networks such as the TPC technique, sleep-mode scheduling, and decreasing control overhead, for example. Among them, TPC is known to decrease transmission power according to the Friis transmission equation. Energy saving with TPC in both the MAC layer [10]–[13] and network layer [2]–[5], [7]–[9] are presented.

Power-aware routing optimization (PARO) is presented as a MAC-layer energy-saving scheme to minimize the

transmission power between source and destination [11]. In PARO, one or more intermediate nodes called "redirectors" are elected to forward packets even when the source and destination can communicate directly. However, in a MAC layer scheme such as PARO, intermediate nodes are selected locally, so the route between source and destination may become longer.

In the network layer, there are energy-efficient route-discovery schemes. Directionality-based power-efficient routing (DPER) [8] is a routing protocol that discovers a power-efficient route by selecting a node located close to the destination as the next hop. In the route-discovery phase, DPER divides the area into round areas centered on the destination. The source node selects a node that communicates with the lowest power, located in the area adjoining the next hop. In DPER, each sender can select the intermediate node through which the overall route gradually approaches the destination. However, DPER needs location information about the other nodes, so much control traffic is generated.

Connectivity set protocol (CONSET) [9] is a cross-layer solution to discover a power-efficient route. CON-SET maintains the connectivity set (CS). The CS is the most energy-efficient set of nodes that guarantees the node's connectivity to the network. When receiving a request to send (RTS), clear to send (CTS), or Hello, CONSET estimates the 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 discovers a power-efficient route by transmitting RREQ with power that 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 an environment that has nodes equipped with antennas that have different characteristics.

In addition, only continuous power control devices are considered in the above route-discovery schemes. A simple energy-efficient routing algorithm is required that has continuous and discrete power-control devices operating with antennas that have different characteristics, without using position information.

## 3. Proposed Scheme

### 3.1 Proposed Routing Algorithm

The proposed scheme operates by the following procedures to discover an energy-efficient route. The proposed scheme has two phases: route discovery phase and data transmission phase.

In the route discovery phase, when a node receives a RREQ, the node calculates the routing level backoff time, referred to as standby time, that is inversely proportional to the received power of the RREQ. The node relays the RREQ with maximum transmission power when the standby time expires, so the node with less standby time relays earlier than the other nodes receiving the same RREQ. This means that a node with the strongest received power domi-
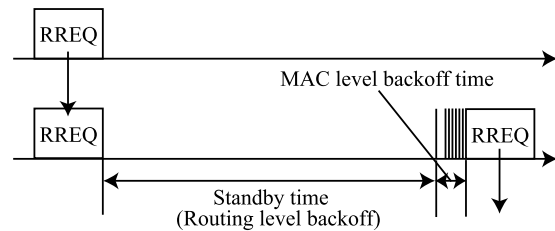


**Fig. 1**  Standby time.

nates in relaying the RREQ to create the least energy route. When the destination node receives the earliest RREQ, it sends back an RREP to the source node along the route. After receiving the RREP, the source node transits to the data transmission phase.

In the data transmission phase, the source and intermediate nodes transmit data packets with minimum transmission power by the power control MAC protocol [10]–[13].

### 3.2 Standby Time

In the proposed scheme, a node that receives a RREQ calculates standby time according to the received power of the RREQ. Standby time $T_{stby}$ second to relay RREQ is calculated as follows;

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

where $P_r$ mW is the received power of a RREQ, $a$ is a parameter that adjusts the scale of the standby time, and $b$ is a parameter that adjusts the priority of a short hop. If the standby time calculated by (1) is shorter than the MAC level backoff time, an unintended change in the order of RREQ forwarding may occur. Therefore, a sufficiently large $a$ should be chosen to set a longer standby time than the MAC level backoff time, as shown in Fig. 1. However, an excessively large $a$ causes an increasing route-discovery delay. Therefore, the largest $a$ that satisfies the required route-discovery delay should be set. On the other hand, a large $b$ increases the standby time when a strong received power is observed. Moreover, a large $b$ increases the number of hops. As the number of hops increases, some disadvantages occur such as queueing delay, MAC backoff time and packet losses. Therefore, packet retransmission occurs and throughput decreases, so the energy efficiency degrades. We should select the appropriate value of $b$.

In addition, according to the Friis transmission equation, $P_r$ becomes smaller exponentially for smaller attenuation constant $n$. Therefore, considering Eq. (1), we should choose larger $b$ for larger $n$ and vice versa.

When a node receives multiple RREQs from different nodes, the standby time is updated to the shortest one.

### 3.3 Example Operation

We assume a topology that has five nodes, as shown in

(a) Node S broadcasts RREQ.  (b) Node A broadcasts RREQ ($T = 10$).  (c) Node B broadcasts RREQ ($T = 30$).
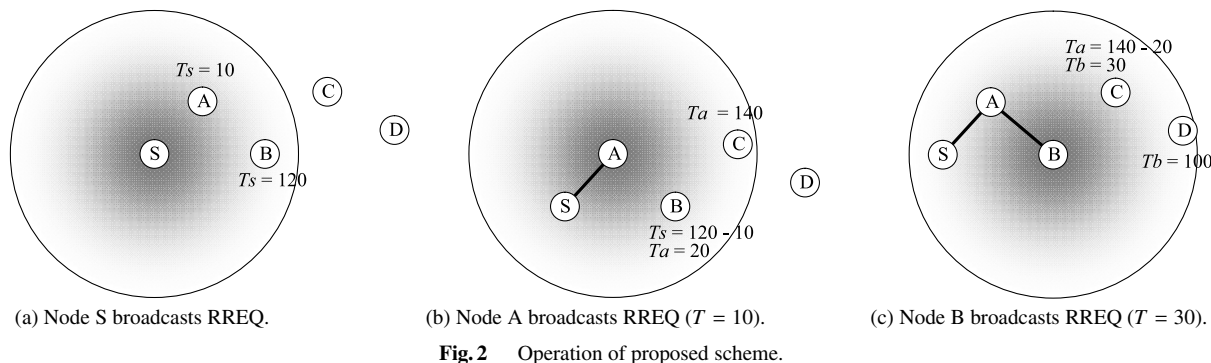
**Fig. 2**  Operation of proposed scheme.

Fig. 2(a). A RREQ to Node D is generated in Node S. S broadcasts the RREQ, and Nodes A and B receive the RREQ. We define that the calculated standby time according to the RREQ from Node S denotes $T_s$. A and B calculate $T_s$ according to the received power of the RREQ. A observes a stronger received power than that at B, so A calculates a shorter $T_s$ than B's $T_s$. We assume $T_s = 10$ at A and $T_s = 120$ at B.

At $T = 10$, the standby time of A expires first, so the RREQ is re-broadcasted by A. The RREQ is received by Nodes S, B, and C, as shown in Fig. 2(b). Each node checks the sequence number of the received RREQ. S judges the RREQ that has already been transmitted by checking the sequence number and cancels forwarding the RREQ. B and C calculate $T_a$, which is the standby time until re-broadcasting the RREQ from each node. We assume $T_a = 20$ at B and $T_a = 140$ at C.

Then, B receives two RREQs from S and A. B compares the remainder of standby times, $T_s$ and $T_a$, and the RREQ that has a longer standby time is canceled. In this example, since $T_s = 120 - 10 > T_a = 20$, $T_s$ is canceled. As shown in Fig. 2(c), the above procedure is repeated, and RREQ is forwarded only through the energy-efficient route. As a result, the route $S \rightarrow A \rightarrow B \rightarrow C \rightarrow D$ is discovered by the proposed scheme. In contrast, in dynamic state routing (DSR), the route with the smallest number of hops tends to be selected, so the route $S \rightarrow B \rightarrow D$, which contains short hops, is discovered.

The proposed scheme has the advantage of adopting an environment where nodes with different antenna characteristics exist in a network. In Fig. 3, an example operation in which nodes with different antenna characteristics exist is shown. In this figure, we assume that only Node E has an antenna with high gain $G_h$. All the other nodes have antennas with normal gain $G$. In this case, we also assume that Nodes A, B, and E receive a RREQ from Node S; then, the calculated standby times are $T_s = 10, 120$, and $5$, respectively. Among A, B and E, the farthest node from S is E. However, only E has a high-gain antenna, so the received power of the RREQ becomes smallest among them. Therefore, in the proposed scheme, a suitable, energy-efficient hop $S \rightarrow E$ is selected.

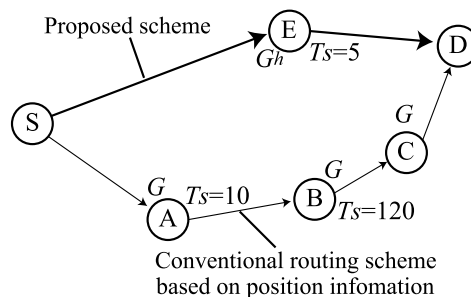In an actual radio-propagation environment, signal



**Fig. 3**  Discovered route when nodes with different antenna characteristics exist.

strength fluctuates. To overcome the problem of unstable links due to channel fluctuations, standby time calculation of the proposed scheme should be modified. Concretely, a margin to the required received power should be introduced. Introducing this margin is also effective node mobility in addition to channel fluctuations. This margin apparently leads to energy expenditure and influences the performance of the protocol. For simplicity, in the performance evaluation of this paper, no channel fluctuation and no node mobility are considered. In general, the reliability of transmission degrades exponentially as the number of hops increases. Therefore, packets are lost more frequently in the proposed scheme because of the increase in the number of hops. This leads to energy expenditure. Introducing margin to the required received power is also effective in this case. We can decrease the packet loss probability of one-hop transmission by setting a larger transmission power. By this setting, we can obtain the same number of total packet losses in a selected route as that of the conventional scheme.

## 4. Numerical Results

We evaluate performances of total transmission power, route discovery delay, and number of hops of the discovered route by means of computer simulations. Simulation assumptions are shown in Table 1. Nodes with no mobility are distributed randomly in an area of $500 \times 250\,\text{m}^2$. The route discovery phase simulates 100 random topologies, and each plot in the following results is the average of 100 simulations. After the route discovery phase, data are transmitted by MAC protocol using TPC. The total transmission power in mW of the

**Table 1** Simulation assumptions.

| Attenuation constant | 3 |
|---|---|
| Antenna gain | 0 dBi |
| Maximum transmission Power | 15 dBm |
| Receive threshold, $P_{thr}$ | −74 dBm |
| Carrier sense threshold | −95 dBm |
| Capture threshold | 10 dBm |
| MAC protocol | CSMA/CA (with TPC) |
| Network area | $500 \times 250\,\mathrm{m}^2$ |
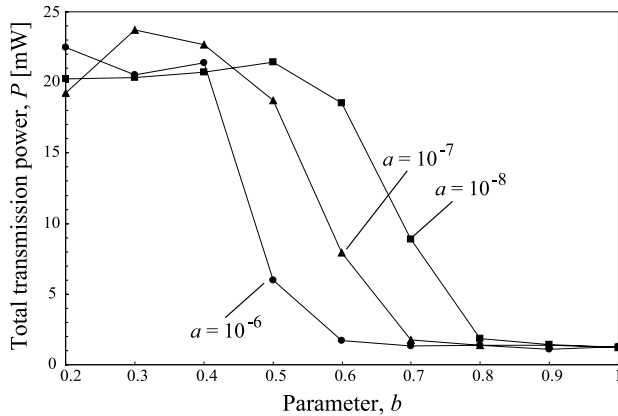


**Fig. 4** Total transmission power for various $a$ and $b$.



**Fig. 5** Route discovery delay for various $a$ and $b$.



**Fig. 6** Number of hops for various $a$ and $b$.

discovered route $P$ is defined as

$$P = \sum_{h=0}^{H} P_{th}, \qquad (2)$$

where $P_{th}$ mW is the transmission power of a node that is $h$ hops from the source node, and $H$ is the number of hops of a discovered route. The route discovery delay $D$ second is defined as

$$D = T_{aceptRREQ} - T_{geneRREQ}, \qquad (3)$$

where $T_{acceptRREQ}$ is the time when the destination accepts the RREQ, and $T_{geneRREQ}$ is the time when the source generates the RREQ. $D$ is defined as the delay to select a route between source and destination.

### 4.1 Evaluation of Parameters

We evaluate parameters $a$, which adjusts the scale of the standby time, and $b$, which adjusts the priority of the short hop. Total transmission power $P$, route discovery delay $D$, and number of hops of the discovered route $H$ for various $a$ and $b$ are shown in Figs. 4, 5, and 6, respectively. In Fig. 4, $P$ becomes small for large $b$. This is because when a large $b$ is set, a long standby time is set for selecting energy-efficient links adequately. As a result, an energy-efficient route can be discovered. In general, the received power $P_r$ is less than 1 mW in Eq. (1). When a small $a$ or small $b$ is chosen, the standby time becomes short. Therefore, when a small $a$ and a small $b$ such as $a = 10^{-8}$ and $b = 0.5$ are set, the standby
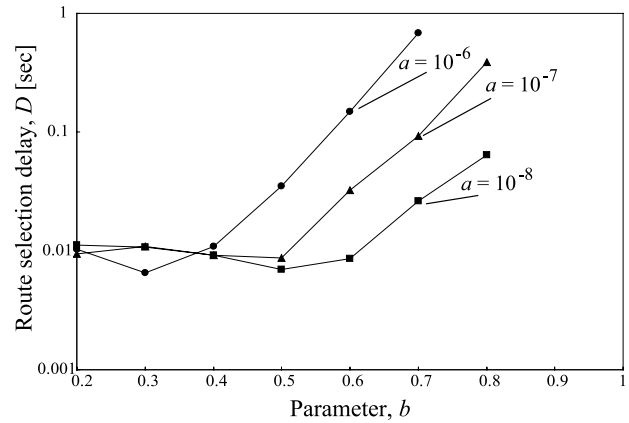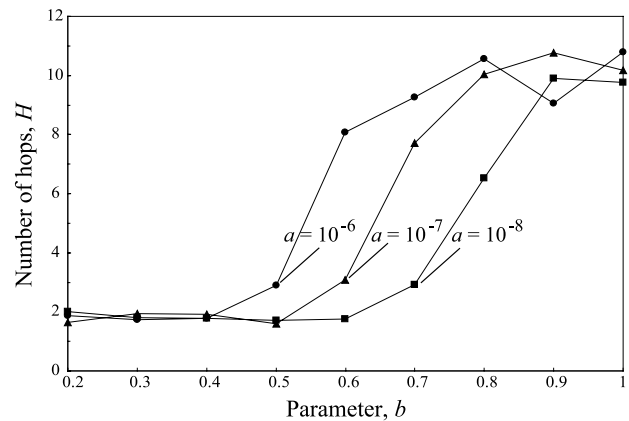
time becomes smaller than the MAC level backoff time. In this case, the standby time to relay RREQ depends on the MAC level backoff time, so an energy-efficient route tends not to be discovered. In contrast, when a large $a$ and a large $b$ such as $a = 10^{-6}$ and $b = 0.8$ is set, energy efficient links are selected appropriately. Therefore, the proposed protocol is effective to reduce total transmission power performance. In Fig. 5, $D$ becomes large for large $b$. This is because when a large $b$ is set, the maximum standby time becomes large. In Fig. 6, $H$ becomes large because short hops have priority, and more small hops are selected. As shown in these figures, there is a design trade-off between $P$ and $D$, and between $P$ and $H$. Therefore, for improving total transmission power, a large $a$ and a small $b$, which satisfy a required route discovery delay and a number of hops should be set. The advantage of the proposed scheme is to discover a power-efficient route without additional control traffic. However, the proposed scheme has a drawback that route-discovery delay increases. In the following evaluations, we use empirical parameters $a = 10^{-6}$ and $b = 0.7$ because the proposed scheme enables discovering a power-efficient route on top of the sacrifice of increasing route-discovery delay. The proposed scheme has design trade-offs between $P$ and $D$, and between $P$ and $H$. Therefore, there is no optimal set of $a$
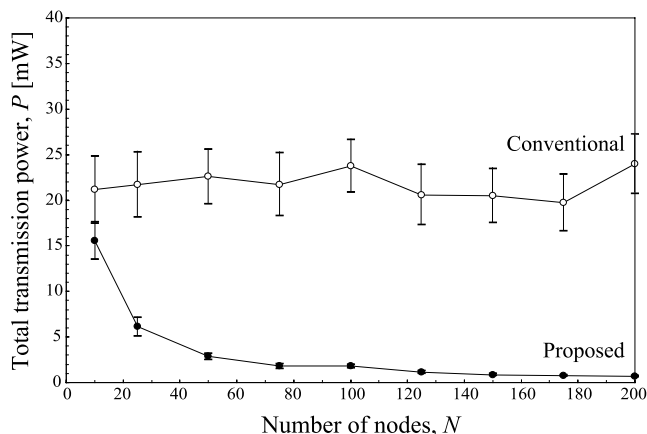
**Fig. 7** Total transmission power performance.



**Fig. 8** Route discovery delay performance.

and $b$. A suitable set depends on the applications. In this evaluation, we assume that the application has a priority to reduce transmission power rather than route selection delay. The set of $a = 10^{-6}$ and $b = 0.7$ is the same level as the set of $a = 10^{-7}$ and $b = 0.7$; however, the transmission power of $a = 10^{-6}$ and $b = 0.7$ is slightly smaller than that of $a = 10^{-7}$ and $b = 0.7$. Therefore, we choose that set in the evaluation. The set $a = 10^{-7}$ and $b = 0.7$ is also a well-balanced parameter, so the set is also appropriate. The proposed scheme should be selected for applications that are tolerant of route-discovery delay. The set of $a$ and $b$ is appropriate for the IEEE 802.11b network interface. In the future, some parameters such as the MAC backoff time and minimum received power may change. In that case, we can set the appropriate $a$ and $b$ by calculating the appropriate standby time. To obtain the appropriate value of the standby time, we should adjust $a$ and $b$ by Eq. (1). When the MAC backoff time changes to a small value, we should set a smaller $a$. In addition, when the minimum received power changes to a small value, we should set a smaller $a$ and a smaller $b$.

### 4.2 Performance Comparison

We compare the performance of the proposed scheme with DSR, which is the typical shortest-hop routing in ad hoc networks.

The simulation results of total transmission power are shown in Fig. 7. In this figure, the y-axis indicates the number of hops of the discovered route. In this simulation, the network area is the same; therefore, the number of nodes indicates the node density. In this figure, we also show two-sided 95 percent confidence intervals. As shown in Fig. 7, the proposed scheme consumes less total transmission power than DSR because the proposed scheme can discover a power-efficient route. In particular, when the number of nodes is large, the performance improvement becomes large. The reason is as follows. The transmission power of DSR is almost constant for all numbers of nodes. In DSR, although the number of nodes is large and the number of selectable small hops becomes large, the selected next
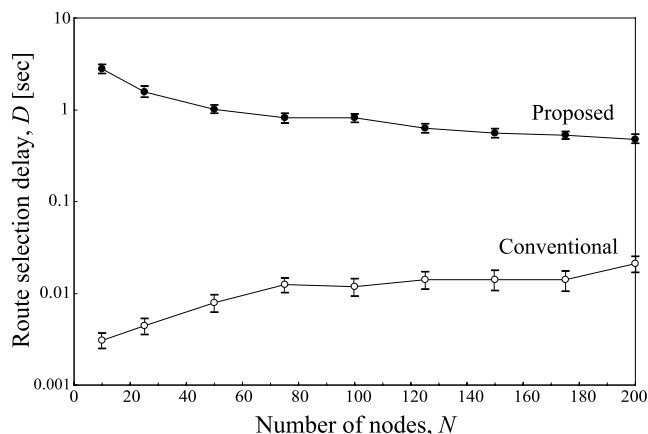
hop does not change. As a result, the transmission power performance is independent of the number of nodes. On the contrary, the transmission power of the proposed scheme becomes small as the number of nodes increases. This is because in the proposed scheme, when the number of nodes is large, smaller hops tend to be selected.

In Fig. 8, route-discovery delay performance is shown. We can find that the proposed scheme requires a longer route-discovery delay than that of DSR. As mentioned above, this is because in the proposed scheme, a sufficiently longer standby time than the backoff time of the MAC protocol is set for selecting small hops. In addition, under a high node-density environment, the route-discovery delay of the proposed scheme decreases. The reason is that the average distance of a hop becomes short under a high node-density environment. Therefore, the average standby time at a node also decreases. As clearly shown in Fig. 8, route discovery performance of the proposed protocol degrades excessively. We consider that this is a drawback of the proposed scheme when the route-discovery phase occurs frequently. However, the proposed scheme is considered to be suitable for an environment with a low node mobility. In an environment with low node mobility, a long valid time of the route cache can be set. Therefore, a discovered route can be used long term.

In Fig. 9, the number of hops of the discovered route is shown. We find that the number of hops of DSR is almost constant for various node densities because DSR is the shortest hop routing. In contrast, in the proposed scheme, the number of hops is proportional to the number of nodes. This is because a more energy-efficient route can be discovered under a higher node density in the proposed scheme. Generally, increasing the number of hops of the discovered route could incur a long data-transmission delay at the MAC layer. On the other hand, we also consider that by using a power-controlled MAC protocol, the interference with neighbor nodes can be alleviated in each hop. Therefore, queueing delay and retransmission delay at the MAC layer can be alleviated. The effect of increasing the number of hops depends on the MAC protocol. Hence, we consider the
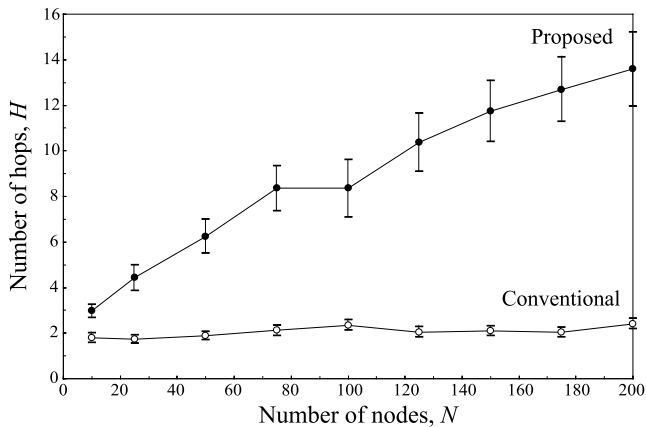
**Fig. 9** Number of hops of the discovered route performance.



**Fig. 10** Discovered route using DPC devices.

evaluation of the power-controlled MAC protocol is out of the scope of this paper.

As shown in Figs. 7, 8, and 9, the proposed scheme can discover energy-efficient routes under all conditions of number of nodes. In particular, the proposed scheme is effective under a high node-density environment.

## 5. Extension for Discrete Power Control

### 5.1 Deterioration Using Discrete Power Control Devices

We have shown that the proposed scheme can reduce the total transmission power of the discovered route using continuous power control (CPC) devices. Some consumer wireless LAN cards can set 32 levels of transmission power. At such fine levels of power control devices, the proposed scheme can reduce transmission power almost the same amount as when using CPC devices. However, some consumer wireless LAN cards only set a few levels of transmission power. For example, only 1, 5, 20, and 30 mW are feasible as transmission powers in Cisco Aironet 350. With such discrete power control (DPC) devices, the proposed scheme, referred to as Continuous version, cannot reduce transmission power sufficiently.

In this paper, we assume that one type of power control device exists in a network. We do not consider the situation in which both CPC and DPC co-exist in a network.

A discovered route of the proposed scheme using CPC devices is shown in Fig. 10. The proposed scheme discovers a route S → A → B, which contains short-distance hops, as indicated by thick lines in Fig. 10. Node S transmitting to Node A is wasteful, despite Node B being received even if S transmits using minimum transmission power. The performance of the proposed scheme deteriorates because of containing so many short hops. We extend the proposed scheme to discover an appropriate route, such as S → B shown in Fig. 10.

### 5.2 Discrete Version of Proposed Scheme
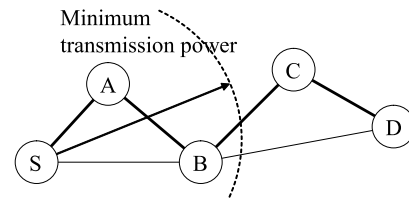
We propose the extended version of the proposed scheme

referred to as the Discrete version. In the Discrete version, only the standby time calculation is modified. The Discrete version selects the node located near the sender and outside of each transmission range to discover a power-efficient route with DPC devices. We consider the standby time calculation $T_{stby}$ with two values $T_1$ and $T_2$ second, as shown in the following expression;

$$T_{stby} = \alpha T_1 + (1 - \alpha)T_2, \qquad (4)$$

where $\alpha$ is the weight of the priority outside of the range.

$T_1$ is introduced to make outside of each transmission range a high priority. $T_1$ is calculated as shown

$$T_1 = T_{max}\left(1 - \frac{P_{thr}}{P_t}\right)^{\beta}, \qquad (5)$$

where $T_{max}$ second is the maximum standby time, $\beta$ is a parameter that changes the priority to outside of the transmission range, and $P_t$ is the minimum discrete transmission power that exceeds the receive threshold $P_{thr}$.

$$P_t = min\{P|P > P_{thr}\} \qquad (6)$$

$T_1$ indicates the discrete curve in Fig. 11 where $T_{max} = 0.1$, $\alpha = 0.2, \beta = 1.0$, and $\gamma = 0.5$.

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

$$T_2 = T_{max}\left(\frac{P_t - P_{min}}{P_{max} - P_{min}}\right)^{\gamma} \qquad (7)$$

where $T_{max}$ and $P_t$ are equal to the explanation in (4). $P_{min}$ and $P_{max}$ are feasible minimum and maximum transmission power, respectively. $\gamma$ is a parameter that changes the priority to near the sender. $T_2$ indicates the discrete curve in Fig. 11. $T_{stby}$ is the weighted summation of $T_1$ and $T_2$, as shown in the discrete curve in Fig. 11.

Discovered routes of DSR, Continuous and Discrete versions of the proposed schemes are shown in Fig. 12. In this figure, DSR is clearly shown to discover the shortest hop route. In contrast, the Continuous version discovers a route with many small hops. The Discrete version discovers a route including larger hops than that of the Continuous version for using discrete transmission power control devices.

### 5.3 Performance Evaluation of Discrete Version

We evaluate the performance of the proposed schemes using DPC devices. In the following simulations, we use empirical
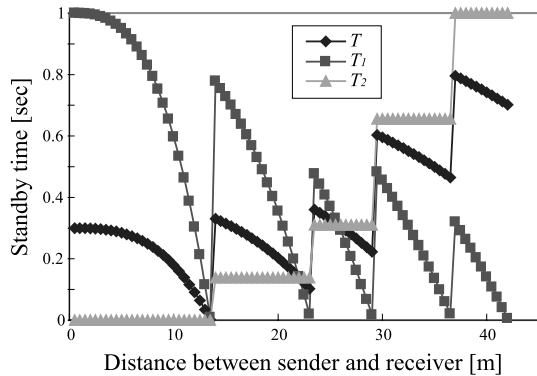
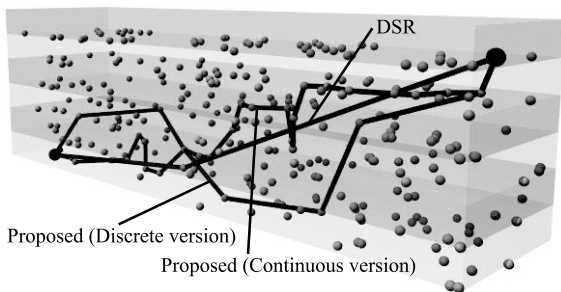**Fig. 11** Standby time function in discrete version of proposed scheme.
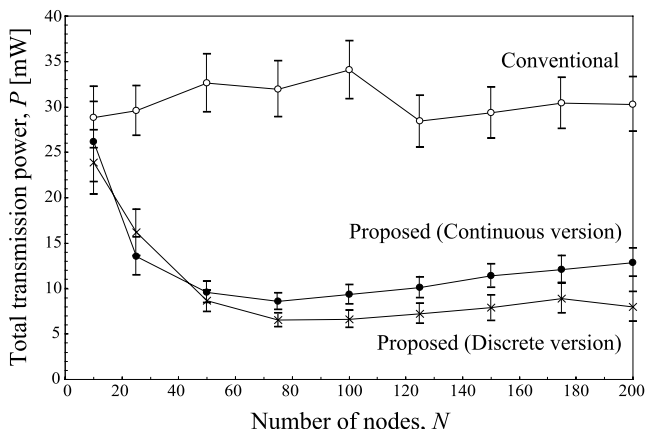


**Fig. 12** Discovered route.



**Fig. 13** Total transmission power using DPC devices.

parameters $T_{max} = 0.1$, $\alpha = 0.2$, $\beta = 1.0$, and $\gamma = 0.5$.

Simulation results of the total transmission power vs. number of nodes are shown in Fig. 13. Comparing Figs. 7 and 13, the Continuous version of the proposed protocol degrades total transmission power performance excessively using DPC devices. In particular, under a high node density, the tendency becomes prominent. For example, when the number of nodes is 200, $P$ is about 0.7 mW using CPC devices, as shown in Fig. 7, and $P$ is about 12.9 mW, as shown in Fig. 13. This means that the Continuous version selects too small hops with DPC devices, as shown in Fig. 10. As shown, both Continuous and Discrete versions achieve better performance than that of DSR for all num-
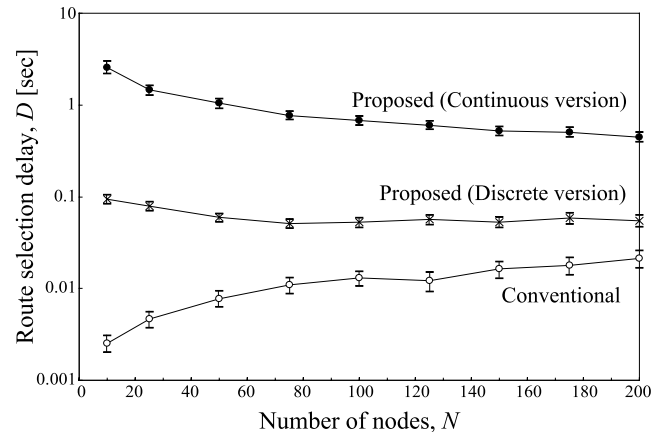


**Fig. 14** Route discovery delay using DPC devices.

bers of nodes. This is because both proposed schemes can select small hops for improving power consumption performance. Moreover, the performance of the Discrete version using DPC devices is shown to be almost the same as that of the Continuous version using DPC devices in the case of a small number of nodes, smaller than about fifty. This is because the number of selectable nodes is small in the case of a small number of nodes. Therefore, the discovered route of both proposed schemes is considered to be almost the same. In the case of a large number of nodes, larger than about fifty, the Discrete version achieves better performance than the Continuous version. In particular, the performance of the Continuous version degrades as larger number of nodes. The reason is that the Continuous version selects too small hops. According to the result, the performance improvement of the Discrete version is small. However, we have evaluated the proposed schemes in a realistic environment where nodes are distributed in a small 3D building topology [14]. We have demonstrated that in the small building topology, the Discrete version can improve the performance more than in a 2D square area. This is because 3D devices tend to be at a higher density. In addition, in a small building topology, the distance between source and destination is shorter than the minimum transmission range.

Simulation results of route-discovery delay are shown in Fig. 14. In this figure, both proposed schemes degrade their route discovery delay performance more than DSR does. This is because introducing the standby time makes the propagation of RREQ large in both proposed schemes. Comparing the two proposed schemes, the route-discovery delay of the Discrete version is smaller than that of the Continuous version. The reason is that the number of hops of the Discrete version is smaller than that of the Continuous version, as shown in Fig. 15. Also in Fig. 15, we find that the number of hops of the Continuous version increases proportionally to the node density. In contrast, that of the Discrete version is almost constant when the number of nodes is larger than fifty. As shown in this phenomenon, the Discrete version does not select too small hops.

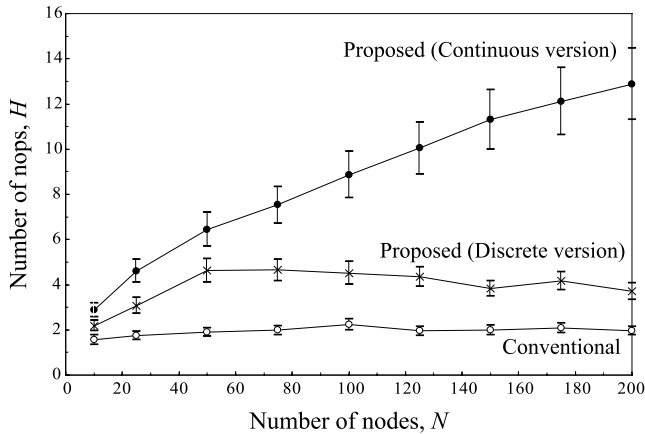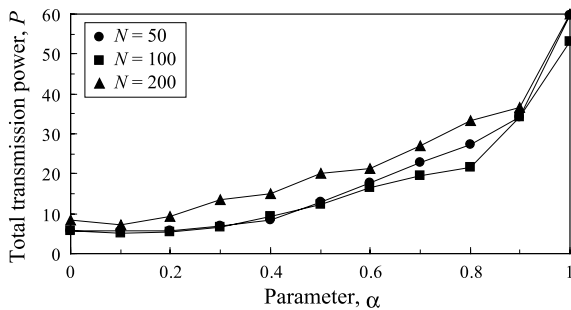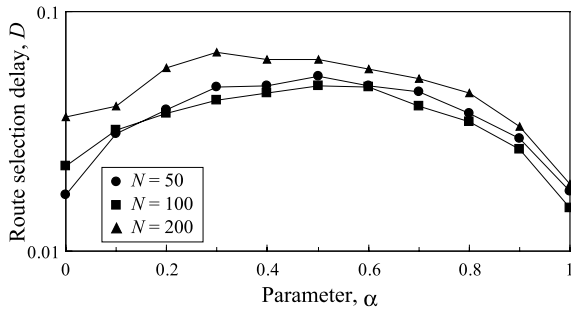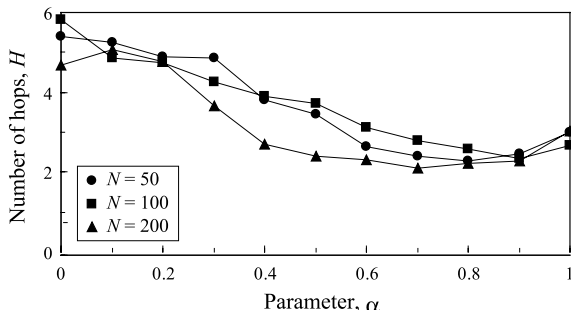In Figs. 13, 14 and 15, we can see the effectiveness of

**Fig. 15**    Number of hops using DPC devices.



(a) Total transmission power.



(b) Route selection delay.



(c) Number of hops.

**Fig. 16**    Parameter $\alpha$ versus $P$, $D$ and $N$ using DPC device.

the Discrete version of the proposed scheme using DPC devices because of its superior performance.

The parameter $\alpha$ vs. total transmission power $P$ mW, route selection delay $D$ second, and number hops $N$ using

DPC device are shown in Fig. 16, where $T_{max} = 0.1, \beta = 1.0$, and $\gamma = 0.5$. As shown in Fig. 16(a), we can find basically that the total transmission power increases as parameter $\alpha$ increases. We find that $P$ becomes the minimum value when $\alpha = 0.1$ or $\alpha = 0.2$. The outside of the range has less priority when $\alpha$ is small and too many small hops are selected, as shown in Fig. 16(c). In that case, we find that the route selection delay decreases, as shown in Fig. 16(b). From these figures, we should set an appropriately small $\alpha$ to improve transmission-power performance.

## 6. Conclusion

In this paper, we have proposed a novel energy-efficient routing scheme with continuous and discrete transmission power control in ad hoc networks. In the proposed scheme, when a node receives a RREQ, the node calculates the standby time inversely proportional to the received power of the RREQ. The node relays the RREQ with maximum transmission power when the standby time expires to discover the most energy-efficient route. Simulation results suggest the proposed scheme can discover routes that are more energy efficient than routes discovered by conventional schemes with both continuous and discrete power control devices. In a future work, we plan to evaluate the performance of the proposed schemes under a more realistic radio propagation and mobility environment. In particular, we investigate TCP performance, and how introducing the margin affects performance. In addition, modification of the standby-time calculation that takes into account other energy-related factors such as residual battery energy is also a future work. Moreover, extending the proposed scheme to the situation in which CPC and DPC devices exist in a network is necessary.

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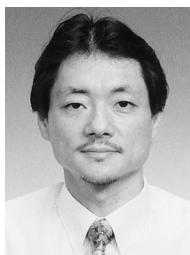
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