Optimal distance geographic routing for energy efficient wireless sensor networks

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Abstract: Wireless sensor networks require energy efficient routing protocols owing to limited resource on the sensor node. In this paper, we develop optimal distance geographic routing (ODGR), an application-independent algorithm that uses geographic information and power control in the transmission scheme to dynamically explore the optimal routing path. ODGR is derived from fundamental radio energy model to minimise total communication energy using convex theory. Case study on a two-dimensional array network shows that ODGR is able to reduce total communication energy by 66.41% and 43.89%, and average latency by 76.45% and 26.27%, when compared to traditional MTE and cluster algorithms.

Keywords: wireless sensor networks; geographic routing; optimal distance; minimum energy.

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1 Introduction

Wireless sensor networks represent an emerging technology that has become very appealing to researchers in recent years. It is considered as the next generation technology to bridge between the internet and the physical world. Many research projects on wireless sensor networks have been reported and developed for military, industrial and biomedical applications (Pottie and Kaiser, 2000; Warneke et al., 2001; Zhao and Guibas, 2004).

Routing protocol is a key component in the network layer of a wireless sensor network (WSN). In literature, many legacy routing protocols have been well studied for wired networks and mobile ad hoc networks (MANET). But these existing protocols may not work well for wireless sensor networks because of the fundamental differences between WSN and these two traditional networks. Generally a wireless sensor network consists of a large number of sensor nodes, and each node has limited capacities, such as battery power, transmission range, data storage, processing speed and mobility. For example, shortest path routing protocol for wired network may not be directly applied to WSN because the sensor node does not have a sizable memory to store the entire routing table of a large network. Existing MANET routing approaches also may not be suitable for sensor networks, because the sensor nodes are normally quasi-static and possess much less energy resource and bandwidth as those in a mobile ad hoc network.

In recent years, various routing protocols have been successfully developed for different applications of wireless sensor networks. The minimum transmission energy (MTE) model is a popular energy-aware routing algorithm (Ettus, 1998). It assumes that the transmission energy is proportional to the square of distance, which is generally true for a power amplifier in free-space transmissions. MTE chooses the nearest neighbour node in the path to forward data such that the total energy consumed by the amplifiers is minimal. MTE ignores the energy consumed by the transmitter and receiver circuitries and does not consider the geographic node locations, therefore may not always produce the lowest energy routing path. A well-known cluster-based algorithm, namely low-energy adaptive clustering hierarchy (LEACH), applies a clustering technique to group a set of neighbourhood nodes into a cluster, and the cluster head is responsible for transmitting data directly to the base station (Heinzelman et al., 2002). An improved LEACH-C protocol rotates the cluster head at the aim of averaging the power consumptions on all nodes. LEACH assumes that all the nodes have enough power to transmit directly to the base station, which is hardly possible for a large-area sensor network because of the radio transmission power constraint and the limitation of energy supply.

There also exist many other well-known routing protocols in wireless sensor networks. Direct diffusion is a data-centric routing algorithm developed for information dissemination in sensor networks (Intanagonwiwat et al., 2000; Ganesan et al., 2004). This algorithm assumes that all nodes in the network are application-aware, and data aggregations can be performed along the routing path. Power-efficient gathering in sensor information systems (PEGASIS) (Lindsey and Raghavendra, 2002) is a near optimal chain-based protocol that is an improvement over LEACH. Karp and Kung (2000) developed greedy perimeter stateless routing (GPSR) that makes greedy forwarding decision using information about its immediate neighbours. Geographic and energy-aware routing (GEAR) is based on query-response model (Yu et al., 2001). A comparison of these existing protocols was given by Ahmed et al. (2003). Most of the protocols listed above are domain-specific, so one may have better performance than others in certain types of particular applications.

While conventional routing algorithms are developed based on applications modelling, we take a different approach to investigate the optimal distance model in multihop routing from the fundamental radio energy equations. The ODGR routing algorithm is then developed based on the optimal distance to find a minimum energy routing path between the source and the destination, assuming every node knows the geographic locations of the destination and all neighbour nodes within a predetermined distance. This new algorithm incorporates two important physical properties of sensor networks: power control and geographic location. In some aspects, ODGR is a hybrid of MTE and LEACH protocols, because it takes the shortest path from source to destination while using direct transmission as much as possible. The ODGR protocol is a novel multihop geographic-based routing approach that can be integrated into many wireless sensor networks.

The rest of paper is organised as follows: Section 2 presents the development the ODGR algorithm to find the optimal number of hops and optimal distance per hop by minimising the total communication energy consumption. Section 3 presents the detailed procedure of ODGR for practical implementation. The performance of ODGR algorithm is then compared with MTE and LEACH protocols through a case study in Section 4, followed by the conclusions in Section 5.

2 Optimal distance geographic routing

In wireless sensor networks, the source and the destination nodes are generally distanced away. As the distance grows larger, direct transmission between source and sink becomes inefficient owing to large energy consumption. Thus, multihop routing through intermediate nodes is necessary. In this section, we develop an energy efficient multihop routing algorithm based on node geographic location information. Starting from the fundamental communication energy model, we use the convexity theory to find the optimal number of hops and the optimal distance per hop such that the total communication energy is minimal. Assuming each node knows the location of the destination and the locations of its neighbour nodes within a preset range, the ODGR algorithm finds a node in the proximity of the desired next hop location and adjusts the transmit power to forward the packet to the next node.

2.1 Radio energy model

We assume a simple model for radio communication energy consumptions that include the energy dissipated by the transmitter circuitry and power amplifier, and the energy consumed by the receiver circuitry. We adopt the energy model from Heinzelman et al. (2002) and define the energy consumptions for free-space ($h < d_0$) and multipath ($h \geq d_0$) radio communications in equation (1).

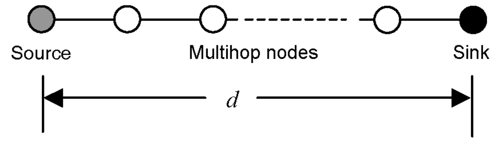
$$E(h) = \begin{cases} 2l\varepsilon_{\text{elec}} + l\varepsilon_{fs-\text{amp}}h^2 \ \textit{if} \ h < d_0 \\ 2l\varepsilon_{\text{elec}} + l\varepsilon_{mp-\text{amp}}h^4 \ \textit{if} \ h \geq d_0 \end{cases} \tag{1}$$

$$d_0 = \sqrt{\frac{\varepsilon_{fs-\text{amp}}}{\varepsilon_{mp-\text{amp}}}}, \tag{2}$$

where l is the number of bits in a packet, h is the distance between the transmitter and the receiver nodes and $\varepsilon_{\text{elec}}$ is the electronics energy for the transceiver circuitry. $\varepsilon_{fs\text{–amp}}$ and $\varepsilon_{mp\text{–amp}}$ denote power amplifier energy dissipations at free-space and multipath modes, respectively, and d_0 is the threshold distance computed in equation (2). These physical parameters are defined by the selected radio device.

There are three approaches to transmit data from source to sink in a simple linear network as shown in Figure 1: (1) the source directly transmits a packet to the sink, also referred as direct transmission; (2) the source transmits a packet to its nearest neighbour in the path, and the same procedure is repeated by every node until the packet reaches the sink; (3) only a few nodes are selected along the transmission path. Apparently, the first and second approaches are special cases of the third one. Although all three approaches are able to deliver the data to the sink, we are interested in the selection of a proper number of multihop nodes to reduce the total radio energy consumptions.

Figure 1 An example of multihop communication



2.2 *Convex optimisation for minimal energy*

A general problem can be formulated as follows: given a distance d between source and sink and the system parameters, find the optimal number of hops n and the distance per hop h_i such that the total communication energy E is minimal. Mathematically, it is a convex optimisation problem, as defined in equation (3).

$$(n,h_i)=\underset{\sum_{i=1}^{n}h_i=d,\ h_i>0,\ n\in N}{\arg\min}\left[\sum_{i=1}^{n}E(h_i)\right]. \tag{3}$$

It is revealed from the convexity theory that uniform distribution of h_i results from the minimal value of total energy, so the distance for every transmission hop is equal to h.

$$h_1=h_2=\cdots=h_n=\frac{d}{n}=h. \tag{4}$$

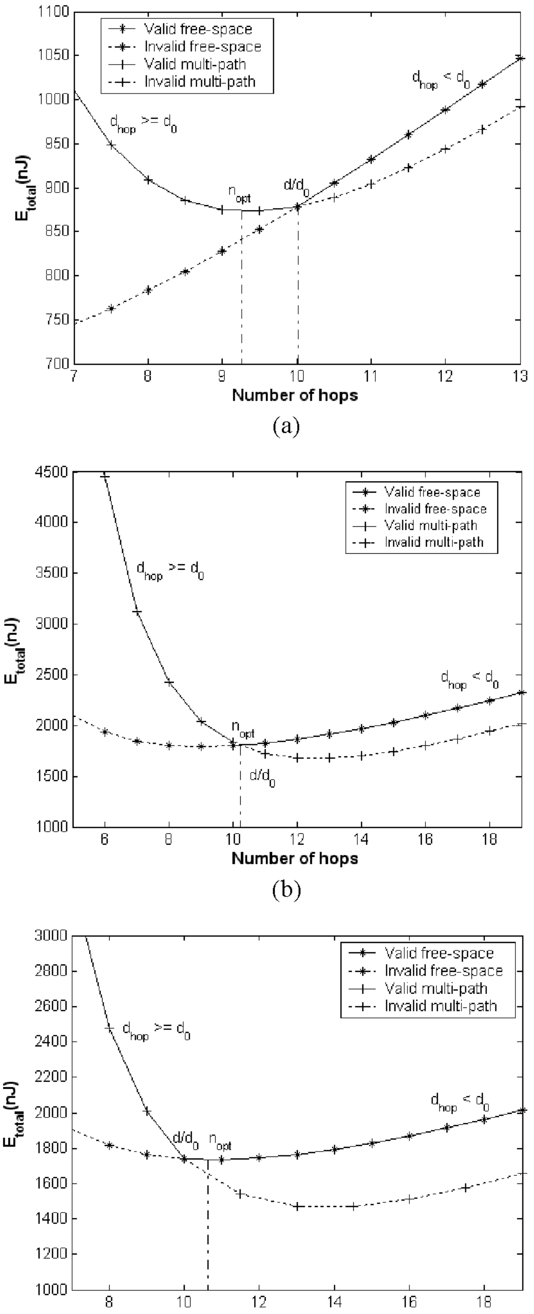
Substituting equations (1) and (4) into equation (3), we can find the optimal number of hops n_{opt} and the distance per hop h_{opt} by setting the derivative of total communication energy with respect to n to zero. Because n_{opt} is a function of system parameters $\varepsilon_{\text{elec}}$, $\varepsilon_{fs\text{-amp}}$ and $\varepsilon_{mp\text{-amp}}$, three network categories are identified in Table 1 and the optimal number of hops is listed for each case as well.

Table 1 The optimal solutions of the minimal energy problem

	Category	n_{opt}	h_{opt}
I	$\varepsilon_{fs-\text{amp}}^2 \le \frac{2}{3}\varepsilon_{\text{elec}}\varepsilon_{mp-\text{amp}}$	$d\sqrt[4]{\frac{3\varepsilon_{mp-\text{amp}}}{2\varepsilon_{\text{elec}}}}$	$\sqrt[4]{\frac{2\varepsilon_{\text{elec}}}{3\varepsilon_{mp-\text{amp}}}}$
II	$\frac{2}{3}\varepsilon_{\text{elec}}\varepsilon_{mp-\text{amp}} < \varepsilon_{fs-\text{amp}}^2 \le 2\varepsilon_{\text{elec}}\varepsilon_{mp-\text{amp}}$	$\frac{d}{d_0}$	d_0
III	$\varepsilon_{fs-\text{amp}}^2 > 2\varepsilon_{\text{elec}}\varepsilon_{mp-\text{amp}}$	$d\sqrt{\frac{\varepsilon_{fs-\text{amp}}}{2\varepsilon_{\text{elec}}}}$	$\sqrt{\frac{2\varepsilon_{\text{elec}}}{\varepsilon_{fs-\text{amp}}}}$

In category I, the optimal number of hop, n_{opt}, is discovered by finding the minimum multipath communication energy function as illustrated in Figure 2(a). Similarly in category III, the optimal value n_{opt} is found at the minimum free-space energy function, as shown in Figure 2(c). While in category II, the optimal solutions for both free-space and multipath energy functions are not valid, based upon the predefined system parameters and threshold distance. Analysing these two energy models, the optimal solution n_{opt} is obtained at the intersection of two curves, as demonstrated in Figure 2(b). The number of hops n should be an integer in practice; simply rounding the optimal value n_{opt} to its nearest integer may not always be the best solution. Further study for the selection of an integer number of hops n is described in Section 2.3.

Figure 2 Energy functions for different system parameter conditions (a) category I: $\varepsilon_{fs-\text{amp}}^2 \le (2/3)\varepsilon_{\text{elec}}\varepsilon_{mp-\text{amp}}$ (b) category II: $(2/3)\varepsilon_{\text{elec}}\varepsilon_{mp-\text{amp}} < \varepsilon_{fs-\text{amp}}^2 \le 2\varepsilon_{\text{elec}}\varepsilon_{mp-\text{amp}}$ (c) category III: $\varepsilon_{fs-\text{amp}}^2 > 2\varepsilon_{\text{elec}}\varepsilon_{mp-\text{amp}}$



(a)

(b)

(c)

2.3 *Discussion on selecting the number of hops*

Since the number of hops n has to be an integer, we consider two choices for n: $\lfloor n_{\text{opt}} \rfloor$ and $\lceil n_{\text{opt}} \rceil$, where $\lfloor n_{\text{opt}} \rfloor$ indicates the greatest integer smaller than n_{opt} and $\lceil n_{\text{opt}} \rceil$ indicates the smallest integer greater than n_{opt}. In this section, we consider the property of the energy functions around n_{opt} for each of the three network categories listed in Table 1 and provide a set of rules for selecting n between $\lfloor n_{opt} \rfloor$ and $\lceil n_{opt} \rceil$.

For category I, the energy function is a parabola when n is close to n_{opt}. Heuristically, we can simply choose the number of hops n as the closest integer to the n_{opt} for the minimum energy solution. However, using the rounding of n_{opt} could result in a fast energy increment if $\lfloor n_{opt} \rfloor > d/d_0$, as illustrated in Figure 2(a). Therefore, it is suggested to use $\lfloor n_{opt} \rfloor$ as the number of hops when $\lceil n_{opt} \rceil > d/d_0$. The analysis on category III is similar to category I. The closest integer of n_{opt} is the best choice as the number of hops in practice, except when $\lfloor n_{opt} \rfloor < d/d_0$, as shown in Figure 2(c). In this case, choosing $\lceil n_{opt} \rceil$ as the number of hops could avoid a sharp energy increase.

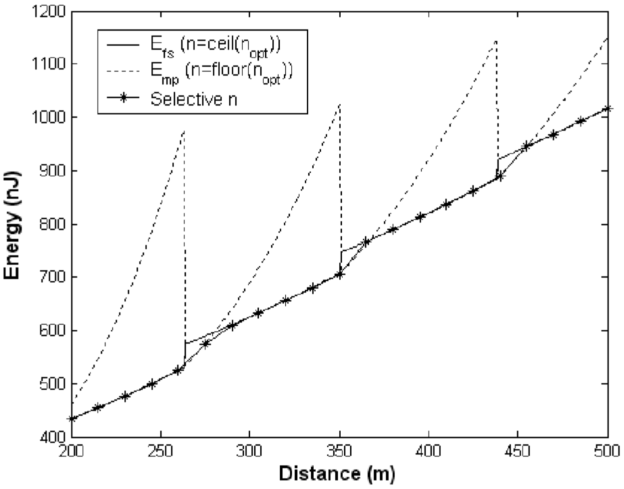
While in category II, n_{opt} is located at the intersection of the multipath and the free-space energy function curves. First, the gradient of each function at n_{opt} is found with $(2\varepsilon_{elec} - \varepsilon^2_{fs-amp}/\varepsilon_{mp-amp})$ for the free-space energy function and $(2\varepsilon_{elec} - 3\varepsilon^2_{fs-amp}/\varepsilon_{mp-amp})$ for the multipath energy function. Next, the value of free-space energy function at $\lfloor n_{opt} \rfloor$ and that of the multipath energy function at $\lfloor n_{opt} \rfloor$ are evaluated using linear approximation. The selection between $\lfloor n_{opt} \rfloor$ and $\lceil n_{opt} \rceil$ is then determined by choosing the one that leads to the smaller energy value. Table 2 lists the selection criteria for each of these three categories.

Table 2 Selection criteria for the number of hops

	$n = \lfloor n_{opt} \rfloor$	$n = \lceil n_{opt} \rceil$
I	$n_{opt} - \lfloor n_{opt} \rfloor < \frac{1}{2}$ or $\lceil n_{opt} \rceil > \frac{d}{d_0}$	$n_{opt} - \lfloor n_{opt} \rfloor \geq \frac{1}{2}$ and $\lceil n_{opt} \rceil \leq \frac{d}{d_0}$
II	$n_{opt} - \lfloor n_{opt} \rfloor < \frac{\varepsilon_{elec}\varepsilon_{mp-amp}}{\varepsilon^2_{fs-amp}} - \frac{1}{2}$	$n_{opt} - \lfloor n_{opt} \rfloor \geq \frac{\varepsilon_{elec}\varepsilon_{mp-amp}}{\varepsilon^2_{fs-amp}} - \frac{1}{2}$
III	$n_{opt} - \lfloor n_{opt} \rfloor < \frac{1}{2}$ and $\lceil n_{opt} \rceil \geq \frac{d}{d_0}$	$n_{opt} - \lfloor n_{opt} \rfloor \geq \frac{1}{2}$ or $\lfloor n_{opt} \rfloor < \frac{d}{d_0}$

Figure 3 compares the energy consumptions when choosing n as $\lfloor n_{opt} \rfloor$, $\lceil n_{opt} \rceil$, and when using the selection criteria. In this example, a set of typical parameters (Heinzelman et al., 2002) are in used: $\varepsilon_{elec} = 50$ nJ/bit, $\varepsilon_{fs-amp} = 10$ pJ/bit/m^2, $\varepsilon_{mp-amp} = 0.0013$ pJ/bit/m^4 and $d_0 = 87.7$ m, which match with the category II as listed in Table 1. For a transmission with communication distance d ($d > d_0$), the optimal value of n_{opt} is d/d_0. Subsequently the selection criteria choose $n = \lfloor n_{opt} \rfloor$ if $n - \lfloor n_{opt} \rfloor < 0.15$ (calculated via substituting the values of parameters into the equation for category II in Table 2) and choose $n = \lceil n_{opt} \rceil$ otherwise. It is clearly observed from Figure 3 that the selection criteria developed in this section ensure the near-optimal energy efficiency. Matlab notation is used in Figure 3, where *ceil* (n_{opt}) = $\lceil n_{opt} \rceil$ and *floor* (n_{opt}) = $\lfloor n_{opt} \rfloor$.

Figure 3 An example of choosing n as $\lfloor n_{opt} \rfloor$ and $\lfloor n_{opt} \rfloor$, and using the selection criteria



3 Procedures of ODGR algorithm

ODGR considers two important physical properties of wireless sensor networks, geographic location and power control. The procedures of ODGR algorithm is developed based on the optimal distance analysis presented in Section 2. ODGR requires each node to know the locations of the neighbour nodes within a specific distance. This distance is set as 1.5 h_{opt}, because for a given distance d and number of hops n, the transmit distance per hop h can be calculated as $h = d/n = h_{opt}\, n_{opt}/n$ and $h < h_{opt}\,(n + 1)/n$, since $n_{opt} < n + 1$. For multihop routing ($n \geq 2$), it proves that $h < 1.5\, h_{opt}$. It implies that ODGR algorithm can always find the next hop node within the distance of 1.5 h_{opt} from the current node location. The location information can be predetermined during deployment or through certain location algorithms during the self-establishment of the network, so ODGR is classified as one type of geographic routing protocols.

The optimal distance geographical routing is applied to discover the practically optimal routing path with the aim of minimising the total energy for communication. If source A is located at (x_A, y_A) and destination B is located at (x_B, y_B), the ODGR routing algorithm finds the next hop node in the following steps:

Step 1: Sets the current node location (x_i, y_i) as the source node location: $x_i = x_A$; $y_i = y_A$.

Step 2: Computes the Euclidean distance from the current node to destination. If the distance d is less than h_{opt}, jumps to Step 7, where $d = \sqrt{(x_i - x_B)^2 + (y_i - y_B)^2}$.

Step 3: Computes $n_{opt} = d/h_{opt}$ and selects the number of hops n based on the network category as described in Table 2. The distance per hop h is then determined as d/n.

Step 4: If $n = 1$, goes to Step 7. Otherwise, computes the estimated location of the next hop node j as,

$$x_j = x_i + \Delta x = x_i + \frac{x_B - x_i}{n}.$$

$$y_j = y_i + \Delta y = y_i + \frac{y_B - y_i}{n}$$

Step 5: Searches for an available node closest to the estimated location (x_i, y_i). If two closest nodes have the same distance, chooses the one closer to the destination.

Step 6: Sends the packet to the next hop node if it is not in the exclusion list of the current node, and waits for an acknowledgement (ACK). If the ACK is successful, sets the next hop node as the current node and goes to Step 2 to continue. If the ACK replies that the packet has visited the node before, adds the next hop node to the exclusion list. If the next hop node is in the exclusion list, no matter whether it is discovered from the most recent ACK or from information obtained during previous search, it goes back to Step 5 to choose a different node. If all available neighbour nodes are in the exclusion list, the algorithm terminates with an announcement that no optimal distance path found.

Step 7: Transmits data directly from the current node to the destination. The ODGR procedure is completed and a practically optimal transmission path is found.

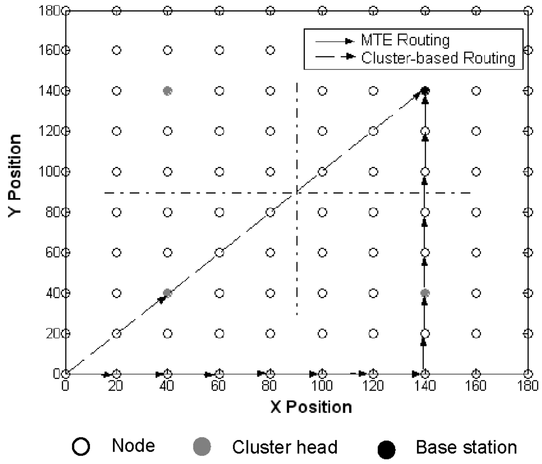
The exclusion list described in Step 6 is designed to avoid deadlocks in the routing process. Every node stores the identifications (ID) of packets it has recently received, and the stored IDs expire automatically after a period of time.

The ODGR algorithm discovers the practical optimal path by finding an optimal location of next hop node in each step to achieve a minimum of total communication energy. Compared to other popular routing protocols, the unique advantage of ODGR is application-independent. It is applicable for any node-to-node communication in wireless sensor networks. It can be used, but not limited, in a form of data collection or dissemination among sensor nodes and base station. In an intelligent environment with both sensors and actuators, node-to-node unicast communication may be necessary for task coordination. ODGR is able to perform unicast routing with less energy consumptions. In addition, ODGR is a dynamic routing algorithm that gradually searches for the best available nodes towards the destination. It has the capability to tolerate node failures and relocations.

4 Case study and performance analysis

A traditional 2D mesh network with 100 nodes (10-by-10) deployed within a 180 m-by-180 m geographic area is analysed. The adjacent nodes are separated by 20 meters in four directions. A node located at (140,140) is randomly chosen as the base station, as shown in Figure 4. It is assumed that every node periodically sends a packet of sensor data to the base station. Performances of three different techniques are compared in this case study including MTE, LEACH and ODGR algorithms. The same set of typical circuit parameters, given in Section 2.3, with its derived rounding scheme is used in simulations. High-level simulation code was developed for the 2D network to compute the routes and power consumptions using the theoretical energy model. The TinyOS simulator (TOSSIM) is then used for packet-level simulation to prove the viability of ODGR algorithm.

Figure 4 Examples of MTE and cluster-based routing in a 100-node 2D array network



4.1 MTE routing

For MTE routing, we choose dimensional-order routing (DOR) algorithm (Wu, 2003) in which each node forwards data to its immediate neighbour in X-direction first. An example showing that a node located at (0,0) sends a packet to the base station at (140,140) is demonstrated in Figure 4, and the number of hops required for each node when sending a packet to the base station is listed in Table 3. The experimental results show that the average latency is 6.26 hops. The communication energy for each hop is computed using equation (1), where distance per hop is 20 m. On using the typical parameter values, the total communication energy for MTE routing is 64.48 mJ/bit, when all nodes send a packet to the base station.

Table 3 Number of hops for each node using MTE in case study

180	9	8	7	6	5	4	3	2	3	4
160	8	7	6	5	4	3	2	1	2	3
140	7	6	5	4	3	2	1	0	1	2
120	8	7	6	5	4	3	2	1	2	3
100	9	8	7	6	5	4	3	2	3	4
80	10	9	8	7	6	5	4	3	4	5
60	11	10	9	8	7	6	5	4	5	6
40	12	11	10	9	8	7	6	5	6	7
20	13	12	11	10	9	8	7	6	7	8
0	14	13	12	11	10	9	8	7	8	9
	0	20	40	60	80	100	120	140	160	180

4.2 Cluster-based algorithm

As shown in Figure 4, the entire network can be tentatively partitioned into four clusters. Each cluster contains 25 nodes and the cluster head is located at the centre of the cluster. All nodes are located within the communication distance to the cluster head. For simplification purpose, we use the fixed-cluster head strategy to estimate the total energy for a single-round of data collection. Randomly selected cluster heads, such as used in LEACH-C, has the advantage of average power depletion of the nodes. However, because there is no data aggregation involved in this case study, using centre node as cluster head is still a good estimation of the total communication energy.

Every node sends data directly to its cluster head, and the cluster heads directly communicate with the base station. Therefore, the latency constantly remains as two hops. To reduce redundant data transfer, base station is also chosen as one of the cluster heads. An example when a node located at (0,0) sends a packet to the base station is illustrated in Figure 4. A total energy of 2.9 mJ/bit is required for gathering data from all 25 nodes to the cluster head within each cluster. Subsequently, each cluster head needs to forward all 25 data packets to base station. Notice that the distance from three cluster heads to the base station is 100 m, 100 m and $100\sqrt{2}\text{m}$, which are greater than the threshold distance d_0. If every node sends one packet to base station using the cluster-based algorithm, the total communication energy is calculated as 38.6 mJ/bit.

4.3 ODGR algorithm

The ODGR procedure is applied for the 2D mesh network. Every node in the network needs to send a packet to the base station through an optimal number of hops. The estimated number of hops at the initial step of the algorithm is listed in Table 4. The average transmission latency is calculated as 1.47 hops using the ODGR algorithm.

Table 4 Number of hops for each node using ODGR in case study

180	2	2	2	1	1	1	1	1	1	1
160	2	2	1	1	1	1	1	1	1	1
140	2	2	1	1	1	1	1	0	1	1
120	2	2	1	1	1	1	1	1	1	1
100	2	2	2	1	1	1	1	1	1	1
80	2	2	2	1	1	1	1	1	1	1
60	2	2	2	2	1	1	1	1	1	1
40	2	2	2	2	2	2	1	1	1	2
20	2	2	2	2	2	2	2	2	2	2
0	3	2	2	2	2	2	2	2	2	2
	0	20	40	60	80	100	120	140	160	180

Figure 5 shows three examples to illustrate the routing process of ODGR. Detail steps of an example that finds an optimal path from source node located at (0,0) to the base station at (140,140) is listed below.

Step 1: Registers the locations of the source node and the destination.

Step 2: The distance d is computed as 198 m.

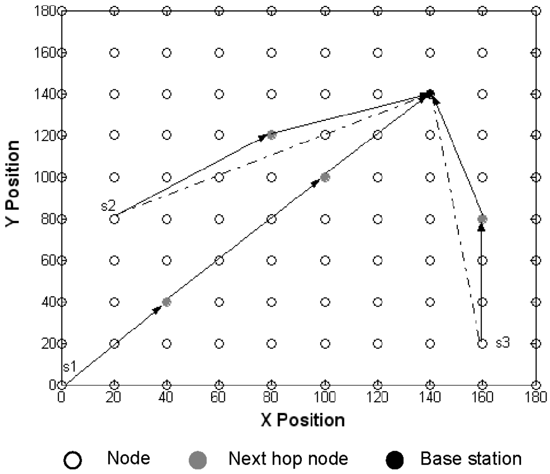
Step 3: Using $h_{\text{opt}} = d_0 = 87.7$ m, n_{opt} is 2.25. According to the rounding scheme in Section 2.3, the estimated number of hops is three, and distance per hop is about 66 m.

Step 4: The next hop node is estimated to be around the coordinate (46.67,46.67).

Step 5: Searching within a radius of $0.5d_0$ from (46.67,46.67), the node closest to the destination is available at (40,40).

Step 6: The source node sends the packet to the node at (40,40), and the returned ACK shows the packet is received successfully. Goes back to Step 2 to continue.

Figure 5 Examples of ODGR routing procedures in a 2D array network



The next iteration of the algorithm is similar to the above steps. The computed distance from (40,40) to the destination is 141.4 m. It would need two more hops, and each hop is about 70.7 m. The next hop node location is then estimated at (90,90) and there are three available nodes that have the same distance to location (90,90): nodes at (100,100), (80,100) and (100,80). Node at (100,100) is selected as the next hop node because it has the shortest distance to the destination. During the last iteration of the algorithm, because the distance from node (100,100) to the destination is less than d_0, data will be directly transmitted to the destination. As a result, the ODGR routing algorithm is completed successfully.

Two additional examples are also illustrated in Figure 5. The source locations are (20,80) and (160,20). Each requires two hops to transfer a packet to the base station. The same ODGR procedures are used to find the energy efficient transmission path.

Following the ODGR procedures as discussed above, all the multihop nodes from any source node in the network to the base station can be determined. The communication energy for each hop is computed using equation (1). For example, transferring a package from the source node at location (0,0) to the base station in three hops consumes a total energy of 436 nJ/bit. For the entire network with 100 nodes and every node sending a packet to the base station, the total communication energy is 21.66 mJ/bit.

Table 5 compares the communication energy and latency for these three routing algorithms. As a result, ODGR is able to reduce the energy consumption by 66.41% and 43.89%, when compared to MTE and LEACH algorithms. The ODGR algorithm also provides smaller communication latency than the other two algorithms. The average latency is reduced by 76.45% and 26.27%, when compared with MTE and LEACH algorithms.

Table 5 Performance comparisons for MTE, LEACH and ODGR

Protocol	*Communication energy* (mJ/bit)	*Latency* (hops)
MTE	66.48	6.26
LEACH	38.60	2.00
ODGR	21.66	1.47

5 Conclusions

This paper develops a routing protocol that utilises power control in the transmission scheme and the available geographic information to explore the optimal routing path in order to reduce the total energy dissipation for communications. The ODGR algorithm is developed from the convexity theory to minimise the total energy consumptions for multihop communications in wireless sensor networks. The step-by-step procedures of searching for the next hop node along the optimal path are also provided. Compared to the traditional MTE and cluster routing algorithms, a case study of 2D mesh network shows that ODGR is able to reduce the communication energy by 66.41% and 43.89%, and reduce the latency by 76.45% and 26.27%. Furthermore, ODGR is not application-specific; it can be integrated into other routing algorithms to reduce the total energy consumptions and extend the system lifetime for wireless sensor networks.

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References

Ahmed, A., Shi, H. and Shang, Y. (2003) 'A survey on network protocols for wireless sensor networks', *Proceedings of the International Conference on Information Technology*, Newark, NJ, August, pp.301–305.

Ettus, M. (1998) 'System capacity, latency, and power consumption in multihop-routed SS-CDMA wireless networks', *Proceedings of the IEEE Radio and Wireless Conference*, Colorado Springs, CO, August, pp.55–58.

Ganesan, D., Cerpa, A., Ye, W., Yu, Y., Zhao, J. and Estrin, D. (2004) 'Networking issues in wireless sensor networks', *Journal of Parallel and Distributed Computing*, Vol. 64, No. 7, pp.799–814.

Heinzelman, W., Chandrakasan, A. and Balakrishnan, H. (2002) 'An application-specific protocol architecture for wireless microsensor networks', *IEEE Transactions on Wireless Communications*, Vol. 1, No. 4, pp.660–670.

Intanagonwiwat, C., Govindan, R. and Estrin, D. (2000) 'Direct diffusion: a scalable and robust communication paradigm for sensor networks', *Proceedings of the Sixth Annual ACM/IEEE International Conference on Mobile Computing and Networking*, Boston, MA, August, pp.56–67.

Karp, B. and Kung, H.T. (2000) 'GPSR: greedy perimeter stateless routing for wireless networks', *Proceedings of the Sixth Annual ACM/IEEE International Conference on Mobile Computing and Networking*, Boston, MA, August, pp.243–254.

Lindsey, S. and Raghavendra, C.S. (2002) 'PEGASIS: power-efficient gathering in sensor information systems', *Proceedings of the IEEE Aerospace Conference*, Big Sky, MT, March, pp.1125–1130.

Pottie, G.J. and Kaiser, W.J. (2000) 'Wireless integrated network sensors', *Communications of ACM*, Vol. 43, No. 5, pp.51–58.

Warneke, B., Last, M., Leibowitz, B. and Pister, K.S.J. (2001) 'Smart dust: communicating with a cubic-millimeter computer', *IEEE Computer*, Vol. 34, No. 1, pp.44–51.

Wu, J. (2003) 'A fault-tolerant and deadlock-free routing protocol in 2D meshes based on odd-even turn model', *IEEE Transactions on Computers*, Vol. 52, No. 9, pp.1154–1169.

Yu, Y., Govindan, R. and Estrin, D. (2001) 'Geographical and energy-aware routing: a recursive data dissemination protocol for wireless sensor networks', *UCLA Computer Science Department Technical Report UCLA/CSD-TR-01-0023*, May.

Zhao, F. and Guibas, L. (2004) *Wireless Sensor Networks: An information Processing Approach*, Morgan Kaufmann, San Francisco, CA, USA.

Bibliography

Akyildiz, I.F., Su, W., Sankarasubramaniam, Y. and Cayirci, E. (2002) 'A survey on sensor networks', *IEEE Communications*, Vol. 40, No. 8, pp.102–116.

Callaway, E.H. (2004) *Wireless Sensor Networks: Architectures and Protocols*, CRC Press, Boca Raton, FL, USA.

Gutierrez, J.A., Naeve, M., Callaway, E., Bourgeois, M., Mitter, V. and Heile, B. (2001) 'IEEE 802.15.4: a developing standard for low-power low-cost wireless personal area networks', *IEEE Network*, Vol. 15, No. 5, pp.12–19.

Hac, A. (2003) *Wireless Sensor Network Designs*, John Wiley & Sons, Hoboken, NJ, USA.

Heinzelman, W., Kulik, J. and Balakrishnan, H. (1999) 'Adaptive protocols for information dissemination in wireless sensor networks', *Proceedings of the Fifth Annual ACM/IEEE International Conference on Mobile Computing and Networking*, Seattle, WA, August, pp.174–155.