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間欠的無線アドホックネットワークのための確率的位置ベースルーティング

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概要：無線アドホックネットワークを構成する無線ノードの通信モジュールにおける電力消費を削減する方法として, 通信モジュールを間欠的に動作させる手法がある. 間欠周期を各無線ノードが自律的に決定する場合, 隣接無線ノードが同期的に動作することは困難である. 次ホップを隣接無線ノードの現在位置に基づいて適応的に決定する位置ベースルーティングは無線ノードの移動に頑強であるが, 間欠通信環境においては隣接無線ノードとの位置情報交換が困難であるという問題がある. 本論文では, 確率的なアプローチによって位置ベースルーティング手法であるGEDIR と間欠通信手法であるIRDT とを組み合わせる手法を提案する. ここで, 次ホップ隣接無線ノードの計算には数値積分を要することから, その計算精度による計算時間と配送遅延短縮効果との関係をシミュレーション実験によって評価し、これらのトレードオフについて議論する.

キーワード：無線アドホックネットワーク, ルーティング, 間欠的通信, 低電力消費, 確率的アプローチ

Probabilistic Location-based Routing for Intermittent Wireless Multihop Networks

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Abstract: For reduction of battery consumption in wireless nodes in wireless adhoc networks, intermittent communication is introduced. In cases that the interval of intermittent communication is determined in each wireless node independently, it is difficult for the wireless nodes to be synchronized. Though location-based routing works well even in highly mobile environments, exchange of location information among neighbor nodes is difficult. In this paper, probabilistic approach for combination of GEDIR location-based routing and IRDT intermittent communication protocol is proposed. In the numerical integration in the proposed approach, the relation between computational overhead for calculation accuracy and reduction of transmission delay of wireless multihop transmissions is evaluated by simulation experiments and their tradeoff is also discussed.

Keywords: Wireless Ad-hoc Networks, Routing Protocol, Intermittent Communication, Low Power Consumption, Probabilistic Approach.

1. Introduction

Intermittent communication technique is widely introduced in wireless ad-hoc networks for reduction of power consumption. In each wireless node, its wireless communication module should be active when it sends data messages and when it forwards data messages in transmission as an intermediate node. Otherwise, i.e., while the wireless node is not engaged in any data message transmissions, it gets in its sleep mode to reduce its battery consumption for longer lifetime. In order to realize the

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intermittent communication, it is difficult for each intermediate node to synchronize with its previous- and next-hop nodes. That is,in an intermediate wireless node, it is required to be active before it receives data messages from one of its neighbor nodes. Hence, it is difficult for the intermediate wireless node to determine when it gets in its active mode.

Intermittent Receiver-driven Data Transmission (IRDT) is an asynchronous intermittent communication protocol for wireless ad-hoc networks [4]. In IRDT, an intermediate wireless node with data messages in transmission waits for its next-hop neighbor node to be active without continuous transmissions of control messages which is required in various Low Power Listening (LPL) [6] protocols. Though it is a power-efficient communication method, it is difficult for conventional ad-hoc routing protocols to be applied since the protocols are designed to support only wireless networks consisting of always-on stationary wireless nodes. In order to realize power-efficient routing with intermittent communication in wireless ad-hoc networks, this paper proposes a combination of IRDT and a well-known location-based greedy ad-hoc routing protocol Geographic Distance Routing (GEDIR) [8]. GEDIR is based on the message-by-message routing, which is suitable for highly mobile ad-hoc networks.

2. Related Works

Battery capacity in wireless nodes is limited and usually there is no continuous power supply to them. Hence, intermittent communication is introduced where nodes switch between their active and sleep modes [11]. Their communication module works only in the active modes. In order for data messages to be transmitted to the destination node along a wireless multihop transmission route, each intermediate node should be in the active mode when its previous-hop node forwards a data message. Such intermittent communication methods are classified into synchronous and asynchronous. In the synchronous methods, all the nodes are closely synchronized and each node transmits data messages according to a predetermined schedule as in Traffic-Adaptive Medium Access Protocol (TRAMA) [10] and Lightweight Medium Access Protocol (LMAC) [5]. On the other hand, in the asynchronous methods, synchronization among neighbor nodes is required only when a node forwards a data message to its next-hop node. In LPL [6], when a node requests to transmit a data message to its next-hop node, it continues transmissions of a preamble message during a mode switching interval and all its neighbor nodes receiving the preamble message should be in an active mode even if they are not the next-hop node as shown in Figure 1. In IRDT [4], a current-hop node N_c waits for receipt of a polling message from its next-hop node N_n as in Figure 2. Every node switches between its active and sleep modes in the same interval and broadcasts a polling message with its ID each time when it changes its mode active. Then, it waits for a transmission request message *Sreq* from its previous-hop node in its active mode. If it does not receive *Sreq*, it goes into its sleep mode. Otherwise, i.e., if N_c receives a polling message from N_n which enters its active mode and transmits *Sreq* to N_n with its ID, N_n transmits an acknowledgement message *Rack* back to N_c and a virtual connection is established between them. Then, data messages are transmitted from N_c to N_n. Different from LPL, a current-hop node N_c does not transmit a preamble message continuously but only waits for receipt of a polling message in IRDT. Therefore, low-overhead, i.e., low battery consuming intermittent communication among wireless nodes is realized.

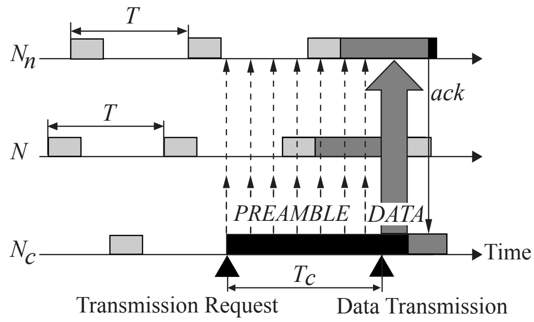

図 1 LPL Intermittent Communication.

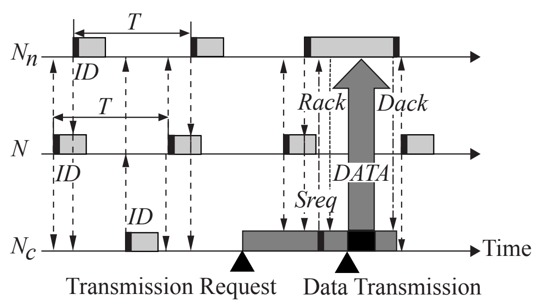

図 2 IRDT Intermittent Communication.

In [7], a wireless multihop routing protocol for IRDT-based ad-hoc networks has been proposed. It is a proactive routing protocol where each node keeps its routing table for the shortest transmission route to a destination node up-to-date. In order for the nodes to determine their next-hop neighbor node, a flooding of a control message initiated by the destination node is applied. Though it works well in usual ad-hoc networks consisting of always-on mobile nodes, it is difficult for networks with intermittent communication since a control message is not always received by all the neighbor nodes due to their sleep mode. Thus, the control message is required to be retransmitted. Hence, in the worst case, a node unicasts the control message to all its neighbor nodes one by one. In addition, in order to support mobile wireless networks, it is difficult for proactive routing protocols to keep the routing tables consistent to the current network topology especially with the intermittent communication among the mobile wireless nodes.

3. Proposal

3.1 Next-Hop Selection

As discussed in the previous section, for wireless multihop transmissions of data messages to reach a destination node with the intermittent communication in mobile wireless nodes, a novel routing protocol is required to be developed. In order to reduce the communication overhead and transmission delay for data message transmissions with intermittent communication, this paper proposes a combination IRDT-GEDIR of IRDT and GEDIR [8] which is one of the well-known location-based ad-hoc routing protocols with low communication overhead for synchronization among nodes. GEDIR is a message-by-message based routing protocol. That is, an intermediate node determines its next-hop node for each data message according to the most up-to-date locations of itself, its neighbor nodes and the destination node. Each node with a GPS-like location acquisition device broadcasts its current location information in a certain interval and thus it achieves location information of its neighbor nodes. The original GEDIR is designed for always-on wireless nodes and the broadcasted location information is surely received by all the neighbor nodes. Only the localized information, i.e., location information of not all but only neighbor nodes, is required to determine its next-hop node according to the following method.

[Next-Hop Selection in GEDIR]
An intermediate wireless node N_c selects one of its neighbor node N_n as its next-hop node where the distance $d_n = |N_n N_d|$ to the destination node N_d is the shortest among all its neighbor nodes as shown in Figure 3. □

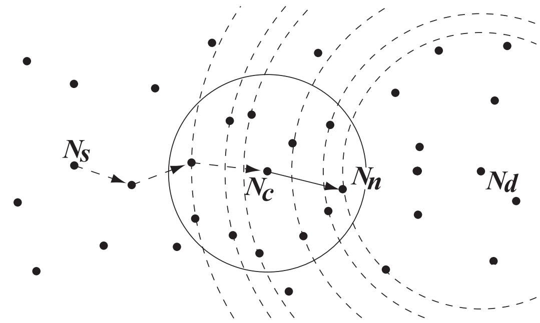

図 3 GEDIR Overview.

In IRDT, each node transmits a polling message each time it enters its active mode. Thus, by piggybacking its location information to the polling message as in Figure 4, its location information is broadcasted without additional communication overhead and notified to its possible previous-hop nodes. However, the polling message is not surely received by all its neighbor nodes since they might be in their sleep mode where their network interfaces do not work. If the nodes are stationary, a neighbor node which receives the polling message by chance holds the location information and uses it for its next-hop determination. However, in a mobile ad-hoc network, the achieved location information gets stale and the most up-to-date location information is required for the next-hop selection.

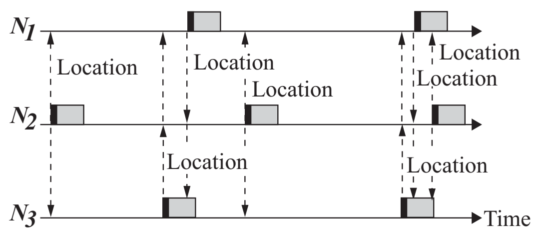

図 4 Location Information Propagation by Polling Messages.

An intermediate node N_c requires location information of its neighbor nodes only when it has a data message to be transmitted to the destination node through its next-hop node. Thus, in our proposal, based on the location information piggybacked to the received polling messages, N_c determines its next-hop node. Here, since a neighbor node N waits for receiving an *Sreq* message only for a predetermined interval after transmission of a polling message from N, N_c should determine during this interval whether it selects N as its next-hop node or not.

In order to solve this problem, according to a certain criterion, N_c evaluates N and compares the evaluation result and an expected evaluation where one of the later activating neighbor nodes are selected as its next-hop node. In

GEDIR, the distance to the destination node is applied as the criterion for selection of its next-hop node for achieving shorter transmission route to the destination node. On the other hand in IRDT-GEDIR, since wireless nodes communicate intermittently, forwarding to the neighbor node nearest to the destination destination node does not always reduce the transmission delay. Even when a node N is not the nearest to the destination node, shorter transmission delay might be achieved by forwarding it to N being active currently. Thus, this paper introduces a novel criterion *pseudo speed* of data message transmission which is achieved by division of difference of distance to the destination node N_d, i.e., $|N_cN_d| - |NN_d|$, by the time duration between the transmission request and receipt of the polling message as shown in Figure 5. It is a reasonable criterion for selection of a next-hop node in intermittent communication environments for shorter transmission delay to the destination node.

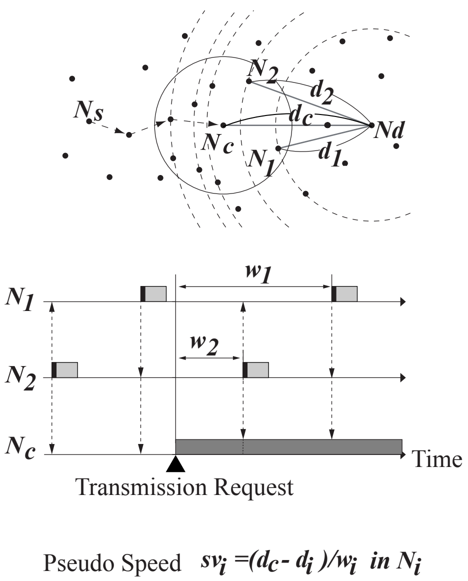

図 5　Next-Hop Selection based on Pseudo Speed.

Due to IRDT intermittent communication, an intermediate node N_c should determine whether it selects a neighbor node N as its next-hop node soon after it receives a polling message from N since N_c should transmits an *Sreq* message to N while N is in its active mode. That is, N_c cannot compare all pseudo speed sv_i each of which is achieved in case that N_c forwards a data message to a neighbor node N_i since each sv_i is only achieved when N_i wakes up and broadcasts its polling message containing its current location information. This is almost the same setting as in the secretaries problem [2].

In our next-hop selection, neighbor nodes get active one by one and an intermediate node with data messages in transmission can evaluate the pseudo speed of data messages to them at that time. It should immediately determine whether it selects the currently active neighbor node as its next-hop node or not even though it cannot evaluate the pseudo speed of data messages to the forthcoming active neighbor nodes. Thus, the solution of our next-hop selection problem is expected to be achieved based on the secretaries problem.

N_c evaluates the pseudo speed sv where it forwards a data message to N from which N_c receives a polling message and the expected pseudo speed $\overline{sv}$ where it forwards it not to N but to one of the later activating nodes. If $sv > \overline{sv}$, N_c transmits an *Sreq* message to N; i.e., it selects N as its next-hop node. Otherwise, i.e., $sv < \overline{sv}$, N_c does not transmit an *Sreq*.

3.2 Expectation of Pseudo Speed

In the proposed method in the previous subsection, an intermediate node determines whether it forwards a data message to a currently active neighbor node from which it receives a polling message by comparison of pseudo speed of transmission of a data message. For the comparison, this subsection discusses the method to evaluate the expected pseudo speed of transmission of a data message in case that the intermediate node forwards the message not to the currently active neighbor node but to one of the later activating nodes. Here, let T be the constant interval of activations in nodes, i.e., the interval of consecutive transmissions of polling messages and n be the number of neighbor nodes of an intermediate node N_c with a data message in transmission.

First, we investigate the distribution of distances $|N_d|$ from neighbor nodes N of N_c to the destination node N_d. As shown in Figure 6, let r, d_c and d be a wireless transmission range of N_c, the distance from N_c to N_d ($d_c > r$) and the distance from N to N_d ($d_c - r \leq d \leq d_c + r$). Under an assumption that nodes are distributed with the same density, the probability $DP(d)$ where the distance $|N_d|$ is shorter than d is as follows:

$$
\begin{aligned}
DP(d) &= \frac{S(d)}{\pi r^2} \\
&= \frac{2}{\pi r^2}\Big(\int_{d_c-d}^{x'} \sqrt{d^2-(x-d_c)^2}dx \\
&\qquad + \int_{x'}^{r} \sqrt{r^2-x^2}dx\Big) \qquad (1)
\end{aligned}
$$

$$\text{(where } x' = (d_c^2 + r^2 - d^2)/2d_c)$$

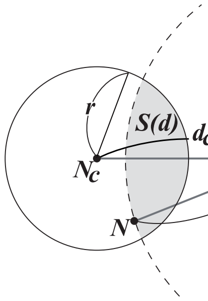

図 6 Area of Candidates of Next-Hop Node.

Since $DP(d)$ is the distribution function of d, the probability density function $dp(d)$ where $|N_d|$ equals to d is as follows:

$$\begin{aligned} dp(d) &= \frac{d}{dd}DP(d) \\ &= \frac{2}{\pi r^2}\frac{d}{dd}\Big(\int_{d_c-d}^{x'}\sqrt{d^2-(x-d_c)^2}dx \\ &\qquad + \int_{x'}^{r}\sqrt{r^2-x^2}dx\Big) \qquad (2) \end{aligned}$$

The probability density function $p(l)$ of the reduction of distance $l = d_c - d$ to N_d achieved by forwarding a data message from N_c to N is as follows:

$$\begin{aligned} p(l) &= dp(d_c-l) \\ &= -\frac{2}{\pi r^2}\frac{d}{dl}\Big(\int_{l}^{x''}\sqrt{(x-l)(2d_c-l-x)}dx \\ &\qquad + \int_{x''}^{r}\sqrt{r^2-x^2}dx\Big) \qquad (3) \end{aligned}$$

$$\text{(where } x''=((2d_c-l)l+r^2)/2d_c\text{)}$$

Next, we examine the distribution of time duration from the transmission request of a data message in N_c to the receipt of a polling message from N. Here, the transmission is supposed to be requested at $t = 0$. Let t_i be the time when the ith polling message is transmitted from one of the neighbor nodes of N_c. Thus, $i-1$ neighbor nodes transmit polling messages in an interval $[0, t_i)$ and the rest $n-i$ neighbor nodes transmit polling messages in an interval (t_i, T). Under an assumption that the transmission time t of the polling messages from the $n-i$ neighbor nodes are distributed in the interval (t_i, T) according to the unique distribution, the probability density function $pp(i, j, t)$ where jth $(i < j \leq n)$ polling message is transmitted from one of the neighbor nodes of N_c at time $t \in (t_i, T)$ is as follows:

$$\begin{aligned} pp(i,j,t) &= {}_{n-i}C_{j-i-1}\left(\frac{t-t_i}{T-t_i}\right)^{j-i-1} \\ &\qquad \times {}_{n-j+1}C_1\frac{1}{T-t_i}\times\left(\frac{T-t}{T-t_i}\right)^{n-j} \\ &= {}_{n-i-1}C_{j-i-1}\frac{(n-i)(t-t_i)^{j-i-1}(T-t)^{n-j}}{(T-t_i)^{n-i}} \qquad (4) \end{aligned}$$

Since the location of a neighbor node and the time when it transmits a polling message are independent each other, the probability density function $g(i, j, t, l)$ where N_c transmits a data message to a neighbor node N which transmits the jth $(i < j \leq n)$ polling message at time t $(t_i < t < T)$ and the distance to the destination node N_d is reduced l by this forwarding is induced by (3) and (4) as follows:

$$g(i,j,t,l) = pp(i,j,t)\cdot p(l) \qquad (5)$$

Here, the pseudo speed sv of transmissions of data messages is l/t.

In case that N_c does not select a neighbor node which transmits the ith polling message at t_i as its next-hop node, N_c selects another node which transmits the jth $(i < j \leq n)$ polling message at t_j $(t_i < t_j < T)$ or a node transmitting its second polling message after $t = T$. In the latter case, kth $(1 \leq k \leq i)$ polling messages are transmitted at t_k $(0 \leq t_k \leq t_i)$ and the distance reduction by forwarding to the neighbor node is l_k. Thus, the pseudo speed achieved by forwarding on receipt of the second polling message is $sv_k = l_k/(t_k + T)$. Since N_c has already achieved both t_k and l_k $(1 \leq k \leq i)$, the expected pseudo speed where N_c forwards a data message at $t \geq T$ is as follows:

$$\overline{sv}_n = \max_{1\leq k\leq i} sv_k = \max_{1\leq k\leq i}\frac{l_k}{t_k+T} \qquad (6)$$

This is an expected pseudo speed in case that N_c does not forward a data message to a neighbor node transmitting the nth polling message. Based on (6), we evaluate the expected pseudo speed $\overline{sv}_j$ when N_c does not forward a data message to a neighbor node transmitting the jth $(i \leq j \leq n)$ polling message.

In case of $j = n$, $p(l)$ and $pp(i, n, t_n)$ are defined in an area $(-r \leq l \leq r$ and $t_i < t_n < T)$ as shown in Figure 7 and $g(i, n, t_n, l)$=$pp(i, n, t_n)\cdot p(l)$. Here, the area is divided into S and S' by a line l=$\overline{sv}_n t_n$. In S, since the pseudo speed l/t_n is higher than $\overline{sv}_n$, N_c forwards a data message to a neighbor node transmitting the nth polling message. On the other hand, since the pseudo speed l/t_n is lower than $\overline{sv}_n$ in S', N_c forwards a data message to the node transmitting not nth but kth polling message which gives the maximum $l_k/(t_k + T)$ in (6). Therefore, $\overline{sv}_{n-1}$ is evaluated by the following formula:

$$\overline{sv}_{n-1} = \int_S \frac{l}{t_n} g(i, n, t_n, l) dS + \int_{S'} \overline{sv}_n g(i, n, t_n, l) dS' \quad (7)$$

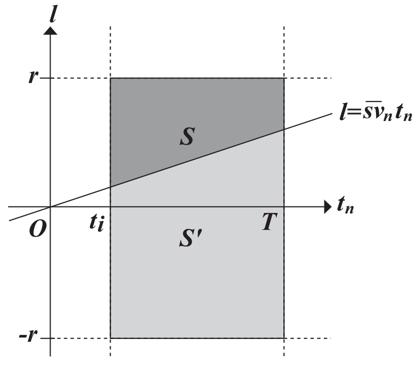

図 7 Expected Pseudo Speed where Transmitter of $n-1$th Polling Message is not Selected as Next-Hop Node.

Generally, the expected pseudo speed when N_c does not forward a data message to a neighbor node transmitting the jth ($i \leq j < n$) polling message is also evaluated as in the same way. That is, the area ($-r \leq l \leq r$ and $t_i < t_{j+1} < T$) in which $g(i, j+1, t_{j+1}, l)$ is defined is divided into sub-areas S and S' by a line $l = \overline{sv}_{j+1} t_{j+1}$ as in Figure 8. In S, since the pseudo speed l/t_{j+1} is higher

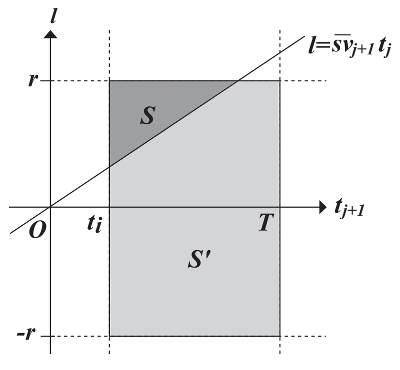

図 8 Expected Pseudo Speed where Transmitter of jth Polling Message is not Selected as Next-Hop Node.

than $\overline{sv}_{j+1}$, N_c forwards a data message to a neighbor node transmitting the $j+1$th polling message. On the other hand, since the pseudo speed l/t_{j+1} is lower than $\overline{sv}_{j+1}$ in S', N_c forwards a data message to the transmitting node of not $j+1$th polling message but a later transmitted polling message. Therefore, $\overline{sv}_j$ is evaluated by the following formula:

$$\overline{sv}_j = \int_S \frac{l}{t_{j+1}} g(i, j+1, t_{j+1}, l) dS + \int_{S'} \overline{sv}_{j+1} g(i, j+1, t_{j+1}, l) dS' \quad (8)$$

According to (6) and (8), N_c calculates $\overline{sv}_i$. Thus, if a neighbor node N which is l_i nearer to the destination node N_d than N_c transmits the ith polling message at time t_i, N_c determines whether it selects N as its next-hop node as follows:

- If $l_i/t_i \geq \overline{sv}_i$, N_c forwards a data message to N.
- Otherwise, i.e., if $l_i/t_i < \overline{sv}_i$, N_c does not forward a data message to N.

In our proposed protocol, only ID and location information of mobile nodes are piggybacked. In a wireless network with stationary nodes, it is enough for precisely estimate the pseudo speed of its neighbor nodes. However, in a mobile wireless network, since no mobility information is piggybacked, it is impossible for an intermediate node to estimate future locations of its neighbor nodes. Thus, it may possible that the achieved locations are changed when the next polling messages are transmitted. That is, l_k might be changed and in the worst case the neighbor node goes out of the wireless transmission range of the intermediate node when it transmits the next polling message. The effect is later discussed in the performance evaluation and the conclusion sections.

4. Evaluation

This section evaluates the multihop transmission performance in mobile wireless networks. In a 100m × 100m square simulation field, 1,000 mobile wireless nodes with 10m wireless signal transmission range are randomly distributed according to the unique distribution randomness. It is assumed that the interval of activations in each node is 1.0s, communication overhead for 1-hop transmission is 0.1s and the activation time offset is also randomly determined in each node according to the unique distribution in [0s, 1s). The speed of mobile wireless nodes is 0.1m/s and their mobility is according to the Random-Way-Point model. A location of a stationary destination node is also randomly determined, which is assumed to be advertised to all the mobile nodes in advance. In IRDT-GEDIR, for calculation of expectation of pseudo speed, the number of neighbor nodes n is needed; however, it is difficult for an intermediate nodes to determine n in an intermittent communication environment. Hence, the average number of mobile nodes in its wireless transmission range is applied as n in the simulation experiments. Thus, in this experiment, $n = 1,000 \div (100 \times 100) \times (10 \times 10 \times \pi) = 31$. End-to-end transmission delay and hop counts of a data message is evaluated in IRDT-GEDIR, Greedy Conventional, Conservative Conventional and Locally Optimum. Figures 9 and Figures 10 show the simulation results of 1,000 trials of end-to-end transmission delay and hop counts, respectively. The x-axis represents distances between a source mobile node and the stationary destination node when the multihop transmission is initiated.

As shown in Figures 9, independently of the mobility speed of wireless nodes, all the simulation results, i.e., both end-to-end transmission delay and hop counts are proportional to the distance between a source node to the destination node. The order of transmission delay is Locally Optimum, IRDT-GEDIR, Greedy Conventional and Conservative Conventional and the order of hop counts is Conservative Conventional, Locally Optimum, IRDT-GEDIR and Greedy Conventional. Though Conservative Conventional achieves the smallest hop counts, which means the lowest power consumption transmissions are realized, it requires too long transmission delay and suffers too high transmission failure ratio. The relation among Locally Optimum, IRDT-GEDIR and Greedy Conventional is almost the same in all the results. In IRDT-GEDIR and Greedy Conventional, 18.56% and 23.06% additional transmission delay and 21.70% and 35.64% additional hop counts are required to those of Locally Optimum. Hence, IRDT-GEDIR achieves improvement in both power consumption and end-to-end transmission delay.

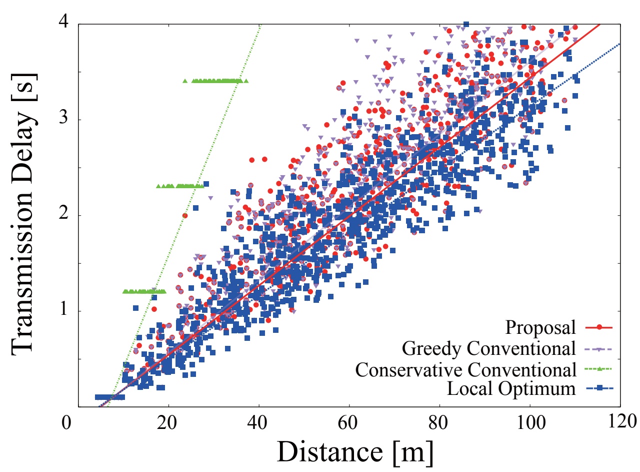

図 9 End-to-End Delay in Wireless Multihop Transmissions (0.1 m/s).

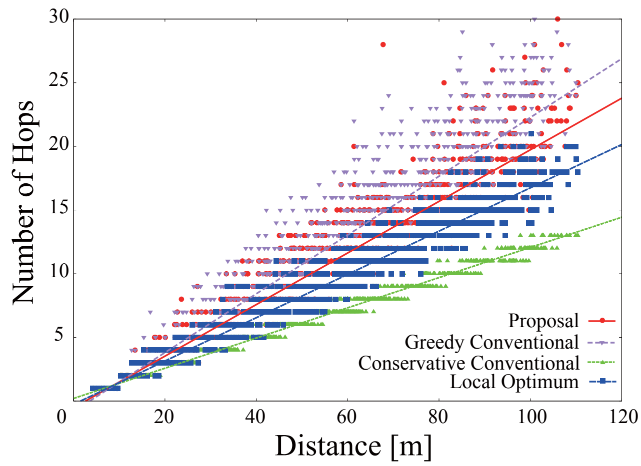

図 10 Hop Counts of Data Message Transmissions (0.1 m/s).

Next, we evaluate the relation of the computation overhead for calculation of the next-hop selection in each intermediate node and the end-to-end multihop transmission delay for data messages. The proposed probabilistic approach based on the solution of the secretary problem requires the numerical integration as in formulas (7) and (8). Thus, the more accurate the numerical integration is, the higher computational overhead is required. Hence, for reduction of end-to-end transmission delay, the trade-off between the accuracy and the computational overhead should be considered. Hence, with the same parameters in the previous simulation experiments, the effect of the interval of the numerical integration on the end-to-end transmission delay is evaluated in simulation experiments. Figure 11 shows the simulation results. The x-axis represents the interval of the numerical integration for both the time-dimension ([s]) and the distance-dimension ([m]) and the y-axis represents the relative pseudo-speed of data messages against the conventional method where data messages are transmitted to the first activated neighbor node as discussed in the previous simulation experiments. As shown in Figure 11, in cases with the short interval, the computational overhead is dominant for the end-to-end transmission delay and the relative performance is not improved. With the interval between 0.01 and 0.1, the better tradeoff is achieved and the end-to-end transmission delay is the most reduced in comparison with the conventional method. On the other hand with the long interval, the achieved calculation accuracy becomes too low, and longer end-to-end transmission delay is required. As discussed here, with the appropriate interval in the numerical integration in the proposed method, the better trade off is achieved, i.e., shorter end-to-end transmission delay is realized.

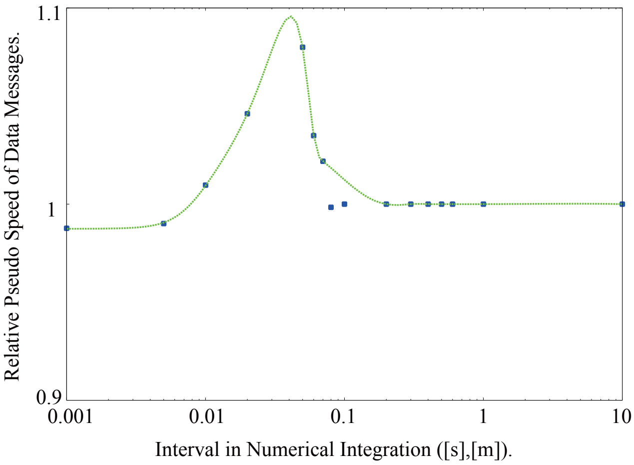

図 11 End-to-End Transmission Delay with Various interval in Numerical Integration.

5. Conclusion

This paper proposes IRDT-GEDIR which is combination of IRDT intermittent communication protocol with lower power consumption and GEDIR location-based message-by-message ad-hoc routing protocol. In intermittent communication, it is difficult for an intermediate node to select its next-hop node due to difficulty to achieve location and activation time information from neighbor nodes. By introduction of a solution of the secretaries problem and a pseudo speed criterion, a novel next-hop selection method is induced. The 1-hop simulation experiments in a stationary network show that the proposed method achieves better next-hop selection with higher pseudo speed. In addition, the wireless multihop transmission experiments in a mobile network show that it is expected for IRDT-GEDIR to achieve shorter end-to-end transmission delay and smaller hop counts of data messages even with the sleep mode in intermediate nodes due to the intermittent communication. Here, no forwarding failure occurs even without mobility information of neighbor nodes. Therefore, IRDT-GEDIR improves the performance of mobile networks.

In this paper, all the mobile nodes assume to have the same activation interval. However, it is required for mobile nodes to have different activation intervals, e.g., depending on the battery capacity. In our future work, the next-hop selection method is extended to support variation of the activation interval in nodes.

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