Hop-based Energy Aware Routing Algorithm for Wireless Sensor Networks

Jin WANG,† *Nonmember*, ***Jinsung CHO***†, Sungyoung Lee†, *Regular members*,
Kwang-Cheng CHEN,*IEEE Fellow* ††, Young-Koo LEE,† *Nonmember*

Summary Energy efficient routing is one of the key design issues to prolong the lifetime of wireless sensor networks (WSNs) since sensor nodes can not be easily re-charged once they are deployed. During routing process, the routes with only few hops or with too many hops are not energy efficient. Hop-based routing algorithms can largely improve the energy efficiency of multi-hop routing in WSNs because they can determine the optimal hop number as well as the corresponding intermediate nodes during multi-hop routing process under medium or high density network. In this paper, we not only focus on studying the relationship between energy consumption and hop number from theoretical point of view but also provide a practical selection criterion of the sub-optimal hop number under practical sensor network so as to minimize the energy consumption. We extend the theoretical deduction of optimal hop number and propose our Hop-based Energy Aware Routing (HEAR) algorithm which is totally distributed and localized. Simulation results show that our HEAR algorithm can reduce the average energy consumption about 10 times compared to the direct transmission algorithm and 2 to 10 times than other algorithms like LEACH and HEED under various network topologies.
Key words: *wireless sensor networks, energy efficiency, hop number, network lifetime, clustering*

1. Introduction

Recent development in Micro-Electro-Mechanical System (MEMS) has made it possible to develop wireless sensor networks (WSNs) consisting of tiny and cheap sensors [1]. The sensor nodes can be randomly deployed in a physical environment and they will transmit their monitored data to the sink node in an autonomous and unattended manner. WSNs may have many potential applications such as military surveillance, industrial product line monitoring, agricultural and wildlife observation, healthcare as well as smart home etc in the near future.

Energy efficiency is one of the primary challenging issues to the successful application of WSNs since the tiny sensors with limited energy can not be re-charged easily once they have been deployed. Since the radio device is the main source of energy consumption, how to design an energy efficient routing algorithm during communication process is one of the key issues for WSNs. There are some other sources of energy consumption by the sensor nodes. For example, the technique of modulation/demodulation and coding/decoding from PHY layer consumes certain amount of energy. In the MAC layer, huge amount of energy will be wasted if states like "active/idle/sleeping" are not well scheduled. Other factors such as packet collision and overhearing will also waste the limited energy resource. In general, the source of the energy consumption consists of three parts, namely sensing, processing and communication. In this paper, we only consider the energy consumption during communication process due to the fact that to transmit one bit of message consumes around 1000 times more energy than to process the message.

Up to now, many studies have been done in the area of energy efficient routing protocols or algorithms for WSNs. However, just a few of them have studied the relationship between energy consumption and hop number, as can be seen from the related work. Among those papers, [8] provided some theoretical analysis of the first radio energy model. However, the authors only consider direct transmission manner under their small scale network environment. The authors in [3] studied different energy consumption models and provided several optimal energy consumption formulas with optimal hop number. However, they treated source and intermediate nodes equally under general wireless network environment. In fact, this is not true since source node only needs $E = E_T$ amount of energy to transmit a message while intermediate nodes need $E = E_R + E_T$ amount of energy to receive and then retransmit the message to the next node. There is some other work which analyzes the selection of transmission manner (single hop or multi-hop) from a probabilistic viewpoint [17]. However, the authors do not make further theoretical analysis and they only consider 2-hop routing as multi-hop routing therein.

How to select the optimal hop number during routing process is an important theoretical and practical issue because it can influence the energy consumption greatly. It is commonly agreed that multi-hop transmission manner is usually more energy efficient than single hop transmission, especially under large scale sensor networks. However, how to determine the optimal hop number as well as the corresponding intermediate nodes under practical network is still not well addressed up to now.

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† The authors are with Computer Engineering Department, Kyung Hee University, South Korea, 449-701,
†† The author is with Electrical Engineering Department, National Taiwan University, Taipei 106, Taiwan.
a) E-mail: wangjin@oslab.khu.ac.kr

To tackle the problems mentioned above, we propose a Hop-based Energy Aware Routing (HEAR) algorithm for WSNs. Based on our HEAR algorithm, the optimal hop number as well as the intermediate nodes can be determined during routing process so that the energy consumption can be largely reduced. Our contribution in this paper lies in the following three aspects. First, we make an extensive study between energy consumption and hop number from both theoretical and experimental point of view. We derive the optimal hop number under linear network and then provide a practical selection criterion of the sub-optimal hop number under real WSNs. Second, we propose our Hop-based Energy Aware Routing (HEAR) algorithm by combing the general routing mechanism in WSNs with the theoretically deduced optimal hop number. Finally, we validate our HEAR algorithm via extensive simulations which show that HEAR can save more than 10 times energy and prolong network lifetime up to 10 times than some of the other routing algorithms such as direct transmission, greedy algorithm, LEACH and HEED algorithm etc. HEAR algorithm can be easily utilized by other routing protocols since it is a simple, distributed and localized routing algorithm.

The rest of the paper is organized as follows. Section 2 explains the motivation of this paper. Section 3 provides some related work Section 4 presents both theoretical and experimental analysis of energy consumption as well as hop number. Section 5 explains our HEAR algorithm in detail and Section 6 provides simulation results which validate the performance of our algorithm. Section 7 gives more discussion and Section 8 concludes this paper.

2. Motivation

During multi-hop routing process, sensor node usually determines its next hop by considering factors like residual energy, relative distance, node degree or a cost function with combination of them. The factor of hop number is not carefully studied. However, hop number has an important impact on many network metrics like energy consumption, interference, routing overhead, latency etc., as is discussed in [4]. In this paper, we try to thoroughly study the relationship between hop number and energy consumption from both theoretical and experimental aspects as the first step. Later on, we will study the relationship between hop number and other metrics.

From energy consumption model point of view, if we choose direct transmission or multi-hop route with only few hops between source and sink node, it will consume a huge amount of energy when the distance d is too large. This is because energy consumption is proportional to the fourth order of distance ($E \propto d^4$). On the other hand, if we choose too many short hops to transmit over d , the energy consumption will also be very large since the hardware circuit also consumes large amount of energy to switch its radio transceiver during each short hop process. Therefore, how to determine the optimal hop number with appropriate intermediate nodes is an important issue.

In the mean time, the hot node phenomena in WSNs can be alleviated based on hop-based routing mechanism. As we know, nodes near sink node will become hot nodes and die quickly since they have to forward the message to sink node frequently during multi-hop routing process. On the other hand, the nodes far away from sink node will also become hot nodes and die quickly during single hop routing (also called direct transmission) process since the energy consumption is proportional to the fourth order of distance. By using hop-based routing mechanism, the nodes far away from sink node can greatly reduce their energy via multi-hop routing. And the nodes near sink node can also reduce their forwarding node number since only the intermediate nodes with proper distance along the source to sink line will be chosen. Thus, the nodes in both cases above can prolong their lifetime, which increases the whole network lifetime.

Based on the observations above, we first try to deduce the optimal hop number with proper intermediate nodes (or distances) to improve energy efficiency during multi-hop routing process. In other words, we will try to optimize the energy consumption function with variables of hop number and intermediate distances under constrain conditions like hardware parameters, distance etc. Then, we will propose our Hop-based Energy Aware Routing (HEAR) algorithm and validate its performance through simulation results in the rest of this paper.

3. Related work

Study of energy efficient routing protocols or algorithms has lasted for many years and many research papers have been published. All these routing protocols can mainly be classified into three categories which are data-centric [5-7], hierarchical [8-12] and location-based [13, 14] protocols. More details can be seen in [2]. They can be used together to get better performance. For example, data aggregation is adopted in hierarchical routing protocols [8-10] and the authors in [10] utilize nodes' location information to form a chain during routing process.

Data aggregation (a.k.a. data fusion) is an important technique adopted by data-centric routing protocols [5-7]. Due to the fact that many nearby sensor nodes may collect similar information, there is certain similarity among collected raw data. Through this technique, both the data size and number of packet can be reduced, causing a large reduction of energy consumption. SPIN (Sensor Protocols for Information via Negotiation [5]) can be viewed as the first data-centric routing protocol which utilizes the data negotiation method among sensor nodes to reduce data redundancy and save energy. Direct Diffusion [6] is another representative data-centric routing protocol for WSNs. The data generated by sensor nodes is named by attribute-value pairs. Once sink node inquires certain type of information (like four-let animal at certain area), it will send a query and the observed data can get aggregated and then be transmitted back to the sink node. In addition, the load balancing can be achieved by forwarding the data on different paths based on probability. Rather than always using the lowest energy paths, the authors in [7] use sub-optimal paths occasionally so that the network lifetime is increased by 40% compared to [6]. Hierarchical routing protocols [8-12] are very suitable for WSNs since they can not only provide good scalability for hundreds or thousands of sensors but also perform data aggregation by cluster head within each cluster. LEACH [8] is one of the most famous hierarchical routing protocols for WSNs. It can prolong network lifetime up to 8 times than other ordinary routing protocols like direction transmission and minimum transmission energy routing protocols. However, the 5% of cluster head nodes are randomly chosen and the cluster head nodes use direct transmission to the sink node therein. PEGASIS [10] is viewed as an improved version of LEACH. It is a chain based routing protocol which can save more energy compared to LEACH. The message can get aggregated along the chain and finally be sent to sink node via direct transmission by one random node on the chain. The main shortcoming is that PEGASIS requires global knowledge of the whole network. HEED clustering protocol [20] can not only minimize the control overhead during communication process but also prolong network lifetime than other clustering algorithms like LEACH since the cluster heads are well distributed. Besides, it does not need global knowledge of the whole network and all intelligent decisions are made locally by sensor nodes. Location-based routing protocols [13, 14] can get location information either through global positioning system (GPS) devices or certain estimation algorithms based on received signal strength. Once the location information is known, the energy consumption can get largely reduced through adjustable power control mechanism and communication overhead can also get reduced. MECN [13] provides a minimum energy network for WSNs under the support of low power GPS. The authors in [14] make an extension of [13] by considering possible obstacles between any pair of communication nodes.

It can be seen that the factor of hop number is not carefully addressed by most of the energy efficient routing protocols above. In fact, it has very important impact on many network metrics like energy consumption, routing overhead, interference etc., as is mentioned in [4]. The authors in [3] present some pioneering work by studying different energy models under general wireless network environment. They mainly focus on theoretical study and proof of the optimal hop number. However, they treat every node equally which is not true for WSNs since source and intermediate node consume different amount of energy, as can be seen from energy model. Also, more simulation work is needed since the real sensor network may not have such sensor nodes which are corresponding to the optimal intermediate nodes. Also the hop number should be an integer rather than a theoretical decimal value therein. The authors in [8] treat energy consumption differently for source and intermediate node. However, they only consider the single hop transmission under their small scale network environment and do not consider multi-hop transmission scenario nor provide a further deduction of optimal multi-hop number for both linear and real sensor network. The authors in [17] study selection of transmission manner from probability point of view. They present a probability of P_i to transmit data through multi-hop manner and a probability $(1-P_i)$ to transmit through single hop manner to sink node. The authors in [18] also study the energy consumption under both single hop and multi-hop transmission manners. They also claim that the preference of multi-hop routing to single hop routing depends on source to sink distance and reception cost, which is consistent with our analysis here. The authors in [17, 18] only treat 2-hop routing as multi-hop transmission in their environment and do not provide further analysis.

The main difference between our work and the work above lies in two aspects. First, we extend the theoretical analysis of [8] and modify the formula in [3] to fit in practical WSNs environment. Also, we consider multi-hop routing with more than 2 hops under the practical sensor network environment.

4. Theoretical Analysis on Energy Model and Hop Number

4.1 Energy Consumption Model

Fig. 1 shows the one dimensional linear network with n number of sensor nodes placed along a line from source to sink node. Usually, one dimensional linear sensor network can be used in linear applications such as highway traffic monitoring, congestion control etc. The distance between each sensor node is r_i. Once source node has data to send to sink node, it will determine transmission manner under constraint conditions like source to sink distance d, radio hardware parameters etc. It is worth mentioning that the parameter values of energy model here is an abstraction of radio device and wireless communication characteristics from physical layer.

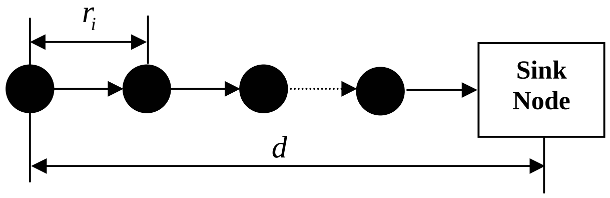


Fig. 1 One dimensional linear network

The energy consumption model here is called first order radio model [3, 8-10]. Radio device will consume E_{Tx} energy to transmit a l -bits message over distance d :

$$E_{Tx}(l,d)=\begin{cases} l\cdot E_{elec}+l\cdot\varepsilon_{fs}\cdot d^2, & if\, d<d_0 \\ l\cdot E_{elec}+l\cdot\varepsilon_{mp}\cdot d^4, & if\, d\geq d_0, \end{cases} \quad (1)$$

E_{Rx} energy to receive the message:

$$E_{Rx}(l)=l\cdot E_{elec}, \quad (2)$$

and E_{Fx} energy to forward the message:

$$E_{Fx}(l,d)=E_{Tx}(l,d)+E_{Rx}(l)$$
$$=\begin{cases} 2l\cdot E_{elec}+l\cdot\varepsilon_{fs}\cdot d^2, & if\, d<d_0 \\ 2l\cdot E_{elec}+l\cdot\varepsilon_{mp}\cdot d^4, & if\, d\geq d_0. \end{cases} \quad (3)$$

The definition of radio parameters is listed in Table 1.

Table 1 Radio parameters

Parameter	Definition	Unit
E_{elec}	Energy dissipation to run the radio device	50 nJ/bit
ε_{fs}	Free space model of transmitter amplifier	10 pJ/bit/m^2
ε_{mp}	Multi-path model of transmitter amplifier	0.0013 pJ/bit/m^4
l	Data length	2000 bits
d_0	Distance threshold	$\sqrt{\varepsilon_{fs}/\varepsilon_{mp}}$ m

If we do not consider the first part E_{elec} in Eq. (3), we can equally divide the distance d into n pieces so that the energy consumption can be reduced from $l\cdot\varepsilon_{amp}\cdot d^\alpha$ to $n\cdot l\cdot\varepsilon_{amp}\cdot(d/n)^\alpha$, $\alpha\in[2,4]$ .Here, $\varepsilon_{amp}=\varepsilon_{fs}$ when $\alpha=2$ and $\varepsilon_{amp}=\varepsilon_{mp}$ when $\alpha=4$. Usually, the larger hop number n is, more energy can be saved. However, E_{elec} can not be neglected usually and that is why we need to further deduce the optimal multi-hop number based on previous work in [3] and extend the deduction to the real sensor network.

Based on the equations above, it will consume $E(n)$ energy to transmit one bit data over n -hop route:

$$E(n)=(E_{elec}+\varepsilon_{amp}\cdot r_1^\alpha)+\sum_{i=2}^{n-1}\varepsilon_{amp}\cdot r_i^\alpha+$$
$$2\cdot(n-1)\cdot E_{elec}=(2n-1)\cdot E_{elec}+\sum_{i=1}^{n}\varepsilon_{amp}\cdot r_i^\alpha. \quad (4)$$

Here, $\sum_{i=1}^{n} r_i=d$. Eq. (4) is the final objective function to optimize with variables of hop number n and distance r_i . It is worth mentioning that the optimal hop number might not be chosen under the constraint $r_i<d_0$ when $\alpha=2$ or $r_i\geq d_0$ when $\alpha=4$. Sometimes, we have to find sub-optimal hop number under practical network environment.

4.2 Optimal Hop Number

Inspired by [3], we first deduce the optimal theoretical hop number under Fig. 1 network environment as follows.

For fixed $\sum_{i=1}^{n} r_i=d$, $\sum_{i=1}^{n} r_i^\alpha$ in Eq. (4) has a minimal value when $r_1=r_2=\ldots=r_n=d/n$. Therefore, $E(n)$ is finally equal to:

$$E(n)=(2n-1)\cdot E_{elec}+\varepsilon_{amp}\cdot n^{1-\alpha}\cdot d^\alpha, \quad (5)$$

Eq. (5) has the minimum when $E'(n)=0$ or

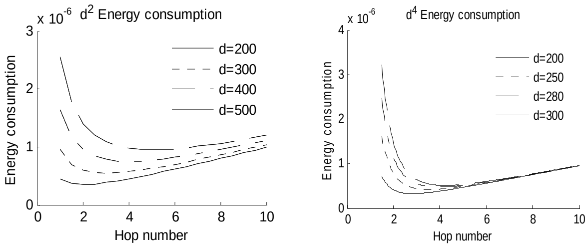
$$2E_{elec}+\varepsilon_{amp}\cdot(1-\alpha)\cdot(d/n)^\alpha=0,$$

Thus, we can get the final optimal hop number as:

$$n_{opt}^*=d\cdot(\varepsilon_{amp}\cdot(\alpha-1)/2E_{elec})^{1/\alpha}. \quad (6)$$

From Eq. (6), it is easy to get the minimal energy for free space model when $n_{opt}^*=\sqrt{\varepsilon_{fs}/2\cdot E_{elec}}\cdot d$ and $r_i=d/n_{opt}^*$ $=\sqrt{2\cdot E_{elec}/\varepsilon_{fs}}=100$ based on parameters in Table 1. Similarly, we can get $n=n_{opt}^*=(3\cdot\varepsilon_{mp}/2\cdot E_{elec})^{1/4}\cdot d$ and distance $r_i=d/n_{opt}^*\approx 71$ for multi-path model.

Fig. 2 shows the energy consumption under both free space and multi-path energy models. Given the distance from source to sink node d , we can equally divide d into n hops based on the analysis in this section. We see that there exists an optimal hop number n_{opt}^* with the minimal energy consumption in Fig. 2. The optimal hop number n_{opt}^* and the energy consumption increases with d , which can also be seen from energy model.

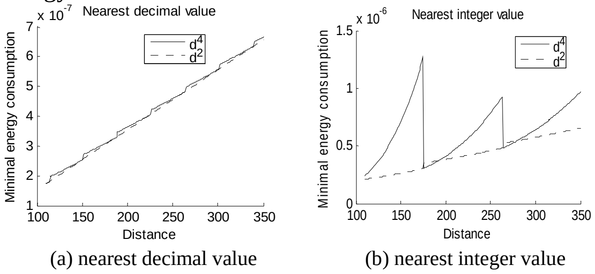


(a) free space energy model (b) multi-path energy model

Fig. 2 Energy consumption under two energy models

However, n_{opt}^* can not be obtained under constraint condition $r_i < d_0$ ($\alpha = 2$), since $r_i = 100 > d_0 \approx 87.7$ here. It is the same under constraint condition $r_i \geq d_0$ when $\alpha = 4$. Thus, we will choose the nearest integer from n_{opt}^* in Eq. (6) which satisfies $r_i < d_0$ or $r_i \geq d_0$. We call it sub-optimal hop number n_{opt} in this paper. The values of hardware parameters are determined by factors like electronic circuit, antenna height, receiver sensitivity etc [9].

Fig. 3 shows the minimal energy consumption under free space and multi-path energy model with different distance d by considering constraint condition $r_i < d_0$ or $r_i \geq d_0$. Here, the optimal hop number is the nearest decimal value in Fig. 3(a) while it is the nearest integer in Fig. 3(b) which satisfies the constraint condition above. From Fig. 3, we find that in most cases, free space model consumes less energy than multi-path model. Especially, free space model is much more energy efficient than multi-path model for nearest integer case, which is similar to the case under practical network. It is worth noting that energy consumption will reduce sharply around distance $d \approx N \cdot d_0$ (N is an integer) for multi-path model. This is because the distance is divided into smaller hops with distance larger and close to d_0, therefore the energy consumption is largely reduced based on the multi-path energy model.



(a) nearest decimal value (b) nearest integer value

Fig. 3 Energy consumption under constraint condition

4.3 Sub-optimal Hop Number

We can not directly use the deduced optimal hop number in Eq. (6) for two reasons. First, the hop number should be an integer rather than a decimal value under real network. Second, it is hard to find the corresponding intermediate nodes under practical sensor network. Therefore, we will provide a practical selection criterion of the sub-optimal hop number based on the theoretical deduction above.

When the distance $d < d_0$, it is obvious to use direct transmission manner. When $d \in (d_0, 2d_0)$, we can either use direct transmission or 2-hop transmission. Let:

$$f(d) = E_{Direct} - E_{Multi-hop}(2) \geq 0,$$

Namely:

$$\begin{aligned} f(d) &= (E_{elec} + \varepsilon_{mp} \cdot d^4) - (3E_{elec} + \varepsilon_{fs} \cdot d^2 / 2) \\ &= \varepsilon_{mp} \cdot d^4 - \varepsilon_{fs} \cdot d^2 / 2 - 2E_{elec} \geq 0. \end{aligned} \quad (7a)$$

Inequality (7a) will always hold true when:

$$d \geq d_c = \sqrt{\frac{\varepsilon_{fs}/2 + \sqrt{\varepsilon_{fs}^2/4 + 8\varepsilon_{mp} \cdot E_{elec}}}{2 \cdot \varepsilon_{mp}}}, \quad (7b)$$

and the critical distance $d_c \approx 104$.

Table 2 Selection criterion of sub-optimal hop number

d	r_i	Hop Number
$(0, d_c)$	$r_1 < d_c$	1
$[d_c, 2d_0)$	$r_1, r_2 < d_0$	2
$\vdots$	$\vdots$	$\vdots$
$[(n-1)d_0, nd_0)$	$r_1, \cdots, r_n < d_0$	n

As is shown in Table 2, we choose single hop routing with multi-path model when $d < d_c$. When $d \geq d_c$, we choose multi-hop routing with $n_{opt} \in (d/d_0, d/d_0 + 1]$ as the sub-optimal hop number. It is worth noting that when $d > d_c$, we can either use n_1-hop multi-path model with distance r_1 or n_2-hop free space model with distance r_2. Here $n_1 \cdot r_1 = n_2 \cdot r_2 = d$ and $n_2 > n_1$. According to the analysis in Fig. 3, we always choose n_2-hop free space model since free space model is more energy efficient in most cases. Even though it consumes a little more energy than multi-path model when $d \approx N \cdot d_0$, the difference is neglectable. Besides, it is hard to find n_1 intermediate nodes under practical sensor network.

5. Hop-based Energy Aware Routing (HEAR) Algorithm

HEAR algorithm is a distributed and localized algorithm for practical sensor network, which combines the general routing mechanism with hop-based nature during routing process in WSNs. It does not need the whole network information such as the location of all sensor nodes. It only needs its own location and the relative distance to its neighbors and to the sink node. Each sensor node has two tables. One is the routing table which contains information like source node, previous node, next node and duration (time to live) etc. in the header of packet. Another table is called neighboring table which contains information of its neighboring nodes like distance between them, distance to sink node, residual energy etc. Thus, each node can make intelligent decision of next hop locally based on HEAR algorithm and the algorithm is easy to implement for practical engineering applications.

The key strength of HEAR algorithm is that under constrain conditions like source to sink node distance d and hardware parameters, we can provide energy efficient route with the sub-optimal hop number and corresponding intermediate nodes under practical sensor network. The energy consumption can be largely reduced and average network lifetime can be prolonged. In the mean time, the hot spot phenomena can also get alleviated.

5.1 Basic Assumption

We make some basic assumptions as follows:
i) The sensor nodes are stationary and homogenous;
ii) The sensor nodes have several adjustable power levels and there is no conflict with MAC layer;
iii) The communication links are symmetric;
iv) The sensor nodes know the distance to their neighbors and to sink node;
v) There is no big obstacle between source and sink node.

Here, we only consider energy consumption during routing process and do not consider that consumed during sensing and processing process. Each node can get the distance to its neighbors based on received signal strength. And it can get the distance to sink node with triangulation method or other positioning or localization techniques in WSN. The symmetric link means if node j can receive packet from its neighboring node i, we also believe that node i can receive packet from node j in a reverse way. Finally, we assume that there is no big obstacle. Or else, the deduced sub-optimal multi-hop route will become meaningless since the optimal next hop node might not be chosen due to obstacles between them.

5.2 HEAR Algorithm

Our HEAR algorithm consists of two phases, which are route setup phase and route maintenance phase.

5.2.1 Route Setup Phase

Once source node has data to send, it will try to set up a route from source to sink node as follows.

First, it determines the transmission manner based on the selection criterion in Table 2. It is worth mentioning that the critical distance d_c is a theoretical value and sometimes direct transmission is more energy efficient when $d_c < d \le d_c + \Delta$ under real network environment. For example, when $d = 120$, it is very hard to find the 2-hop route with $r_1 = r_2 = 60$. Thus, direct transmission is better than 2-hop with $r_1 = 65, r_2 = 71$ under real sensor network. The value of Δ is dependant on network density and we set $\Delta \in [20,40]$ in this paper under different network topologies.

Once multi-hop transmission manner is chosen with sub-optimal hop number n_{opt}, the source node will choose a series of its neighbors with $d_i \in [d/n_{opt}, d/n_{opt} + \Delta]$ as candidates of its next hop. Finally, the neighbor closest to the sink node will be chosen as the next hop. It is worth emphasizing that the candidate nodes within the range above can be easily found under medium or high density sensor network. However, if there is no such node with $d_i \in [d/n_{opt}, d/n_{opt} + \Delta]$ under very low density sensor network, the source node will simply choose the neighbor which is closest to sink node as its next hop node (similar to greedy algorithm).

When the next hop node is chosen, the source node will send a short length Route Request (RREQ) message to its neighboring node directly with its own location information encapsulated inside RREQ. Once the neighbor receives the RREQ message, it will send an acknowledge (ACK) message back to its previous node. Then, it will add its own location information again into the RREQ message and send it to its next hop neighbor in an iterative manner like above. Finally, the RREQ message will reach the sink node carrying the complete route information and a Route Reply (RREP) message will be sent back to the source node based on the assumption of symmetric link.

The traffic can get started once source node gets RREP message with complete route information from sink node. After the traffic session is closed, each node on the route will update its routing table as well as neighboring table.

The whole route setup phase can be summarized as the following 4 main steps:

Step 1: The source node will first determine transmission manner as well as the sub-optimal hop number based on Table 2;

Step 2: If multi-hop transmission is chosen with sub-optimal hop number n_{opt}, source node will then choose its optimal next hop neighbor as follows:

Step 2.1: It will first choose a set of its neighbors with distance $d_i \in [d/n_{opt}, d/n_{opt}+\Delta]$ as its next hop candidates under medium or high density network. If there is no such candidate node under very low density network, it will treat all its neighbors as candidate nodes;

Step 2.2: It will finally choose the neighbor nearest to sink node as the next hop node;

Step 2.3: It will then send a RREQ message directly to the final next hop node containing its location;

Step 3: Once the next hop neighbor receives the RREQ, it will send an ACK message back and then choose its next hop in an iterative way above;

Step 4: Once the RREQ message reaches the sink node, a RREP message will be sent back to source node based on assumption of symmetric link. If there is link failure, a RERR message will be sent to the source node and the route maintenance phase will be initiated.

It is worth noting that each node has a neighboring table containing its neighbors' information like distance between them, distance to sink node, residual energy etc. Therefore, it can easily find the proper next hop neighbor and then send its data to the specific neighbor afterwards. Here, each node can dynamically adjust its power level based on the relative distance between them and all intelligent decisions are made locally.

5.2.2 Route Maintenance Phase

If a node does not receive an ACK message from its next hop neighbor within certain TTL (time-to-live) time, link failure will be detected and route maintenance phase will be initiated. Link failure might be caused by reasons like interference, node dies out of energy or continuous packet collision etc.

If the source node detects a link failure, it will restart the route setup phase by choosing another appropriate neighbor based on its neighboring table. If an intermediate node detects a link failure, it will first attempt a local link repair process. In other words, it will try to choose another proper neighbor in a similar way like Step 2. This local repair process will last for certain time until an ACK message is received from proper neighbor node or when time is expired.

If the local link repair process fails, a route error (RERR) message will be sent from intermediate node to source node in a reverse way based on the information stored in RREQ. Finally, this route will be deleted from source node as well as the intermediate nodes and a new route setup phase will be initiated.

It is worth mentioning that we can also consider the factor of remaining energy during hop-based routing. For example, we can choose the candidate with maximum residual energy as next hop in Step 2.2. In that case, the network lifetime could get further prolonged and the possibility of link failure can also get reduced. This is our future research work.

6. Performance Analysis

6.1 Simulation Environment

We use MATLAB simulator for the performance analysis. As is shown in Table 3, there are 80 to 500 sensor nodes randomly deployed in a WSN ranging from $200\times200\,m^2$ to $800\times800\,m^2$. The sink node is placed either inside or outside WSN. The transmission radius can be adjusted from 80 to 300 meters based on network density as well as the location of sink node.

Each node will transmit a 2000 bits message to the sink node using either direct transmission or multi-hop transmission based on different routing algorithms. Thus, the traffic is many-to-one. During multi-hop transmission, the intermediate nodes will consume additional energy to forward the message.

Table 3 Simulation Environment

Parameter	Value
Network size	$[200\times200, 800\times800]\,m^2$
Node number	[80, 500]
Radius	$[80, 300]\,m$
Sink node location	Inside or outside
Data size	2000 bits
Initial energy	2 J
E_{elec}	50 nJ/bit
ε_{fs}	10 pJ/bit/m^2
ε_{mp}	0.0013 pJ/bit/m^4
d_0	$\sqrt{\varepsilon_{fs}/\varepsilon_{mp}} \approx 87.7m$

We compare our HEAR algorithm with the following five popular routing algorithms. The first three ones are flat routing algorithms while the latter two are hierarchical routing algorithms.

- **Direct transmission algorithm**: Each sensor node transmits its data directly to remote sink node.
- **Greedy algorithm:** Each sensor node will choose the neighbor which is closer to the sink node than itself as the next hop to transmit its data.
- **Maximal remaining energy (MRE) algorithm**: Each node will choose the neighbor with maximal remaining energy to transmit its data.
- **LEACH algorithm [8]**: At first, 5% sensor nodes are randomly chosen as cluster heads in turn by comparing its random number with threshold value. Then, each cluster head will transmit its fused data directly to remote sink node.
- **HEED algorithm [20]**: Node with more residual energy will have a higher probability to be chosen as cluster head. It does not need global knowledge and it is an improved version of LEACH.
- **HEAR algorithm**: Our algorithm.

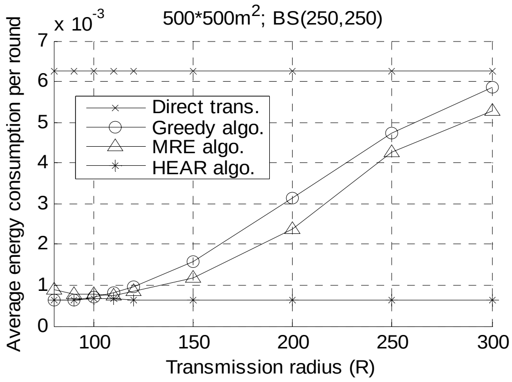
6.2 Performance Analysis

We consider two scenarios with sink node placed either inside or outside the monitoring area for the five flat and hierarchical routing algorithms. We study the performance of average energy consumption, network lifetime, hop number as well as reachability in this section.

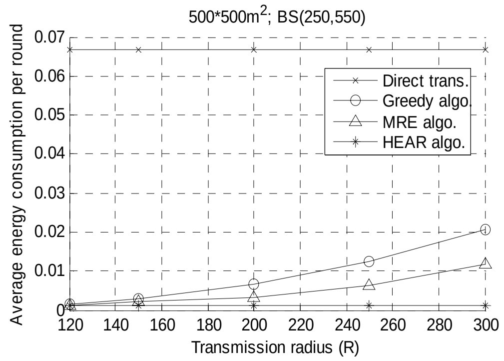
6.2.1 Average Energy Consumption

Fig. 4 shows the average energy consumption for a 500× 500 m^2 network with 300 randomly placed sensor nodes. The sink node is placed either inside or outside the area.

From the two figures, we find that direct transmission consumes the largest amount of energy since the average distance is large and multi-path model is used in most cases. Our HEAR algorithm consumes the least energy and it almost does not change. This is because $R \geq 120$ ensures the intermediate distance corresponding to the sub-optimal hop number can be found under practical sensor network. The performance of greedy and MRE algorithm is in the middle and their energy consumption increases with R because they tend to choose the next hop neighbor with larger distance, which causes more energy consumption. For small radii, the three algorithms consume similar the energy since energy consumption of free space model with small distance is relatively small. However, this does not mean that small radius can achieve high energy efficiency. If the R is even smaller, the energy consumption will be larger since more hop number is needed.



(a) BS placed inside



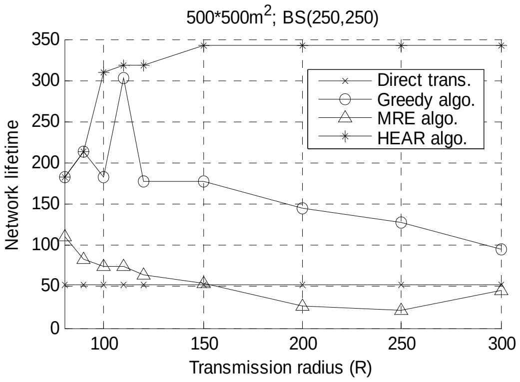
(b) BS placed outside

Fig. 4 Average energy consumption

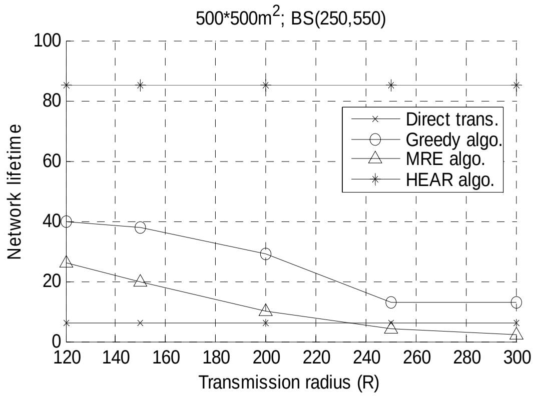
In Fig. 4(a), direct transmission almost consumes 10 times more energy than HEAR algorithm. In Fig. 4(b), the ratio is about 51 with BS placed outside. This is because the average distance from each source to sink node is much larger in Fig. 4(b). Taking $R = 150$ as an example, the energy consumption of greedy algorithm is about 2.5 times more than HEAR in Fig.4 (a) and it is about 2.2 times in Fig. 4(b). The ratio is about 1.9 times between MRE and HEAR in Fig.4 (a) and 1.8 times in Fig.4 (b). The ratio between greedy/MRE algorithm and our HEAR algorithm will be larger as R increases. It is worth noting that the energy consumption of HEAR does not change with R because the sub-optimal hop number and the corresponding intermediate distances are nearly kept as a constant, as can be seen from Eq. (6) and Table 2.

6.2.2 Network Lifetime

Fig. 5 shows the performance of network lifetime under the same network environment as in Fig. 4. Here, the definition of network lifetime is the time when the first node dies out of energy since this might cause network partition or isolated area quickly once the first node dies.



(a) BS placed inside



(b) BS placed outside

Fig. 5 Network lifetime

As can be seen from Fig. 5, network lifetime usually decreases with R since more energy will be consumed on average. In Fig. 5 (a), we found that greedy algorithm has a longer lifetime when $R \approx 110$ (sharp increase). This is because it tends to choose the next hop with distance near R and $R = 110$ is near the critical distance d_c with better energy efficiency. When $R \leq 100$, the lifetime of HEAR is relatively short because the sub-optimal hop number can not be chosen and a large hop number is needed. For example, we will choose 2-hop routing instead of direct transmission when $d = 102$ which causes more energy consumption. The lifetime of MRE algorithm is worse than direct transmission sometimes, because there may be such route with too many hops which causes more energy consumption.

The network lifetime of our HEAR algorithm is about 6.5 times longer than direct transmission in Fig. 5(a) and the ratio is about 14 times in Fig.5 (b). When $R \geq 150$, lifetime of HEAR is about 1.9 times of greedy algorithm and 6.5 times of MRE in Fig.5 (a). The ratio between HEAR and the other two algorithms is about 2.3 and 4.3 in Fig.5 (b). As R increases, the ratio will even be larger.

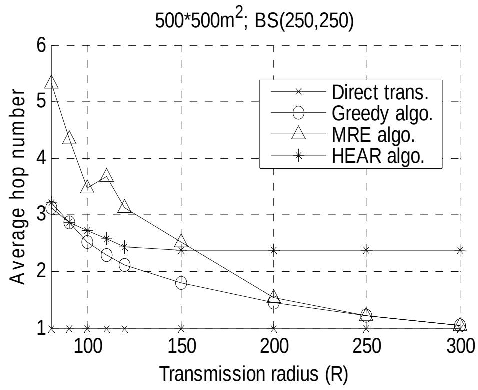
From Fig. 4 and 5, we also observe that:

a) $R \in [120,150]$ can ensure desirable energy efficiency of HEAR because it ensures that corresponding intermediate distance of sub-optimal hop number can be chosen under practical sensor network. If R is too large, it will cause larger communication overhead and interference while the network lifetime can not be further prolonged.

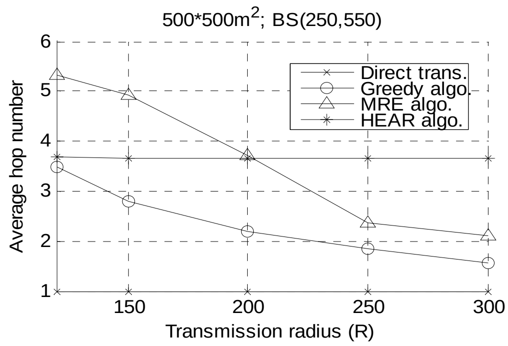
b) The average source to sink node distance is larger when sink node is placed outside the monitoring area. Thus, the average energy consumption will increase and network lifetime will decrease. In Fig. 5 (a) and 5 (b), the network lifetime difference for direct transmission is about 9 times and it is 4 times for HEAR algorithm. In Fig. 4, the energy consumption difference for direct transmission is about 11 times and 2 times for HEAR algorithm.

6.2.3 Average Hop Number

Fig. 6 shows the performance of average hop number under the same network environment as Fig. 4 and Fig. 5. We can see that direct transmission algorithm has the best performance of hop number which is equal to one. MRE algorithm has the worst performance due to initial random distributed energy. The performance of HEAR and greedy algorithm is in the middle.



(a) BS placed inside



(b) BS placed outside

Fig. 6 Average hop number

When $R \geq 120$, our HEAR algorithm has an average hop number of 2.4 in Fig. 6 (a) and it is 3.7 in Fig. 6 (b). Even though greedy algorithm and MRE algorithm has a smaller average hop number than HEAR algorithm, their energy consumption is much larger. The performance of our HEAR algorithm is desirable since the difference between HEAR and the other two is very small. Here, we can also see that HEAR algorithm is a tradeoff between direct transmission and too-many-hop routing algorithm.

6.2.4 Comparison with LEACH and HEED

We also compare our HEAR algorithm with the other two hierarchical routing protocols, namely LEACH and HEED in the aspects of average energy consumption and network lifetime. The clustering and radio parameters are the same as [8, 20]. Here, we consider the following 4 scenarios:

- **Scenario 1**: In a $200 \times 200\, m^2$ network, there are 100 sensor nodes with sink node at (100, 200).
- **Scenario 2**: In a $500 \times 500\, m^2$ network, there are 300 sensor nodes with sink node at (250, 250).
- **Scenario 3**: In a $500 \times 500\, m^2$ network, there are 300 sensor nodes with sink node at (250, 550).
- **Scenario 4**: In a $800 \times 800\, m^2$ network, there are 500 sensor nodes with sink node at (400, 800).

From Table 4 we can see that the average energy consumption of LEACH and HEED increases with the network scale as well as source to sink node distance. Our HEAR algorithm has a very desirable performance due to its hop-based nature. We can also see that the performance of HEED is better than LEACH, which consists with [20]. The difference between them becomes larger as network scale and source to sink node distance increases. The main reason is that LEACH uses direct transmission from each cluster head to the sink node while HEED uses multi-hop transmission between cluster heads and the sink node. Our HEAR algorithm has even more advantage over HEED for two reasons. First, the cluster heads in HEED are well distributed in terms of remaining energy rather than geographic location. In fact, the distance between ordinary nodes and cluster head as well as between cluster heads is randomly distributed in HEED. However, each multi-hop distance is carefully chosen based on theoretical deduction in HEAR. Second, there is additional clustering overhead like control message and energy consumption in HEED.

Table 4 Average energy consumption (J) for 3 algorithms

Algorithm \ Scenario	1	2	3	4
LEACH	0.0013	0.0060	0.0676	0.2664
HEED	0.001	0.0027	0.0272	0.0837
HEAR	0.0004	0.0007	0.0020	0.0029

From Table 5, we can draw similar conclusion of network lifetime for three algorithms. The performance of network lifetime decreases with network scale as well as source to sink node distance. Our HEAR algorithm has about 2 to 10 times longer lifetime than LEACH and HEED. Since the nodes with high residual energy have a high probability to be chosen as cluster heads in HEED, the nodes with low residual energy can get protected from dying quickly. Thus, the network lifetime of HEED is longer than LEACH which chooses cluster head randomly. Due to the same reasons as average energy consumption above, our HEAR algorithm has better performance than HEED. It is worth noting that network lifetime can get further prolonged if we consider residual energy during the selection of next hop node, as is mentioned above.

Table 5 Network lifetime for 3 algorithms

Algorithm \ Scenario	1	2	3	4
LEACH	476	256	23	7
HEED	537	458	93	11
HEAR	769	667	294	17

6.2.5 Reachability

Finally, we study the performance of reachability under different network topologies. Here, reachability is defined as the percentage of nodes which can successfully send their packets to the sink node. There are 50 to 100 sensor nodes randomly deployed in an $800 \times 800\, m^2$ network and the sink node is placed in the center of the network. The maximum transmission radius R is set as 110, 120, 130 and 140 meters which shows various network topologies.

Table 6 gives several network metrics under very low density network topologies when N=50. Here, isolated node means the node which can not reach the sink node through its neighbors. Void node means the node which can not forward the data to its neighbors according to greedy algorithm. In other words, it has no neighboring node which is closer to sink node than itself. We found that low reachability is mainly caused by isolated node with no neighbors or several isolated nodes which form an isolated area under very low density network. Also, void nodes [19] can cause low reachability since it will send its data to the neighbor which is further to the sink node than itself. Sometimes, the ordinary nodes which are connected or routed through void nodes can also cause packet delivery failure or low reachability.

We can see from Table 6 that the average neighbor number increases with R. Isolated and void nodes are the main reasons which cause low reachability or failed nodes. High network density and even node distribution can ensure better performance of reachability. Taking uniform node distribution as an example, the reachability is always

100% since all nodes are well connected and there are no isolated or void nodes. Under medium or high density random sensor network, the average neighbor number is usually above 15 and the reachability is above 95%. In Fig. 4-6, the average neighbor number is usually above 20. Therefore the reachability is always 100%. The average neighbor number is about 13 in [19] and the reachability of our HEAR is always 100% under their application environment. That is why we illustrate a low density network here to study the performance of reachability. From Table 6 and Fig. 7 we can see that HEAR algorithm can achieve desirable reachability even under very low density network.

Table 6 Network metrics under various topologies

R	110	120	130	140
Isolated nodes	13	12	8	0
Void nodes	5	3	1	0
Avg. neighbor	3	3.5	4	4.6
HEAR failed nodes	17	14	11	0

We compared our HEAR algorithm with flooding algorithm in Fig. 7. The flooding algorithm is viewed as the ideal algorithm since it can guarantee the highest reachability. We found that for the same node number N, reachability increases with R, which is also explained in Table 6. For the same R, the reachability increases with node number N.

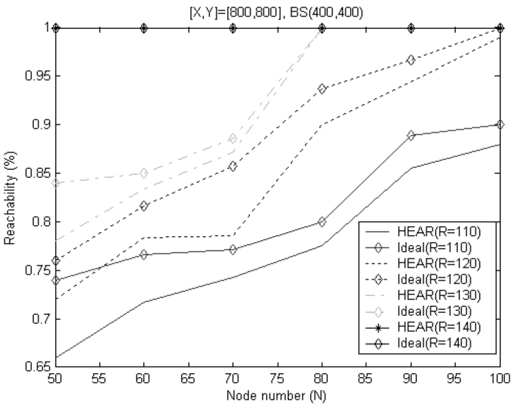


Fig. 7 Reachability

It is worth noting that reachability is dependant on the network topology since the sensor nodes are randomly deployed. Sometimes, a high node number and R could also cause low reachability due to the existence of isolated or void nodes. HEAR algorithm has a high reachability under medium or high density networks. It can also guarantee desirable reachability even under very low density sensor network.

7. Discussion

Once the hardware parameters and distance d are given, the sub-optimal hop number as well as the corresponding intermediate distances can be determined based on the theoretical analysis above. The hardware parameters are determined by factors like electronic circuit, antenna height and receiver sensitivity etc [9]. Different set of parameters will cause different values of the optimal hop number as well as intermediate distances. For example, direct transmission is always more energy efficient than multi-hop transmission in [8] with the hardware parameter value $\varepsilon_{fs} = 100\, pJ/bit/m^2$ under the small scale network environment. However, we can determine the sub-optimal hop number and intermediate distances by using the same methodology regardless of the hardware parameters.

HEAR algorithm can not only provide an effective sub-optimal hop number selection criterion under practical sensor network but also alleviate the hot node phenomena. As can be seen from Table 4, the energy consumption of HEAR is much smaller than the other two algorithms. Thus, for the nodes far away from sink node, their average energy consumption is can be greatly reduced via multi-hop routing process. Even for the nodes near sink node, we will choose a few of them which are placed along the multi-hop route from source to sink node with proper intermediate distances.

The mechanism of HEAR algorithm can be adapted by other routing protocols. It is a simple distributed and localized algorithm. No global knowledge is needed and each node makes intelligent local decisions based on its neighboring table during routing process. It is similar to [10] because a chain-like multi-hop route is built therein. The shortcoming of HEAR algorithm is the assumption that each node needs to know its own location information so that it can know the relative distance from itself to its neighbors as well as to the sink node. Also, we do not consider the case when there are big obstacles in the network. In that case, the proper next hop node may not be found and the final route length from source to sink node could be several times larger than the direct distance between them, which will cause more energy consumption. However, our HEAR can still find the detour route even though the final hop number is larger than n_{opt} hops.

8. Conclusion and Future Work

Hop-based routing algorithms can not only improve the energy efficiency of WSNs but also play an important role in improving many other network metrics like latency, interference, routing overhead etc. In this paper, we primarily focus on studying the relationship between hop number and energy consumption. We derive the optimal theoretical hop number under linear network environment. Also, we provide an effective selection criterion of the sub-optimal hop number under practical sensor network. Then we propose our Hop-based Energy Aware Routing (HEAR) algorithm based on the deduction of sub-optimal hop number which is more energy efficient than other five flat and hierarchical routing algorithms, especially under medium or high dense network environment.

In the future, we plan to extend our work by studying the influence of hop number on other network metrics such as latency, communication overhead, packet delivery ratio etc. Also, we will consider data fusion as well as the factor of residual energy so as to further improve energy efficiency during routing process.

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Jin Wang received the B.S. and M.S. degree in the Electronical Engineering from Nanjing University of Posts and Telecommunications, China in 2002 and 2005, respectively. Since 2005, he has been pursuing Ph.D. degree in Ubiquitous Computing laboratory in the Computer Engineering Department of Kyung Hee University Korea. His research interests include routing protocol and algorithm design, analysis and optimization, and performance evaluation for wireless ad hoc and sensor networks.

Jinsung Cho received his B.S., M.S, and Ph.D. degrees in computer engineering from Seoul National University, Korea, in 1992, 1994, and 2000, respectively. He was a visiting scholar at IBM T.J. Watson Research Center in 1998 and a research staff at SAMSUNG Electronics in 1999~2003. Currently, he is an assistant professor of Department of Computer Engineering at Kyung Hee University, Korea. His research interests include mobile networking & computing and embedded systems & software.

Sungyoung Lee received his B.S. from Korea University, Seoul, Korea. He got his M.S. and PhD degrees in Computer Science from Illinois Institute of Technology (IIT), Chicago, Illinois, USA in 1987 and 1991 respectively. He has been a professor in the department of Computer Engineering, Kyung Hee University, Korea since 1993. He is a founding director of the Ubiquitous Computing Laboratory, and has been affiliated with a director of Neo Medical ubiquitous-Life Care Information Technology Research Center, Kyung Hee University since 2006. Before joining Kyung Hee University, he was an assistant professor in the Department of Computer Science, Governors State University, Illinois, USA from 1992 to 1993. His current research focuses on Ubiquitous Computing and applications, Context-aware Middleware, Sensor Operating Systems, Real-Time Systems and Embedded Systems. He is a member of the ACM and IEEE.

Kwang-Cheng Chen received B.S. from the National Taiwan University in 1983, M.S. and Ph.D. from the University of Maryland, College Park, United States, in 1987 and 1989, all in electrical engineering. From 1987 to 1998, Dr. Chen worked with SSE, COMSAT, and IBM Thomas J. Watson Research Center, National Tsing Hua University in mobile communication networks and related research. Dr. Chen is the Distinguished Professor and Irwin T. Ho Chair Professor at the Institute of Communication Engineering and Department of Electrical Engineering, National Taiwan University, Taipei, Taiwan, ROC. He hold several visiting positions with Technical University of Delft in Netherlands, HP Labs. in US, Aalborg University in Denmark. Dr. Chen actively involves the technical organization of numerous leading IEEE conferences, including 1996 IEEE International Symposium on Personal Indoor Mobile Radio Communications, IEEE Globecom 2002, 2007 IEEE Mobile WiMAX Symposium, and IEEE Vehicular Technology Conference Spring 2010. He has served editorship with many prestigious international journals: IEEE Transaction on Communications, IEEE Communications Letters, IEEE Communication Surveys, IEEE Wireless Communications Magazine, International Journal of Wireless Information Networks, IEEE Journal on Selected Area in Communications, ACM/Blatzer Journal on Wireless Networks, Wireless Personal Communications, and Frontier of Communications and Information Theory, etc. Dr. Chen has authored and coauthored over 200 technical papers and 18 US patents. Dr. Chen is an IEEE Fellow, and recipient of many awards and honors. Dr. Chen's research interests include wireless communications and wireless networks, cognitive and nano-communications.

Young-Koo Lee got his B.S., M.S. and PhD in Computer Science from Korea Advanced Institute of Science and Technology, Korea. He is a professor in the Department of Computer Engineering at Kyung Hee University, Korea. His research interests include ubiquitous data management, data mining, and databases. He is a member of the IEEE, the IEEE Computer Society, and the ACM.