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An Integrated Sleep-Scheduling and Routing Algorithm in Ubiquitous Sensor Networks Based on AHP

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SUMMARY Ubiquitous sensor networks (USNs) are comprised of energy constrained nodes. This limitation has led to the crucial need for energy-aware protocols to produce an efficient network. We propose a sleep scheduling scheme for balancing energy consumption rates in a single hop cluster based network using Analytical Hierarchy Process (AHP). We consider three factors contributing to the optimal nodes scheduling decision and they are the distance to cluster head (CH), residual energy, and sensing coverage overlapping, respectively. We also propose an integrated sleep scheduling and geographical multi-path routing scheme for USNs by AHP. The sleep scheduling is redesigned to adapt the multi-hop case. For the proposed routing protocol, the distance to the destination location, remaining battery capacity, and queue size of candidate sensor nodes in the local communication range are taken into consideration for next hop relay node selection. The proposed schemes are observed to improve network lifetime and conserve energy without compromising desired coverage. In the multi-hop case, it can further reduce the packet loss rate and link failure rate since the buffer capacity is considered.
key words: *ubiquitous sensor networks, AHP, energy balance, lifetime, sleep scheduling, routing*

1. Introduction

Ubiquitous sensor networks (USNs) are expected to be widely employed in various applications such as medical care, military, environmental monitoring and industry [1]. Currently, energy supply is one of the fundamental bottlenecks. It is very costly and unpractical to replace sensor node batteries once they are deployed, both because of the large number of sensing nodes and the typically hazardous or unfriendly environment in which these nodes are deployed. Hence, prolonging network life becomes a primary concern in network design.

The sleeping technique has been used to conserve energy of battery powered sensors. Several researchers even suggest putting redundant sensor nodes into the network and allowing the extra sensors to sleep to extend network lifetime [2]. This approach is practical due to the low cost of individual sensors. When a sensor node is put into the sleep state, it is completely shut down, leaving only one extremely low power timer on to wake itself up at a later time. In a dense sensor network, rotating active and inactive sensors among the low power sensor members, some of which provide redundant data, is an intelligent way to manage sensors to extend its network lifetime. This leads to the following sleep scheduling problem: How does the cluster head (CH) or base station (BS) select which sensor nodes to be put into sleep, without compromising the sensing coverage capabilities of the whole network?

For a multi-hop USN rather than a single hop USN, an energy efficient routing protocol also needs to be considered. Hence, there exist more challenges than single hop networks, for example,

- The routing path (link) failure may happen during data transmission because of collision, node dying out (no battery), node busy, or other accidents. Some applications require real time information and data, which means retransmission is not possible. This motivates us to design a multi-path routing scheme for USNs.
- There exists energy constraint in USNs because most sensors are battery operated. This motivates us to consider energy aware routing.

In this paper, we investigate the energy constraint problem in USNs and propose a sleep scheduling scheme in a single hop network based on Analytical Hierarchy Process (AHP). In addition, an integrated sleep scheduling and routing algorithm in a multi hop environment is proposed again based on AHP. In a single hop network, three factors contributing to the optimal nodes scheduling decision are considered and they are 1) distance to CH, 2) residual energy, and 3) sensing coverage overlapping, respectively. Our goal is to balance energy consumption in low power sensor nodes and extend the sensor network lifetime while maintaining adequate sensing coverage capabilities. In a multi hop network, we propose an integrated AHP based sleep scheduling and multipath routing scheme for USNs, each of which has three different criteria considered as well. We evaluate the efficiency of both proposed schemes in terms of energy consumption, lifetime and coverage, and compare with related work, that is, Linear Distance-based Scheduling (LDS) and random scheduling in single hop heterogeneous sensor networks case, and Hop-based Sleeping Scheduling (HSS) algorithm and Geographical Multipath Routing (GMR) scheme in the multi hop case.

The rest of the paper is organized as follows. We introduce the background of AHP and related work in Sect. 2. The 3rd section presents our sleep scheduling scheme in a single hop network. We present an integrated sleep scheduling and routing protocol in a multi-hop network in Sect. 4.

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Section 5 evaluates and analyzes the performance of the proposed method. Finally, we draw the conclusion and discuss future work in Sect. 6.

2. Background

2.1 Analytical Hierarchy Process

The Analytical Hierarchy Process (AHP) [3] is a multiple criteria decision-making method which decomposes a complex problem into a hierarchy of simpler and more manageable sub problems. These sub-problems are usually called decision factors and weighted according to their relative dominances to the problem. AHP synthesizes their importance to the problem, and finds the best solution.

AHP performs following four main steps: decomposition, pair-wise comparison, local weight calculation, and weight synthesis.

2.1.1 Structuring Hierarchy

Structuring a problem as a hierarchy of multiple criteria is the first step of implementing AHP. The decision factors of the problem are identified and inserted into the hierarchy. The overall objective is placed at the topmost level of the hierarchy. The subsequent level presents the decision factors. The solution alternatives are located at the bottom level.

2.1.2 Calculating Local Weights

The second step is the evaluation stage where each factor is compared to all other factors within the same parent. Local weights consist of two parts: the weight of each decision factor to the goal and the weight of each nominee to each factor. Both of them are calculated with the same procedure. Taking the former as an example, we describe the procedure as the following three steps.

- *Making Pairwise Comparison*

The evaluation matrices are built up through pairwise comparing each decision factor under the topmost goal. The comparison results are based upon user expertise experience by asking questions such as "Which is more important and by how much?" These initial values are captured in square matrix A as

$$A = (a_{ij})_{n\times n} = \begin{pmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{pmatrix} \tag{1}$$

where a_{ij} denotes the ratio of the ith factor weight to the jth factor weight, and n is the number of factors. The fundamental 1 to 9 scale can be used to rank the judgments as shown in Table 1 [20]. The smaller one in a pair is chosen as a unit and the larger one is estimated as a multiple of that unit and assigned a number based on the perceived intensity of importance. Similarly, the reciprocals of these numbers are used to show the inverted comparison results. We thus obtain a reciprocal matrix where the entries are symmetric with respect to the diagonal.

Table 1 A fundamental scale of 1 to 9 (2, 4, 6, 8 indicate the medium value of pairwise comparison).

Number Rating	Verbal Judgment of Preferences
1	Equally
3	Moderately
5	Strongly
7	Very
9	Extremely

- *Calculating Weight Vector*

For the given matrix A in Eq. (1), its eigenvalue equation is written as $AW=\lambda_{max}W$, where W is a non-zero vector called eigenvector, and λ_{max} is a scalar called eigenvalue. W and λ_{max} appear as a pair and cannot be taken apart. After standardizing the eigenvector W, we regard the vector element of W as the local weight of each decision factor approximately, which can be denoted as:

$$W_j^T = \{\omega_1, \omega_2, \dots, \omega_n\} \tag{2}$$

As a result, the weights of the decision factors can be achieved by calculating the eigenvector of AHP matrix and the eigenvalue that approximately equals the number of assessed elements.

- *Checking for Consistency*

If every element in Eq. (1) satisfies equations $a_{ij} = 1/a_{ji}$ and $a_{ik} \cdot a_{kj} = a_{ij}$, the matrix A is the consistency matrix. However, the evaluation matrices are often not perfectly consistent due to people's random judgments. These judgment errors can be detected by a consistency ratio (CR), which is defined as the ratio of consistency index (CI) to random index (RI). CI can be achieved by

$$CI = (\lambda_{max} - n)/(n-1) \tag{3}$$

where λ_{max} is the eigenvalue and

$$\lambda_{max} = (1/n)\sum_{i=1}^{n}(AW)_i/W_i \tag{4}$$

The RI is given in Table 2 [3]. When CR $\leq$ 0.1, the judgment errors are tolerable and the weight coefficients of the global weight matrix W_j are the weights of decision factor under the topmost goal. Otherwise, the pairwise comparisons should be adjusted until matrix A satisfies the consistency check, i.e. matrix A needs to be reinitialized.

2.1.3 Calculating Global Weights

From above steps, we can obtain not merely the weights of decision factors towards the topmost goal from W_j but also the weights of alternatives towards each factor. If there are k candidates, all the k weight matrixes of alternatives under

Table 2 Random index.

n	RI
1	0
2	0
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49
11	1.51

n factors construct a $k \times n$ matrix, denoted as $W_{n_i/j}$, $i = 1, 2, \ldots, k$, $j = 1, 2, \ldots, n$.

The global weight of each alternative can be achieved through multiplying the local weight by its corresponding parent. So the final weight matrix in the symbol of W_{n_i} is calculated as

$$W_{n_i} = W_{n_i/j} \cdot W_j \tag{5}$$

where the final weight of each alternative is calculated as

$$W_{n_i} = \sum_{j=1}^{n} W_{n_i/j} \cdot W_j \tag{6}$$

The larger the final weight of alternative, the higher the probability it is eligible to be selected.

2.2 Related Work

Sleep scheduling which aims to conserve the energy of the sensor nodes has been studied in the literature. In [2], nodes are allowed to sleep based on routing information, and nodes switch between sleep and active state based on the traffic of the network. As a modification to this basic algorithm, reactive features have been added to the node's schedule. The node would wake up more frequently based on the route discovery interval. Another widespread option is to turn off redundant nodes in the network [4]. In this scheme, the density of low power sensors is high enough to maintain the sensing coverage of the entire network even when some nodes are turned off. Each node studies the activity of their neighbors and decides to sleep if the coverage can be maintained by the active nodes. A back-off based approach has been used to prevent neighboring nodes to turn themselves off simultaneously.

In [5], a few nodes are selected as coordinators which would then decide the sleep/awake schedule of the other nodes in the network. While coordinators are awake at all times, the other nodes in the network sleep in order to conserve the overall network energy. In [6] nodes are randomly selected to go to the sleep mode and in [7] a Linear Distance-based Scheduling (LDS) technique has been used to define the sleep schedule of the nodes in a cluster based homogeneous network. In [8], the authors release the single hop communication assumption of [7] and introduce a Hop-based Sleeping Scheduling (HSS) algorithm in a circular sensor network which is divided by a number of levels. The overall result of these sleep schedules is a considerable reduction in the energy consumption of the sensor network.

In [9], the authors propose a cross-layer sleep-scheduling-based organizational approach, called SS-Trees, in order to increase monitoring coverage and operational lifetime of mesh-based USNs. An integer linear programming (ILP) formulation and an iterative algorithmic approach are suggested to determine the feasible SS-Tree structures for these purposes. The ILP approach requires the determination of objective functions and several constraints, which is often complicated. Hence the proposed AHP based approach is different and simpler in that we only need to give the estimated weight to several factors as an input for AHP to finish the whole process of optimal decision making without knowing the objective functions and constraints. From this point-of-view, AHP is easier to carry out with the achievement of the same performance goals.

Many routing protocols have also been developed for ad hoc networks, which can be summarized into two categories: table-driven (e.g., destination sequenced distance vector [10], cluster switch gateway routing [11]) and source-initiated on-demand (e.g., ad hoc on-demand distance vector routing [12], dynamic source routing (DSR) [13]). In [14], Lee and Gerla propose a Split Multi-path Routing protocol that builds maximal disjoint paths, where data traffic is distributed in two roots per session to avoid congestion and to use network resources efficiently. A Multi-path Source Routing (MSR) scheme is proposed in [15], which is an extension of DSR. Their work focuses on distributing load adaptively among several paths. Nasipuri and Das [16] present the On-Demand Multi-path Routing scheme which is also an extension of DSR. In their scheme, alternative routes are maintained, which can be utilized when the primary one fails.

In sensor networks, location is often more important than a specific node ID. For example, in sensor networks for target tracking, the target location is much more important than the ID of reporting node. Therefore, some location-aware routing schemes have been proposed for USNs. A greedy geographic forwarding with limited flooding to circumvent the voids inside the network is proposed in [17], and some properties of greedy geographic routing algorithms are studied in [18]. Jain et al. [19] proposes a geographical routing using partial information for USNs.

The AHP algorithm for CH selection is proposed in [20]. However, our approach is different from theirs in that we apply AHP to sleep scheduling and moreover use different AHP factor namely overlapping coverage.

3. Sleep-Scheduling in a Single-Hop Cluster Based Network

We adopt the same radio model as stated in [21] with $\epsilon_{fs} = 10\,\mathrm{pJ/bit/m^2}$ as amplifier constant, $E_{elec} = 50\,\mathrm{nJ/bit}$ as the energy being dissipated to run the transmitter or receiver cir-

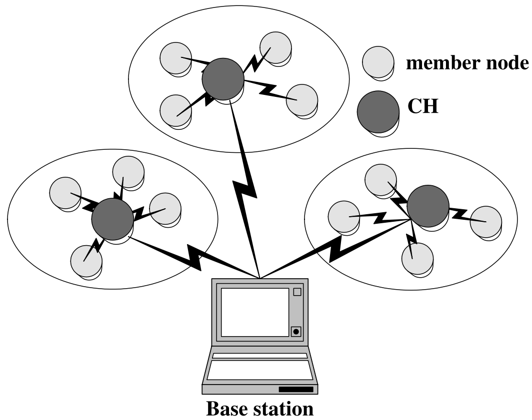


Fig. 1 Cluster based sensor network topology.

cuitry. It is assumed that the transmission between the common nodes or between the CH and its individual member node follows a second-order power loss model. The energy cost of transmission for sensor nodes at distance d from each other in transmitting an l-bit data is calculated as:

$$E_T(l, d) = LE_{elec} + l\epsilon_{fs}d^2 \quad (7)$$

A typical sensor network could contain thousands of small sensors. In some specific applications, clustering has been employed to group a number of sensors, usually within a geographic neighborhood. In such a cluster based topology, sensors can be managed locally by a CH which is a node responsible for management in the cluster and for communication between the cluster and the base station.

We aim to enhance the efficiency of the given sensor network by enabling a balanced usage of energy across the nodes and an improved network lifetime without compromising network coverage. Figure 1 is the illustration of cluster based sensor network topology in which our proposed single hop sleep scheduling scheme is designed. We focus on energy consumption at the cluster level.

3.1 Assumptions

We consider the sleep node scheduling problem under several assumptions as follows:

- The target sensor network is heterogeneous with a large number of low power sensor nodes to serve as member nodes and a small number of more powerful nodes to serve as CHs. The motivation behind is to confine the complex hardware and additional battery to a few CH nodes. The low power nodes are simple in hardware and perform basic functions such as sensing and simple computations;
- A large number of sensor nodes are deployed over a sensing field, such that at least some sensor nodes can be put into the sleep state without degrading the sensing coverage of the network;
- The CHs can communicate directly with BS and vice-versa. Similarly, the CH can reach all the sensor members in the cluster in one hop and vice-versa. Thus, it is not needed for any routing strategy from the BS to any specific CH or from any CH to the individual sensor member.
- The application can tolerate some delay in reports from some sensors in each round.

3.2 Network Parameters

The user-defined parameters used in defining the network are listed below:

1. Fraction of nodes selected to sleep in a given round, ‘r’: This is the fraction of the total number of nodes in the network that are selected to sleep in each round.
2. Threshold limit, ‘θ’: This denotes the fraction of nodes in the network, which, when dead, determines the lifetime of the network.

3.3 Sleep Scheduling Scheme by AHP

In our design, three factors influence the load balance and coverage directly, that is, 1) distance to CH, 2) residual energy, and 3) sensing coverage overlapping:

1. Distance to CH: Distance of a node to its CH. It can be approximated by the signal strength of radio transmission. The node with longest distance to the CH is preferred to be put into sleep.
2. Residual energy: Remaining battery of the sensor node. The initial energy is predefined. In addition, the energy consumption for transmission is calculated using Eq. (7) by CH.
3. Sensing coverage overlapping: Overlapped sensing range of a node by neighbor nodes. The node with larger overlapping degree, i.e., the node with higher redundancy, is desired to be selected as sleeping node.

This optimized sleep scheduling process is a multiple factors optimization problem and can be achieved by AHP, which is used to select the nodes eligible to sleep in one cluster. It is carried out in three steps:

Step 1 Collect information and formulate the sleeping nodes selection problem as a decision hierarchy of independent factors.
Step 2 Calculate the relative local weights of decision factors or alternatives of each level.
Step 3 Synthesize the above results to achieve the overall weight of each alternative nodes and choose the one with largest weight as the eligible sleeping node.

The goal of the decision “select a node eligible to sleep” is at the top level of the hierarchy as shown in Fig. 2. The next level consists of the three decision factors. At the bottom level there exist the m alternative sensor nodes to be evaluated. In AHP modeling, the evaluation matrix A, here denoted as A1, is determined based on Eq. (1) as follows:

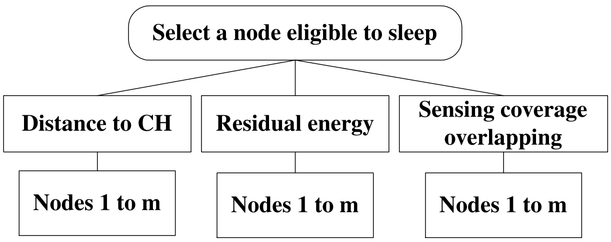


Fig. 2 AHP hierarchy for sleeping nodes selection in a single hop case.

$$
\begin{array}{c} \\ A1 = \end{array}
\begin{array}{c} \\ \alpha \\ \beta \\ \gamma \end{array}
\begin{array}{c} \begin{array}{ccc} \alpha & \beta & \gamma \end{array} \\ \left[\begin{array}{ccc} \alpha/\alpha & \alpha/\beta & \alpha/\gamma \\ \beta/\alpha & \beta/\beta & \beta/\gamma \\ \gamma/\alpha & \gamma/\beta & \gamma/\gamma \end{array}\right] \end{array}
$$

$$
= \left[\begin{array}{ccc} 1 & 2/1 & 3/1 \\ 1/2 & 1 & 2/1 \\ 1/3 & 1/2 & 1 \end{array}\right]
$$

where the three criteria (distance to CH, residual energy and sensing range overlapping) are denoted by α, β and γ respectively. The selection of these initial values is motivated by our choice that "Distance to CH" is the most important, than "Residual energy" is the next important followed by "Sensing range overlapping" as the least important factor. This choice reflects a typical set of parameters for energy conservation.

The computed eigenvector W = [0.5396 0.2970 0.1634]. It indicates the local weight of the distance to CH, residual energy, and sensing coverage overlapping respectively so that we can see clearly that the distance to CH is the most important criterion, and sensing coverage overlapping is the least. According to Eq. (4), we can get the eigenvalue $\lambda_{max} = 3.0093$. Consequently, consistency ratio can be calculated as $CR = 0.0047 < 0.1$, thus matrix A satisfies the consistency check.

Each sensor node determines the weight matrices of alternatives under three factors and then gets global weight based on its specific situation. Afterwards, its eligibility as a sleeping node can be finally decided.

If there are eight candidate nodes in each cluster, all the eight weight matrixes of alternatives under three factors construct a 8×3 matrix, denoted as $W_{n_i/j}$, i=1, 2, ..., 8, j=1, 2, 3. The final weight of each alternative is calculated using Eq. (6) with n =3. The larger the final weight of node, the higher the probability of node which is eligible to be put into sleep. Thus, the r fraction of nodes with the largest weight are selected as the sleeping nodes in the current round.

4. Integrated Sleep-Scheduling and Routing Algorithm

In multihop environment, we investigate the sleep scheduling problem as well as multipath routing problem and propose an integrated AHP based sleep scheduling and routing (A-SR) scheme in a ring based multi-hop network topology with the destination (or BS) at the center, as shown in Fig. 3. In the existing multi hop sleep scheduling scheme (e.g., [8]), although routing is integrated, residual energy is the only factor considered. In the existing geographical routing approach (e.g., [19]), the path selection doesn't consider the remaining battery capacity of each node, which is a very important factor for energy constraint sensor networks. In our A-SR sleep scheduling part, distance to destination, residual energy, and sensing coverage overlapping are included, with the latter two factors the same as the single hop case. In contrast with the single hop case, the node with shorter distance to destination is preferred to be put into sleep since they are more energy hungry as a relay. In routing part, distance to the destination, residual energy, and queue size of each sensor node are included, with the former two factors the same as the proposed multi hop sleep scheduling. Our scheme is a fully distributed approach where each sensor only needs the above parameters, and we use AHP to handle these parameters in the A-SR.

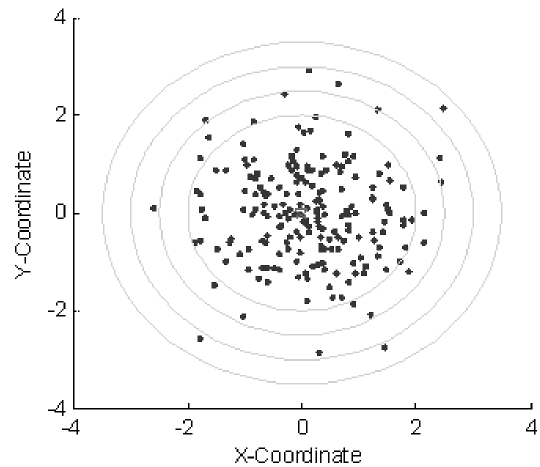
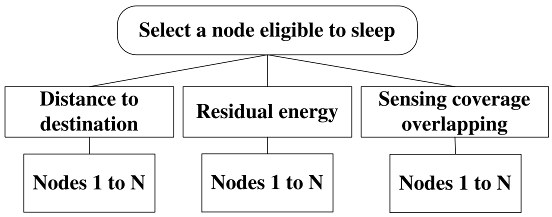


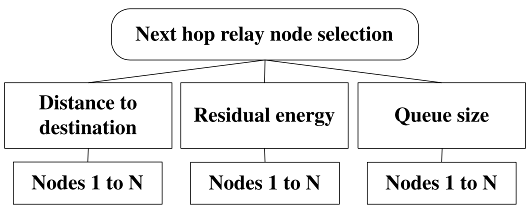
Fig. 3 Ring based multihop network topology.

In our A-SR scheme, we only keep the second assumption from single hop case. And we need to additionally assume that the event detection by the nodes in the network occurs periodically and all nodes are synchronized. Thus our A-SR can be executed round by round based on the period. For A-SR routing part, the detailed explanations of the three criteria for next hop relay node selection are given as follows:

1. Distance to destination: Distance of a node to BS which is the destination. The geographical location of destination is known to the source node (as in [19]), and the physical location of each sensor node can be estimated easily if the locations of three sensor nodes (within a communication range) are known in a USN. The node with shorter distance to the destination is preferred to be selected.
2. Residual energy: Remaining battery of the sensor node. The energy consumption for transmission and reception can be calculated using Eqs. (7) and (8).
3. Queue size: It indicates the buffer capacity at the node. This parameter helps avoid packet drops due to congestion at the receiver.



(a) AHP hierarchy for sleep nodes selection.



(b) AHP hierarchy for next hop relay nodes selection.

Fig. 4 AHP hierarchy for decision making in a multi-hop network.

The optimized node selection in multipath routing is also a multiple factors optimization problem and can be achieved using AHP.

In our A-SR for M-path routing, the source node select M nodes in its communication range for the first hop relay. Assume there are N (N >M) nodes in its communication range, nodes that are farther to the destination node than the source node are not considered. Choosing M nodes from remaining eligible nodes is based on AHP (as will be described in detail). Starting the second hop, each node in the M-path selects its next hop node also using AHP.

In the AHP hierarchy model, the goal of the decision "next hop relay node selection" is at the top level of the hierarchy as shown in Fig. 4(b). The next level consists of the three decision factors and at the bottom level there exist the N alternative sensor nodes to be evaluated.

We assume that each sensor node keeps a table which has some information about its neighbor nodes: locations, battery level, and queue size. The table is updated periodically by the locally-broadcasted information (beacon) from each neighbor node. We define a time interval T, during which the three parameters (locations, battery level, and queue size) do not change very much. This time interval T is the shortest time duration that a sensor node will send another beacon. Each sensor examines itself the status of the three parameters in every period T, and if a certain parameter has changed above a threshold, it will locally broadcast a beacon.

In the route discovery phase, the source node uses AHP model to evaluate all eligible nodes (closer to destination) in its communication range based on the parameters of each node: distance to destination, residual energy, and queue size. The source node chooses the top M nodes based on the local weight that this node will be selected. And the source node sends a Route Acknowledgement (RA) packet to each desired node, and each desired node will reply using a REPLY packet if it is available. The structure of RA and REPLY is summarized in Table 3. If after a certain period of time, the source node did not receive REPLY from some desired node, it will pick the node with highest weight among the remaining N-M nodes. In the second hop, the selected node in each path will choose its next hop node using the same process. As illustrated in Fig. 5, node B needs to choose one node from four eligible nodes C, D, E, and F based on their three parameters, and sends RA packet to the selected node and waits for REPLY. If the top one node is unavailable (for exmaple, selected by another path), then the top second node will be selected. Consequently, M paths can be set up.

Table 3 RA and REPLY message structure.

Type
Desired Node ID
Self Node ID
Dest_X
Dest_Y
Src_ID

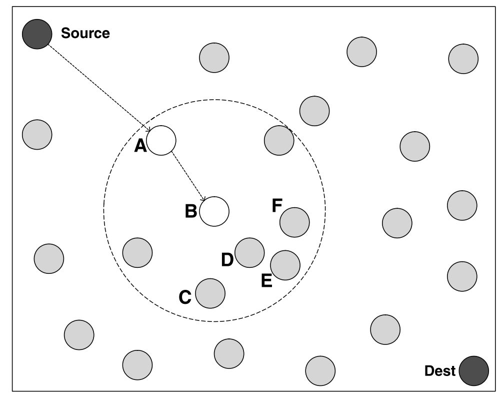


Fig. 5 Illustration of next hop node selection.

For A-SR sleep scheduling part, we only present its AHP hierarchy model which is shown in Fig. 4(a), due to the similarity to the single hop case.

For energy analysis, we adopt the previously presented transmission energy model, i.e., Eq. (7). In multihop networks, the energy for reception and data aggregation also need to be taken into account. Thus, to receive an l-bit data, the radio expends:

$$E_R(l) = lE_{elec} \tag{8}$$

and the energy for data aggregation is set as $E_{DA} = 5$ nJ/bit, the same as [21].

In AHP modeling, the evaluation matrices for A-SR, here denoted as A2, is determined based on Eq. (1) as follows:

$$A2 = \begin{matrix} & \alpha & \beta & \gamma \\ \alpha \\ \beta \\ \gamma \end{matrix} \begin{bmatrix} 1 & 2/1 & 3/1 \\ 1/2 & 1 & 2/1 \\ 1/3 & 1/2 & 1 \end{bmatrix}$$

where the three criteria, shown in Figs. 4(a) and (b) from left to right, are denoted by α, β and γ respectively. The computed eigenvector W has the same value as the single hop case since we assumed the same evaluation matrix. So we can observe that the distance to destination is the most important criterion, and sensing coverage overlapping and queue size are the least. We can again get the eigenvalue $\lambda_{max} = 3.0093$, and consequently matrix A2 satisfies the consistency check.

Each sensor node determines the weight matrixes of alternatives under three factors and then gets global weight based on its specific situation. Its eligibility as next hop relay node and sleep node can be finally decided by the AHP hierarchy model.

5. Performance Evaluations

In order to evaluate the single hop sleep nodes scheduling scheme by AHP, we compare it with the upper (lower) bound (which optimizes merely the current factor), LDS [7] and random scheduling scheme. In our simulation, the 50 m by 50 m square monitored area is assumed. All nodes except CHs equip with identical sensors and the sensing and communication range are equal to 8 m and 16 m respectively. Initial energy in each node is 2 J. We set the total number of nodes to be N_t=50 and number of static clusters to be 2. Thus the number of nodes in each cluster is 25 by assuming a uniform distribution of nodes.

Assume the CH plans to allow 25r nodes in its cluster to sleep in each cycle. In the random scheduling scheme, the CH randomly selects r fraction sensor nodes to sleep. At first, we compare the average energy consumption in a cluster by AHP based scheme and random scheduling scheme to show the energy that can be conserved by our scheme. Figure 6 provides the energy consumption verses the fraction of sleeping nodes of the three schemes. Furthermore, we also consider the ideal case where Eq. (7) is used to determine the minimum energy consumption which provides a lower bound on average energy consumption. It shows that the energy consumption in case of the proposed AHP based scheme is less than that of the random scheme, however slightly more than that of the LDS. The energy savings can be enhanced with an increasing value of r. For an r value of “0.7,” the energy consumed by the AHP based scheme is 49.3% less than by random scheme and 9% more than LDS.

Network lifetime can be defined as the time when a fraction of nodes, θ, run out of energy. In Fig. 7, we evaluate the lifetime of the three schemes and the upper bound for various values of r and θ. The length of each round is 5 seconds. We can see that the lifetime of both schemes is prolonged with the increasing of r and the proposed AHP based scheme greatly outperforms the random scheme and is close to LDS. This is in line with the analysis that the proposed scheme can balance the energy consumption among all the member nodes. We also can see that the lifetime of all the schemes increases with an increase of θ. This is because the network can be alive up to the time when θ fraction of nodes are drained of their energy.

Figure 8 provides the comparison of coverage ratio verses the fraction of sleeping nodes r. The coverage here is defined as the ratio of the union of all sensor nodes’ sensing areas to the whole monitored environment. For the detailed explanation of coverage ratio calculation method, please refer to [22]. Figure 8 shows that for the three schemes (AHP, LDS [7] and random) the coverage ratio decreases with the

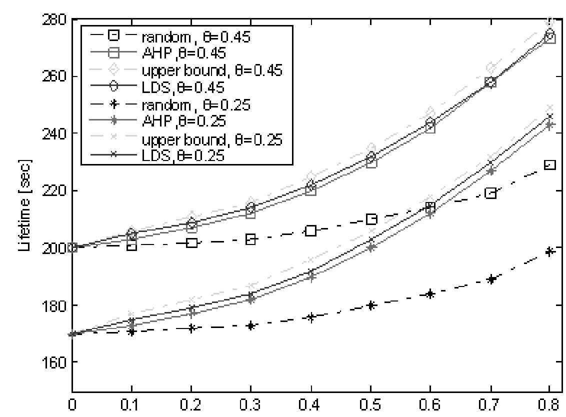


Fig. 7 Lifetime comparision.

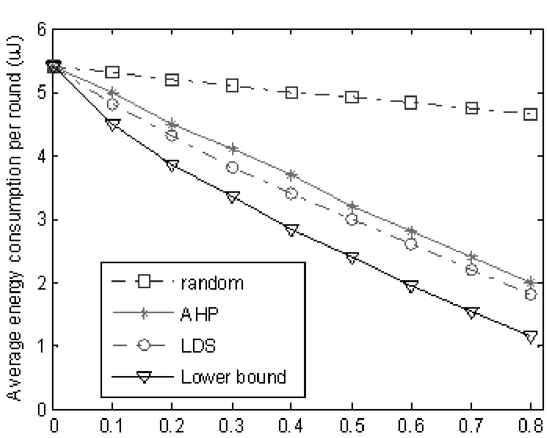


Fig. 6 Energy consumption in the cluster per round.

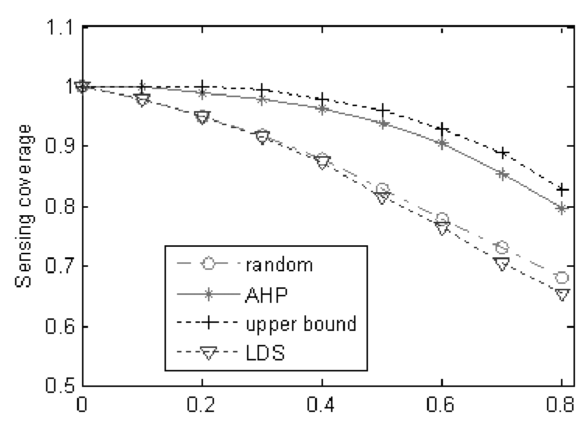


Fig. 8 Coverage verses the fraction of sleeping nodes.

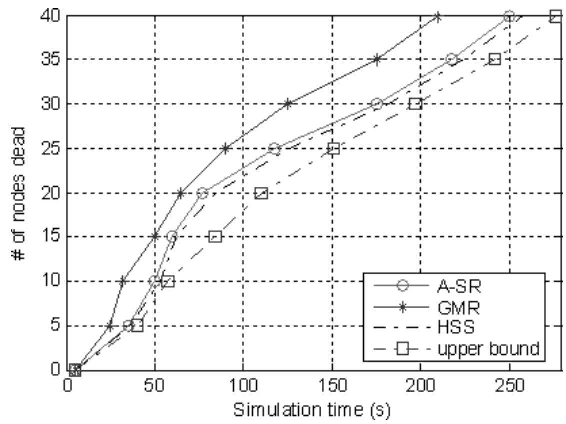


Fig. 9 Lifetime comparison.

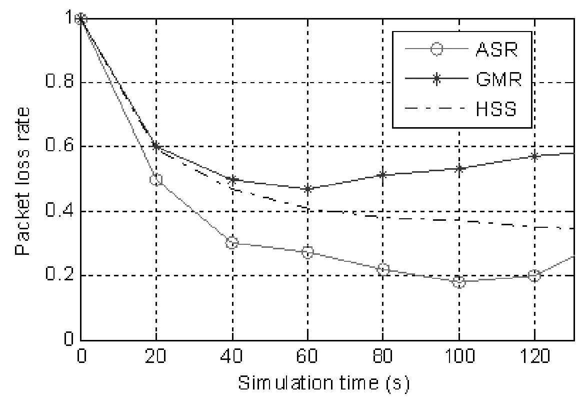


Fig. 10 Simulation time vs. packet loss rate.

increasing of the fraction of sleeping nodes, r. LDS shows similar sensing coverage ratio with random scheme (though different pattern) since the sensing coverage of the LDS scheme in the border area is lower than that in the central area, as sensor nodes close to the border are put into sleep with higher probability. However, in case of the proposed AHP based sleeping scheme, the coverage ratio still can maintain above the desired value of 0.98 when up to 30% nodes are put into sleep. It indicates that the tradeoff in terms of coverage is not very critical using the AHP based scheme. AHP based scheme outperforms the LDS and is close to the upper bound in that the AHP takes overlapping coverage as one of the impact factors while the LDS does not but only energy saving.

To evaluate the integrated sleep scheduling and routing in multi hop networks by AHP, we have used J-Sim [23] as the simulation environment. 60 sensors are randomly deployed in an area of $100\,\text{m} \times 100\,\text{m}$. The source and destination sensors are set as 2 J initially, and 5 couples of source and destination nodes are communicating at the same time in this network. All the other sensors have initial energy of 0–2 J. The buffer capacity of each sensor node has been taken as 5 packets with packet length 512 bit and bit rate 9.6 kbit/s. The time interval T is set as 10 s in our simulation. The source node select M=3 nodes in its communication range for the first hop relay. From the second hop, each node along the three paths selects only one node toward its next hop.

We compare our A-SR with Hop-based Sleeping Scheduling (HSS) algorithm [8], upper bound and the geographical multipath routing (GMR) [19] scheme where only distance to the destination is considered. In Fig. 9, we plot the simulation time versus the number of nodes dead. It shows that when 50% nodes (30 nodes) die out, the network lifetime for A-SR has been extended more than 40%. A-SR significantly outperforms GMR and has similar performance to HSS. In Fig. 10, we compare the packet loss rate of these three schemes. Packets are dropped either due to insufficient buffer capacity at the receiver or because of the lack of energy needed to transmit the packet. Observe that our A-SR outperforms the GMR and HSS with about 20% and 10% less packet loss respectively resulting in greater reliability. The average latency during transmission (end-to-end) is 424.23 ms for our A-SR, 407.5 ms for GMR and 422.8 ms for HSS, and link failure rate for A-SR is 6.51%, but for GMR is 10.42% and for HSS is 10%. Due to the integrated sleep scheduling, in our proposed scheme, the network coverage ratio does not drop below the satisfactory value 0.97 when up to around 30% nodes are put into sleep.

6. Conclusions and Future Work

In this paper, we proposed a sleeping scheduling scheme in a single hop network and an integrated sleep scheduling and routing protocol in a multi hop network based on AHP. In the single hop network, three factors contributing to the optimal nodes scheduling decision are considered and they are 1) distance to CH, 2) residual energy, and 3) sensing coverage overlapping, respectively. In the multi hop network, our proposed A-SR scheme includes distance to destination, residual energy, and sensing coverage overlapping for sleep scheduling, and distance to the destination, residual energy, and queue size of each sensor node for routing. To evaluate the performance, in the single hop network case, we evaluated the efficiency of our proposed scheme in terms of energy consumption, lifetime and coverage ratio, and compared with the upper (lower) bound, LDS and traditional random sleep scheduling scheme in heterogeneous clustered sensor networks. The proposed scheme was observed to improve network lifetime and conserve energy. We also evaluated the efficiency of the proposed scheme in the multi-hop environment and the results showed that it could extend the network lifetime much longer than the original geographical routing scheme which only considered distance to the destination location, and it had similar lifetime performance with HSS. Moreover, the proposed scheme could reduce the packet loss rate and link failure rate since the buffer capacity was considered. In both single hop and multi hop network environment, the sensing coverage capabilities were not compromised.

In the future work, we may consider the node mobility as another factor for decision making and design such protocol. Moreover, different node distributions will be further considered.

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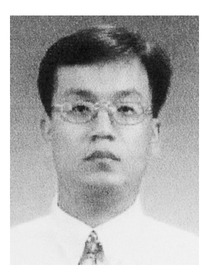

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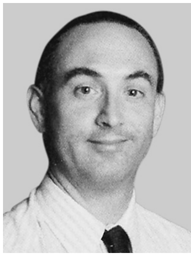

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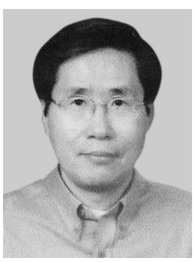

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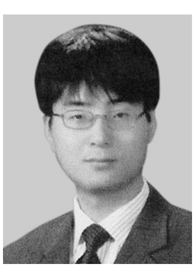

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