

Probabilistic Location-based Routing Protocol for Mobile Wireless Sensor Networks with Intermittent Communication

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Abstract: In a sensor network, sensor data messages reach the nearest stationary sink node connected to the Internet by wireless multihop transmissions. Recently, various mobile sensors are available due to advances of robotics technologies and communication technologies. A location based message-by-message routing protocol, such as Geographic Distance Routing (GEDIR) is suitable for such mobile wireless networks; however, it is required for each mobile wireless sensor node to know the current locations of all its neighbor nodes. On the other hand, various intermittent communication methods for a low power consumption requirement have been proposed for wireless sensor networks. Intermittent Receiver-driven Data Transmission (IRDT) is one of the most efficient methods; however, it is difficult to combine the location based routing and the intermittent communication. In order to solve this problem, this paper proposes a probabilistic approach IRDT-GEDIR with the help of one of the solutions of the secretaries problem. Here, each time a neighbor sensor node wakes up from its sleep mode, an intermediate sensor node determines whether it forwards its buffered sensor data messages to it or not based on an estimation of achieved pseudo speed of the messages. Simulation experiments show that IRDT-GEDIR achieves higher pseudo speed of sensor data message transmissions and shorter transmission delay than achieves shorter transmission delay than the two naive combinations of IRDT and GEDIR in sensor networks with mobile sensor nodes and a stationary sink node. In addition, the guideline of the estimated numbers of the neighbor nodes of each intermediate sensor node is provided based on the results of the simulation experiments to apply the probabilistic approach IRDT-GEDIR. *Copyright © 2015 IFSA Publishing, S. L.*

Keywords: Wireless Sensor Networks, Routing protocol, Intermittent Communication, Low Power Consumption, Mobile Sensor Nodes, Probabilistic approach.

1. Introduction

A sensor network is anticipated to play an important role of a fundamental infrastructure for Internet of Things (IoT) and the big data support. A sensor network consists of multiple wireless sensor nodes and a stationary sink node connected to the

Internet. Sensor data messages are transmitted along a wireless multihop transmission route which is a sequence of wireless sensor nodes to the sink node. Then, the sensor data messages reach a dedicated server computer through the Internet [1]. Since only limited battery capacity is available in each sensor node, it is not reasonable for each sensor node to

transmit sensor data messages directly to the sink node. Hence, each sensor node transmits sensor data messages to one of its neighbor nodes within its wireless signal transmission range. In order for the sensor data messages to reach the sink node, intermediate sensor nodes forward the received sensor data messages. For such wireless multihop transmissions, various ad-hoc routing protocols have been proposed [11]. In most of such routing protocols, it is assumed that all wireless nodes are always active; i.e., the wireless nodes can send and receive data messages anytime. However, in wireless sensor networks, due to limitation of battery capacity and difficulty for continuous power supply, low-power communication is required. Especially, for support of mobile wireless sensor networks, such as mobile robot networks with various sensors, human centric sensor networks and vehicle-mounted sensor networks for Intelligent Transport Systems (ITS), the low-power consumption requirement is serious.

Intermittent communication technique is widely introduced in sensor networks for reduction of power consumption. In each wireless sensor node, its wireless communication module should be active when it observes objects and creates sensor data messages as a source sensor node and when it forwards sensor data messages in transmission as an intermediate sensor node. Otherwise, i.e., while the wireless sensor node is not engaged in any sensor data transmissions, it gets in its sleep mode to reduce its battery consumption for longer lifetime. In order to realize the intermittent communication, it is difficult for each intermediate sensor node to synchronize with its previous- and next-hop sensor nodes. In a source sensor node, its wireless communication module is required to be active only after the sensor node observes certain objects and achieves its sensor data. Hence, it simply enters its active mode. On the other hand, in an intermediate wireless sensor node, it is required to be active before it receives sensor data messages from one of its neighbor sensor 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 sensor networks [4]. In IRDT, an intermediate wireless sensor node with sensor data messages in transmission waits for its next-hop neighbor wireless sensor 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 sensor nodes. In order to realize power-efficient routing with intermittent communication in wireless sensor networks, this paper proposes IRDT-GEDIR under an assumption that a location acquisition device, such as a GPS module is in each

sensor node. IRDT-GEDIR [8] is a combination of IRDT and a well-known location-based greedy ad-hoc routing protocol Geographic Distance Routing (GEDIR) [9]. GEDIR is based on the message-by-message routing, which is suitable for various sensor networks where short sensor data messages are usually transmitted and especially for dynamic sensor networks whose topology is not stable due to mobility of sensor nodes and their removal caused by battery consumption and failure. An asynchronous intermittent communication reduces power consumption; however, the transmission delay of sensor data messages usually gets longer by synchronization overhead in each intermediate sensor node with its previous- and next-hop sensor nodes. In addition, for combination of IRDT and GEDIR, location acquisition overhead for next-hop selection is not negligible in mobile wireless sensor networks. In IRDT-GEDIR, introduction of a novel probabilistic next-hop selection method reduces the transmission delay of data messages.

This paper is organized as follows: Section 2 shows the related works for intermittent sensor data transmission protocols. In Section 3, we propose IRDT-GEDIR which combines intermittent sensor data transmissions and a geographical ad-hoc routing protocol. Section 4 evaluates the performance of IRDT-GEDIR. Section 5 concludes this paper and shows the future works.

2. Related Works

Battery capacity in sensor nodes consisting of wireless sensor networks is limited and usually there is no continuous power supply to them. Hence, intermittent communication is introduced where sensor nodes switch between their active and sleep modes [10]. Their communication module works only in the active modes. In order for sensor data messages to be transmitted to the sink node along a wireless multihop transmission route, each intermediate sensor node should be in the active mode when its previous-hop node forwards a sensor data message. Such intermittent communication methods are classified into synchronous and asynchronous. In the synchronous methods, all the sensor nodes are closely synchronized and each sensor node transmits sensor data messages according to a predetermined schedule as in Traffic-Adaptive Medium Access Protocol (TRAMA) [12] and Lightweight Medium Access Protocol (LMAC) [5]. However, they are based on the close synchronization among sensor nodes which requires frequent exchange of control messages as the distributed clock synchronization protocols [3]. Even though the required clock synchronization overhead is acceptable, additional control messages are required to be transmitted to update their sleep-wakeup schedules consistently to follow the unstable network topology due to the mobility of the wireless sensor nodes.

On the other hand, in the asynchronous methods,

synchronization among neighbor nodes is required only when a sensor node forwards a sensor data message to its next-hop sensor node. In LPL [6], when a sensor node requests to transmit a sensor data message to its next-hop sensor 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 sensor node as shown in Fig. 1. In IRDT [4], a current-hop sensor node N_c waits for receipt of a polling message from its next-hop sensor node N_n as in Fig. 2. Every sensor 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 sensor nodes is realized.

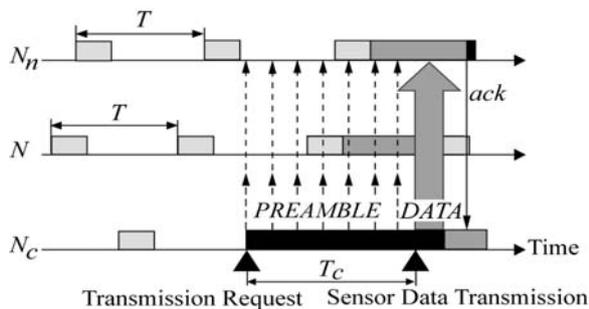


Fig. 1. LPL Intermittent Communication.

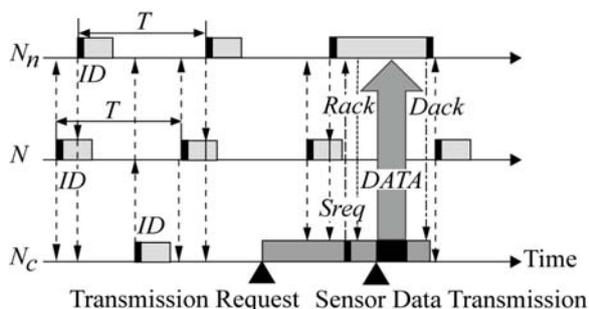


Fig. 2. IRDT Intermittent Communication.

In [7], a wireless multihop routing protocol for IRDT-based sensor networks has been proposed. It is a proactive routing protocol where each sensor node

keeps its routing table for the shortest transmission route to a sink node up-to-date. In order for the sensor nodes to determine their next-hop neighbor sensor node, a flooding of a control message initiated by the sink node is applied. Though it works well in usual ad-hoc networks consisting of always-on mobile nodes, it is difficult for sensor networks with intermittent communication since a control message is not always received by all the neighbor sensor nodes due to their sleep mode. Thus, the control message is required to be retransmitted. Hence, in the worst case, a sensor node unicasts the control message to all its neighbor nodes one by one. In addition, in order to support mobile wireless sensor 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 sensor nodes.

3. Proposal

3.1. Next-Hop Selection

As discussed in the previous section, for wireless multihop transmissions of sensor data messages to reach a stationary sink node with the intermittent communication in mobile wireless sensor nodes, a novel routing protocol is required to be developed. In order to reduce the communication overhead and transmission delay for sensor data message transmissions with intermittent communication, this paper proposes a combination IRDT-GEDIR of IRDT and GEDIR [9] which is one of the well-known location-based ad-hoc routing protocols with low communication overhead for synchronization among sensor 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 sensor 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.

An intermediate wireless sensor node N_c selects one of its neighbor sensor node N_n as its next-hop node where the distance $d_n = |N_n S|$ to the sink node S is the shortest among all its neighbor sensor nodes as shown in Fig. 3.

In IRDT, each sensor node transmits a polling message each time it enters its active mode. Thus, by piggybacking its location information to the polling message as in Fig. 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 sensor nodes since they might be in their sleep mode where their network interfaces do not work. If the sensor 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 sensor network, the achieved location information gets stale and the most up-to-date location information is required for the next-hop selection.

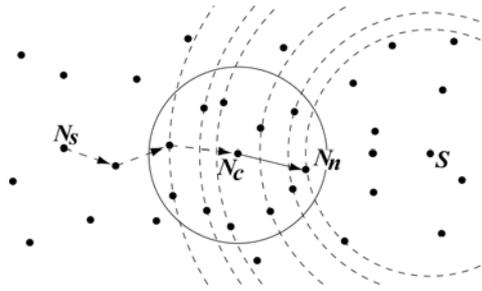


Fig. 3. GEDIR Overview.

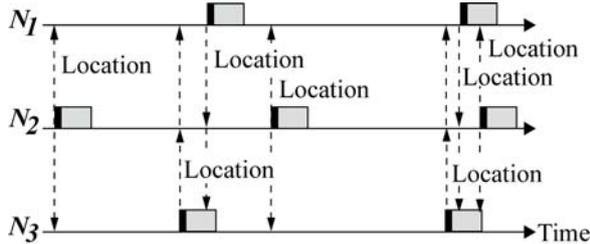


Fig. 4. Location Information Propagation by Polling Messages.

An intermediate sensor node N_c requires location information of its neighbor nodes only when it has a sensor data message to be transmitted to the sink node through its next-hop sensor node. Thus, in our proposal, based on the location information piggybacked to the received polling messages, N_c determines its next-hop sensor node. Here, since a neighbor sensor 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 sensor nodes are selected as its next-hop node. In GEDIR, the distance to the destination sink node is applied as the criterion for selection of its next-hop node for achieving shorter transmission route to the sink node. On the other hand in IRDT-GEDIR, since wireless sensor nodes communicate intermittently, forwarding to the

neighbor sensor node nearest to the destination sink node does not always reduce the transmission delay. Even when a sensor node N is not the nearest to the sink 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 sensor data message transmission which is achieved by division of difference of distance to the sink node S , i.e., $|N_c S| - |NS|$ by the time duration between the transmission request and receipt of the polling message as shown in Fig. 5. It is a reasonable criterion for selection of a next-hop sensor node in intermittent communication environments for shorter transmission delay to the sink node.

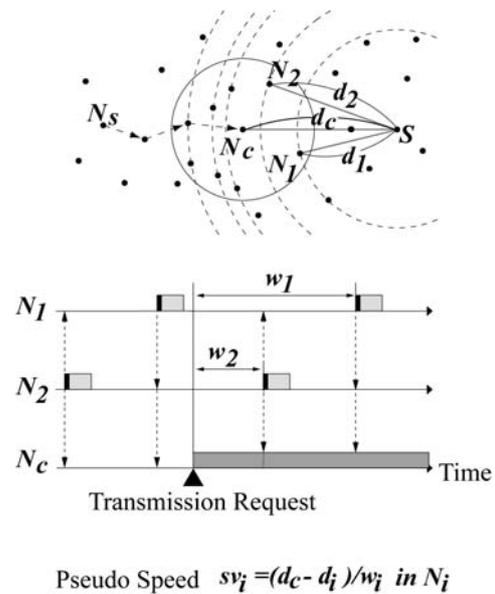


Fig. 5. Next-Hop Selection based on Pseudo Speed.

Due to IRDT intermittent communication, an intermediate sensor node N_c should determine whether it selects a neighbor sensor node N as its next-hop node soon after it receives a polling message from N since N_c should transmits a *Sreq* message to N while N is in its active mode. That is, N_c can't compare all pseudo speed sv_i each of which is achieved in case that N_c forwards a sensor 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].

The secretaries problem is one of the famous problems of the optimal stopping theory. It has been studied extensively in the fields of applied probability, statistics and decision theory. The basic form of the problem is as follows:

- An administrator is willing to hire the best secretary out of n rankable candidates.
- The candidates are interviewed one by one in a random order.

- A decision about each particular candidate is to be taken immediately after the interview.
- Once rejected, a candidate cannot be recalled.
- During the interview, the administrator can rank the candidate among all candidates interviewed so far; however, it cannot rank the candidate among unseen forthcoming candidates.
- The problem is about the optimal strategy to maximize the expectation of the rank of the selected candidate.

In our next-hop selection, neighbor nodes get active one by one and an intermediate sensor node with sensor 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 sensor 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 sensor nodes. If $sv > \overline{sv}$, N_c transmits a *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 a *Sreq*.

3.2. Expectation of Pseudo Speed

In the proposed method in the previous subsection, an intermediate sensor node determines whether it forwards a sensor data message to a currently active neighbor sensor 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 sensor nodes, i.e., the interval of consecutive transmissions of polling messages and n be the number of neighbor sensor nodes of an intermediate sensor node N_c with a sensor data message in transmission.

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

$$DP(d) = \frac{S(d)}{\pi r^2} = \frac{2}{\pi r^2} \left(\int_{d_c-d}^{x'} \sqrt{d^2 - (x-d_c)^2} dx + \int_{x'}^r \sqrt{r^2 - x^2} dx \right), \quad (1)$$

where $x' = (d_c^2 + r^2 - d^2)/2d_c$.

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

$$dp(d) = \frac{d}{dd} DP(d) = \frac{2}{\pi r^2} \frac{d}{dd} \left(\int_{d_c-d}^{x'} \sqrt{d^2 - (x-d_c)^2} dx + \int_{x'}^r \sqrt{r^2 - x^2} dx \right) \quad (2)$$

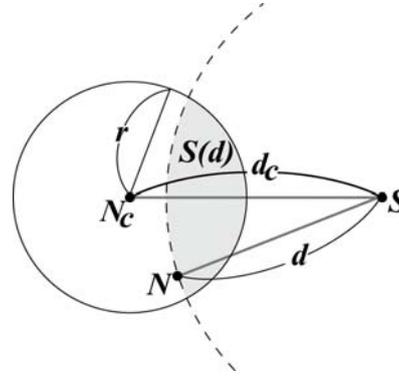


Fig. 6. Area of Candidates of Next-Hop Node.

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

$$p(l) = dp(d_c - l) = -\frac{2}{\pi r^2} \frac{d}{dl} \left(\int_l^{x''} \sqrt{(x-l)(2d_c - l - x)} dx + \int_{x''}^r \sqrt{r^2 - x^2} dx \right), \quad (3)$$

where $x'' = ((2d_c - l)l + r^2)/2d_c$.

Next, we examine the distribution of time duration from the transmission request of a sensor 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 i^{th} polling message is transmitted from one of the neighbor nodes of N_c . Thus, $i - 1$ neighbor sensor nodes transmit polling messages in an interval $[0, t_i)$ and the rest $n - i$ neighbor sensor 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 sensor nodes are

distributed in the interval (t_i, T) according to the unique distribution, the probability density function $pp(i, j, t)$ where j^{th} ($i < j \leq n$) polling message is transmitted from one of the neighbor sensor nodes of N_c at time $t \in (t_i, T)$ is as follows:

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

Since the location of a neighbor sensor 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 sensor data message to a neighbor sensor node N which transmits the j^{th} ($i < j \leq n$) polling message at time t

($t_i < t < T$) and the distance to the sink node S is reduced l by this forwarding is induced by (3) and (4) as follows:

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

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

In case that N_c does not select a neighbor sensor node which transmits the i^{th} polling message at t_i as its next-hop node, N_c selects another sensor node which transmits the j^{th} ($i < j \leq n$) polling message at t_j ($t_i < t_j < T$) or a sensor node transmitting its second polling message after $t = T$. In the latter case, k^{th} ($1 \leq k \leq i$) 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 sensor data message at $t \geq T$ is as follows:

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

This is an expected pseudo speed in case that N_c does not forward a sensor data message to a neighbor node transmitting the n^{th} polling message. Based on (6), we evaluate the expected pseudo speed \bar{sv}_j when N_c does not forward a sensor data message to a neighbor node transmitting the j^{th} ($i \leq j \leq n$) 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 Fig. 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 $l = \bar{sv}_n t_n$. In S , since the pseudo speed l/t_n is higher than \bar{sv}_n , N_c forwards a sensor data message to a neighbor node transmitting the n^{th} polling message. On the other

hand, since the pseudo speed l/t_n is lower than \bar{sv}_n in S' , N_c forwards a sensor data message to the node transmitting not n^{th} but k^{th} polling message which gives the maximum $l_k/(t_k + T)$ in (6). Therefore, \bar{sv}_{n-1} is evaluated by the following formula:

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

Generally, the expected pseudo speed when N_c does not forward a sensor data message to a neighbor node transmitting the j^{th} ($i \leq j < n$) 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 $l = \bar{sv}_{j+1} t_{j+1}$ as in Fig. 8.

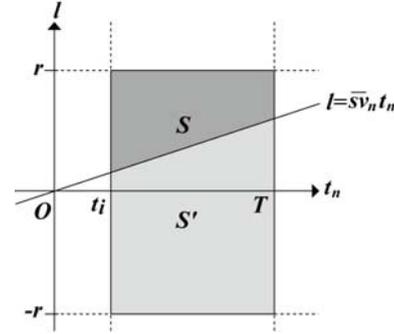


Fig. 7. Expected Pseudo Speed where Transmitter of $(n-1)^{th}$ Polling Message is not Selected as Next-Hop Node.

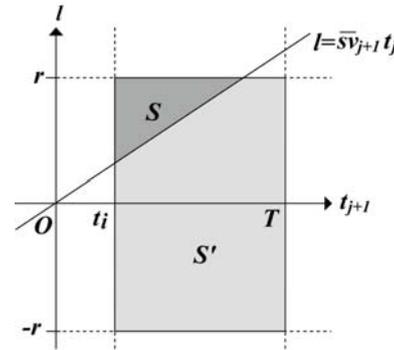


Fig. 8. Expected Pseudo Speed where Transmitter of j^{th} Polling Message is not Selected as Next-Hop Node.

In S , since the pseudo speed l/t_{j+1} is higher than \bar{sv}_{j+1} , N_c forwards a sensor 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 \bar{sv}_{j+1} in S' , N_c forwards a sensor data message to the transmitting node of not $(j+1)^{th}$ polling message but a later transmitted polling message. Therefore, \bar{sv}_j is evaluated by the following formula:

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

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

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

In our proposed protocol, only ID and location information of mobile sensor nodes are piggybacked. In a wireless sensor network with stationary sensor nodes, it is enough for precisely estimate the pseudo speed of its neighbor nodes. However, in a mobile wireless sensor 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

4.1. 1-hop Performance and Estimation of Number of Neighbor Nodes

First, we evaluate the 1-hop transmission performance achieved by the proposed IRDT-GEDIR next-hop selection method. Here, pseudo speed is evaluated in IRDT-GEDIR and two conventional naive methods. A wireless transmission range of a wireless sensor node is assumed 10 m and the distance from an intermediate node N_c currently holding a sensor data message to the sink node is 100 m.

5-20 neighbor sensor nodes are randomly distributed in a wireless signal transmission range according to the unique distribution randomness. All sensor nodes are assumed stationary. The interval of activations in each sensor node is 1 s and the initial activation time is also randomly determined. The proposed IRDT-GEDIR is compared with the following two conventional methods and an unrealistic locally optimum method:

- N_c forwards a sensor data message to the neighbor node which transmits the first polling message after the transmission request in N_c . (Greedy Conventional).
- N_c forwards a sensor data message to the neighbor node which provides the highest pseudo

speed determined after receiving polling messages from all the neighbor nodes of N_c . (Conservative Conventional).

· N_c forwards a sensor data message to the neighbor node which provides the highest pseudo speed determined by the information of locations and activation times in all the neighbor nodes. (Locally Optimum).

Locally Optimum is evaluated only for comparison since it is impossible for N_c to achieve location information of its neighbor nodes without any overhead. If N_c is a dead-end node which cannot select its next-hop node, the pseudo speed is evaluated as 0 m/s.

Figs. 9-12 show the results of simulation experiments. Here, the value of the distribution function $f(sv) = p(sv' < sv)$ of Probability where pseudo speed sv' is lower than sv .

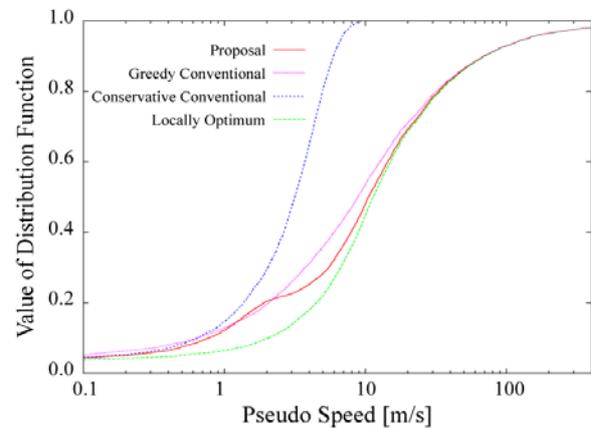


Fig. 9. 1-Hop Transmission Performance (5 Neighbor Nodes).

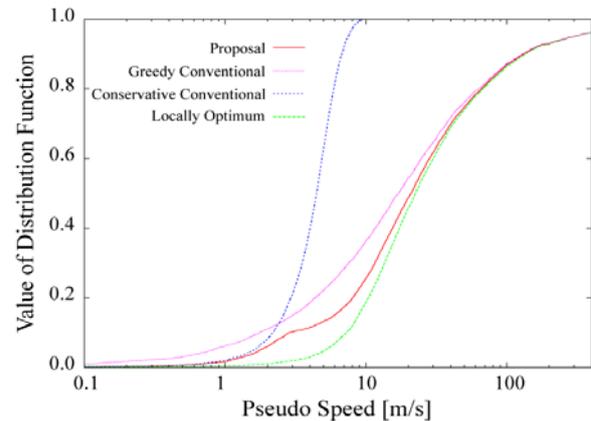


Fig. 10. 1-Hop Transmission Performance (10 Neighbor Nodes).

In all the results, higher pseudo speed is achieved in the order IRDT-GEDIR, Greedy Conventional and Conservative Conventional. Locally Optimum provides the ideal pseudo speed, since N_c achieves all the required information to determine its next-hop node in advance. The performance of Conservative

Conventional is low since the overhead to receive all the polling messages is too high. Though the performance of Greedy Conventional and IRDT-GEDIR is almost the same in low density environments, higher pseudo speed is achieved by IRDT-GEDIR in more dense environments. In IRDT-GEDIR, no additional control messages are required to determine its next-hop node as discussed in the previous section. Therefore, IRDT-GEDIR is expected to realize low-power shorter-delay transmissions of sensor data messages in intermittent wireless sensor networks.

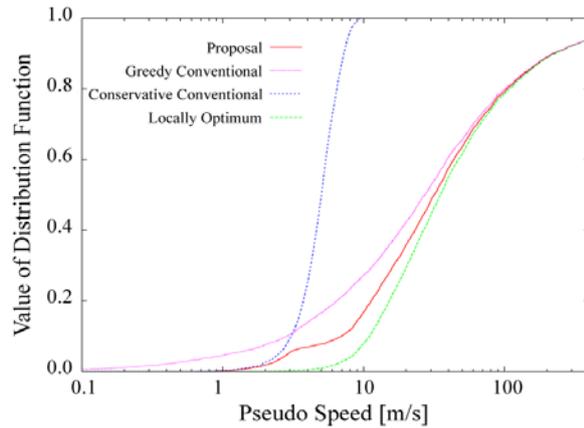


Fig. 11. 1-Hop Transmission Performance (15 Neighbor Nodes).

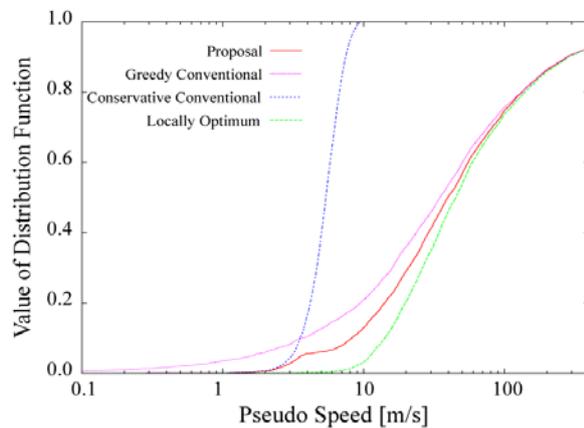


Fig. 12. 1-Hop Transmission Performance (20 Neighbor Nodes).

In the proposed IRDT-GEDIR, a number n of neighbor sensor nodes of an intermediate sensor node is mandatory to select its next-hop node to which sensor data messages in transmission is forwarded. If the sensor network is designed cautiously, i.e., all the sensor nodes are placed prudently, the schedule of their intermittent communication is carefully designed and all the sensor nodes are always sound without autonomous mobility and accidental failure, all the sensor nodes always achieve the precise numbers of their neighbor nodes. However, in

environments to which IRDT-GEDIR is applied, each sensor node communicates intermittently and it is difficult for the sensor node to achieve the number of its neighbor nodes precisely. This is because a sensor node cannot always receive the polling messages transmitted from its neighbor nodes, there may be hardware- and software-faults in its neighbor sensor nodes, battery capacity may be exhausted in some neighbor sensor nodes and the topology of the sensor network may be changed since all or part of the sensor nodes are mobile. Therefore, even though it is difficult or almost impossible for an intermediate sensor node to achieve the precise number of its neighbor nodes, it is required for it to estimate the number of its neighbor nodes. Here, we evaluate the effects on the transmission performance, i.e., pseudo speed of sensor data messages, of the difference between the real number n of its neighbor nodes and its estimation n^e .

The simulation settings are almost the same as the 1-hop performance evaluation experiments. Fig. 13 shows the results of the experiments where the number of the neighbor sensor nodes of the intermediate sensor node is 5 ($n=5$) and the estimation n^e of the number of the neighbor sensor nodes in the next-hop selection algorithm is varied ($2 \leq n^e \leq 10$). Here, when the intermediate node applies the precise estimation ($n^e=n$) to the next-hop selection algorithm, the highest performance is achieved. If the estimation is smaller ($n^e < n$), though the achieved pseudo speed is lower than the best one, the performance degradation is not so high. Otherwise, if the estimation is larger ($n^e > n$), the achieved pseudo speed is also lower than the best one. Though the performance degradation when $n^e = n + 1$ is exceptionally small, it is remarkable and unacceptable when $n^e > n + 1$. Fig. 14 shows the results of the experiments where the estimated number of the sensor nodes of the intermediate sensor node is fixed ($n^e=5$) and the real numbers of the neighbor sensor nodes are varied ($2 \leq n \leq 10$). The results show almost the same inclination as the previous experiments. The best performance is achieved when $n^e = n$ and almost the same distribution of the achieved pseudo speed when $n^e \leq n - 1$. However, the performance becomes extremely lower when $n^e < n - 1$. Therefore, it is recommended that the number of the neighbor sensor nodes is estimated slightly smaller for achieving higher pseudo speed of sensor data messages averagely.

4.2. Multihop Transmission Performance

Next, we evaluate the multihop transmission performance in mobile wireless sensor networks. In a $100 \text{ m} \times 100 \text{ m}$ square simulation field, 1,000 mobile wireless sensor nodes with 10 m wireless signal transmission range are randomly distributed according to the unique distribution randomness. It is

assumed that the interval of activations in each sensor node is 1.0 s, communication overhead for 1-hop transmission is 0.1 s and the activation time offset is also randomly determined in each sensor node according to the unique distribution in [0 s, 1 s).

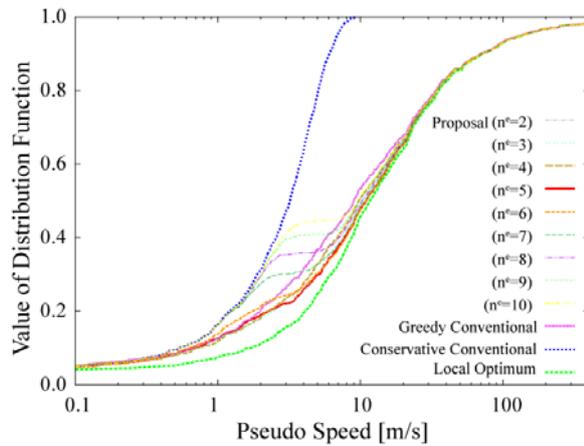


Fig. 13. Performance Evaluation with Various Estimation Numbers of Neighbor Sensor Nodes.

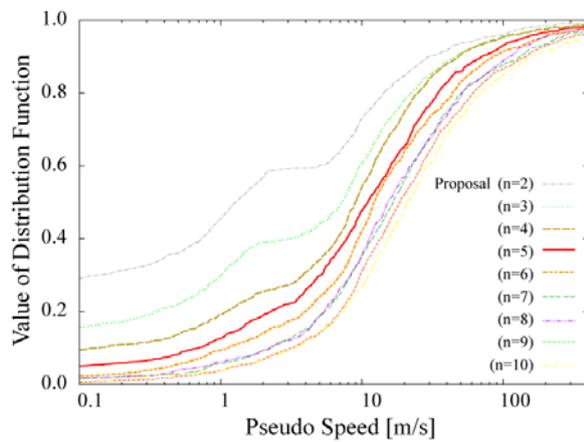


Fig. 14. Performance Evaluation with Various Numbers of Neighbor Sensor Nodes and Fixed Estimation.

The speed of mobile wireless nodes is 0.1-2.0 m/s and their mobility is according to the Random-Way-Point model. A location of a stationary sink node is also randomly determined, which is assumed to be advertised to all the mobile sensor 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 intermediate sensor nodes to determine n in an intermittent communication environment. Hence, the average number of mobile sensor nodes in its wireless transmission range is applied as n in the simulation experiments. Thus, according to the discussion of the estimation of the number of the neighbor nodes in the previous subsection, in these experiments,

$n = \lfloor 1,000 \div (100 \times 100) \times (10 \times 10 \times \pi) \rfloor = 31$. End-to-end transmission delay and hop counts of a sensor data message is evaluated in IRDT-GEDIR, Greedy Conventional, Conservative Conventional and Locally Optimum. Fig. 15-19 and Fig. 20-24 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 sensor node and the stationary sink node when the multihop transmission is initiated.

Though an intermediate sensor node transmits a sensor data message soon after it receives a polling message from one of its neighbor sensor nodes in Greedy Conventional and Locally Optimum. However, it determines its next-hop sensor node after receipt of all the polling message always in Conservative Conventional and sometimes in IRDT-GEDIR. In such cases, due to the interval between the receipt of the polling message and the transmission of a sensor data message and mobility of the sensor nodes, it may fail to forward the sensor data message if the neighbor node moves out of the wireless transmission range. In our simulation results, only Conservative Conventional fails to forward as shown in Table 1. Thus, it is not suitable especially for high speed mobility.

Table 1. Ratio of Forwarding Failure in Conservative Conventional.

Mobility Speed [m/s]	0.1	0.2	0.5	1.0	2.0
Failure Ratio [%]	15.9	26.1	64.6	74.0	88.3

As shown in Fig. 15-24, independently of the mobility speed of wireless sensor nodes, all the simulation results, i.e., both end-to-end transmission delay and hop counts are proportional to the distance between a source sensor node to the destination sink 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.

7. Conclusions

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.

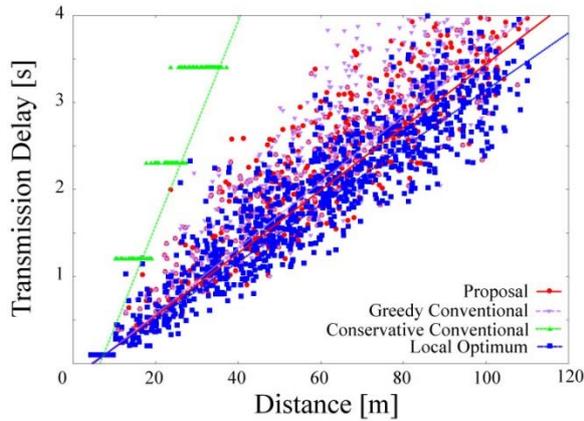


Fig. 15. End-to-End Delay in Wireless Multihop Transmissions (0.1 m/s).

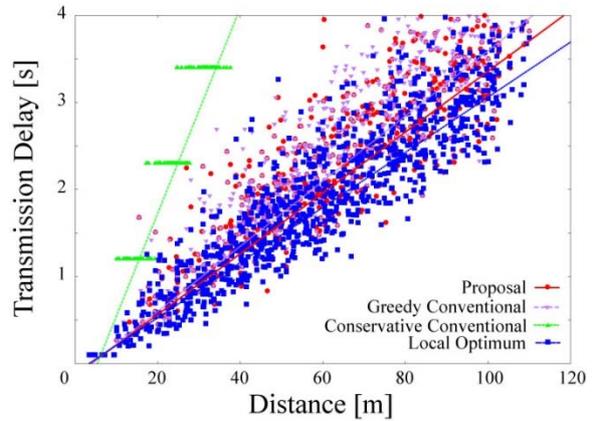


Fig. 16. End-to-End Delay in Wireless Multihop Transmissions (0.2 m/s).

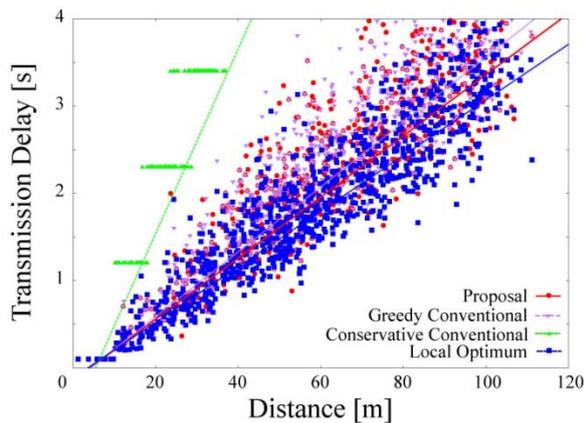


Fig. 17. End-to-End Delay in Wireless Multihop Transmissions (0.5 m/s).

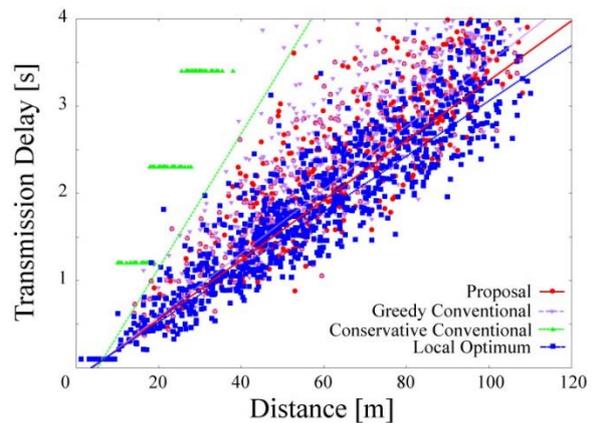


Fig. 18. End-to-End Delay in Wireless Multihop Transmissions (1.0 m/s).

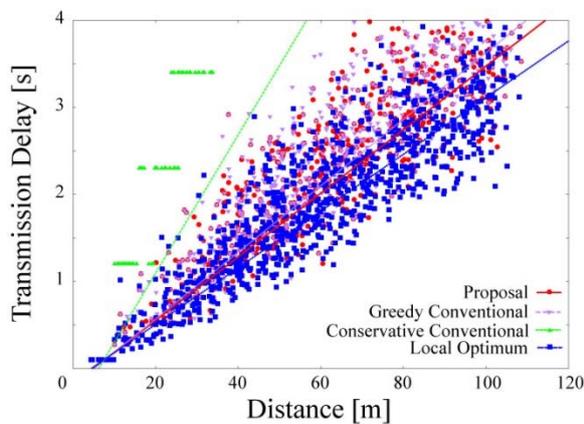


Fig. 19. End-to-End Delay in Wireless Multihop Transmissions (2.0 m/s).

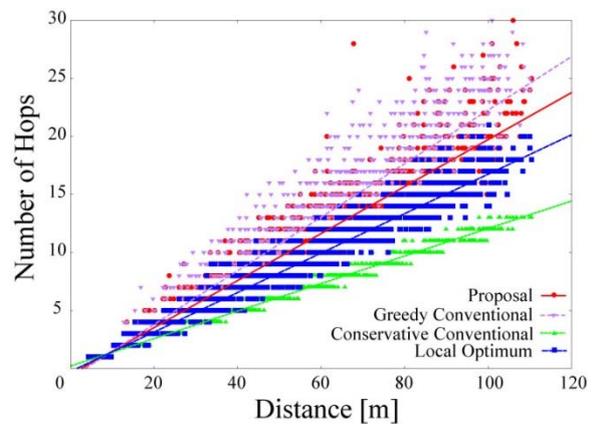


Fig. 20. Hop Counts of Data Message Transmissions (0.1 m/s).

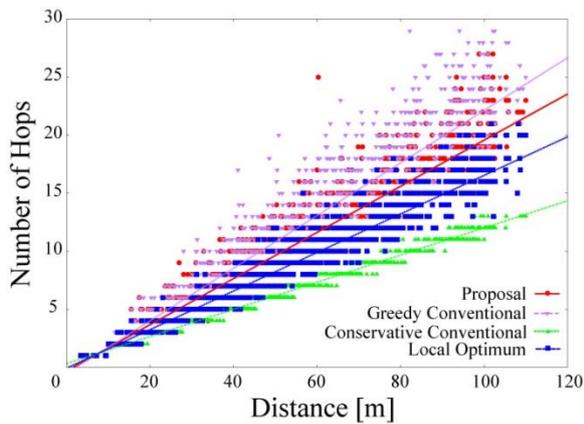


Fig. 21. Hop Counts of Data Message Transmissions (0.2 m/s).

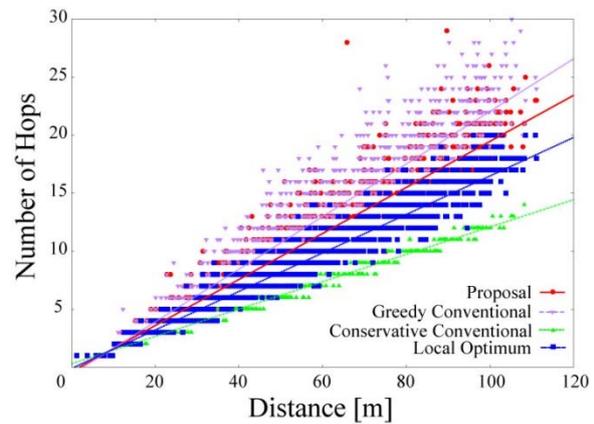


Fig. 22. Hop Counts of Data Message Transmissions (0.5 m/s).

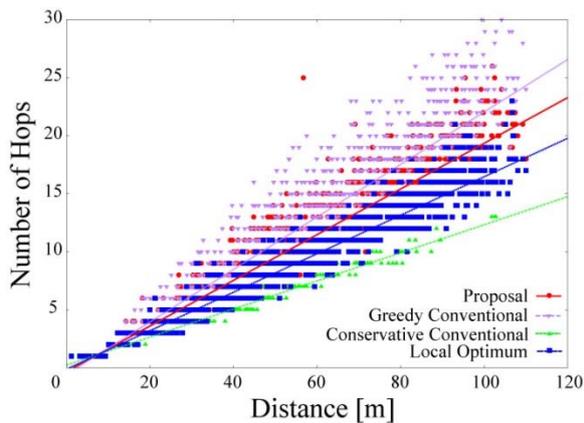


Fig. 23. Hop Counts of Data Message Transmissions (1.0 m/s).

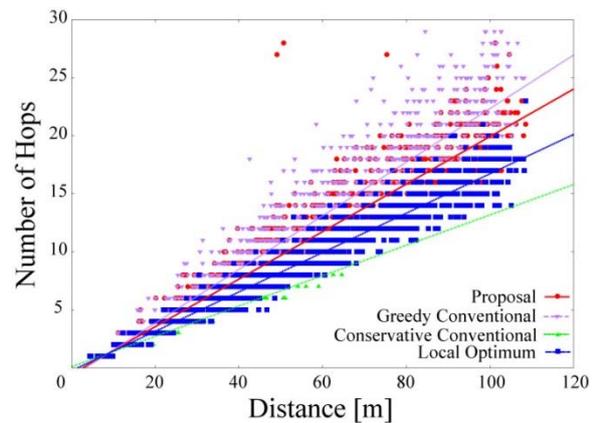


Fig. 24. Hop Counts of Data Message Transmissions (2.0 m/s).

The 1-hop simulation experiments in a stationary sensor 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 sensor network show that it is expected for IRDT-GEDIR to achieve shorter end-to-end transmission delay and smaller hop counts of sensor data messages even with the sleep mode in intermediate sensor 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 sensor networks.

In this paper, all the mobile sensor nodes assume to have the same activation interval. However, it is required for mobile sensor 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 sensor nodes.

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