IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

SPECIAL SECTION ON CONVERGENCE OF SENSOR NETWORKS, CLOUD COMPUTING, AND BIG DATA IN INDUSTRIAL INTERNET OF THING

Received January 21, 2018, accepted February 16, 2018, date of publication February 27, 2018, date of current version April 18, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2809663

An Energy-Efficient Ring Cross-Layer Optimization Algorithm for Wireless Sensor Networks

WENBO ZHANG[1], XUANREN WEI[1], GUANGJIE HAN[2,3], (Member, IEEE), AND XIAOBO TAN[1]
[1]School of Information Science and Engineering, Shenyang Ligong University, Shenyang 110159, China
[2]Key Laboratory for Ubiquitous Network and Service Software of Liaoning province, School of Software, Dalian University of Technology, Dalian 116024, China
[3]State Key Laboratory of Acoustics, Institute of Acoustics, Chinese Academy of Sciences, Beijing 100190, China

Corresponding author: Guangjie Han (hanguangjie@gmail.com)

This work was supported in part by the Liaoning Fourth Batch of Distinguished Professor Project in 2014, in part by the Liaoning BaiQianWan Talents Program in 2016, in part by the Liaoning Natural Science Foundation under Grant 20170540793, in part by the Open fund of State Key Laboratory of Acoustics under Grant SKLA201706, in part by the Fundamental Research Funds for the Central Universities, under Grant DUT17RC(3)094, and in part by the general project of Liaoning province under Grant 2015465.

ABSTRACT In wireless sensor networks, cross-layer optimization is a hot topic. In order to balance energy consumption a clustering based cross-layer optimization model is established in this paper. In this model, the network layer could get the related information from physical layer and the datalink layer to effectively route packets. Based on the cross-layer optimization model, an energy-efficient ring cross-layer optimization algorithm is proposed and a new routing algorithm called Leach-Cross-Layer Optimization (CLO) is also proposed for a ring monitoring domain. This Leach-CLO routing algorithm is based on the typical Leach algorithm. The experiment results show that this routing algorithm could effectively and efficiently balance the energy consumption in wireless sensor networks compared with related algorithms.

INDEX TERMS Wireless sensor networks, cross-layer optimization, CLO routing algorithm.

I. INTRODUCTION

Recent advances in micro-electro-mechanical systems [1], [2] and wireless communications have provided the ability of designing and manufacturing sensor nodes [3], [4]. Sensor nodes can receive information from the environment or other sensor nodes and send the gathered information to the sink [5]. Wireless sensor networks consist of many sensor nodes which monitor the environment by interacting and cooperating with each other. These networks have the advantages such as scalability, reliability, flexibility as well as low cost and easy placement compared with the conventional networks. These advantages led to the wide use of wireless sensor networks in various applications ranging from environmental and military monitoring to commercial and health applications [6]. Nevertheless, the fundamental constraint in wireless sensor networks is the limited energy budget of embedded devices (wireless sensor nodes) they are composed of. Thus, it is required to implement energy management methods, especially in order to lessen the consumption of wireless communications and to prolong system lifetime without jeopardizing the performance [7].

Quality of Service (QoS) requirements of communications and energy constraints of battery-powered sensor nodes, necessitate the design of reliable and energy-efficient communication protocols for wireless sensor networks. In typical wireless sensor networks model, the information of energy consumption is only exchanged between sensor nodes. It is difficult to share the energy consumption information between the different protocol layers in one sensor even if it is more efficient and effective for energy saving that the information is shared for each layer [8]. Cross-layer approaches have been proven to provide better optimization results than their layered counterparts. Indeed, layer cooperation in cross-layer based schemes well enhances the overall wireless sensor networks performance [9]. For instance, in a cross-layer scheme, the QoS requirements at the application layer can be communicated with the MAC layer in order to achieve better resource allocation for the running monitoring application. Furthermore, the channel state information and battery level can be fed to the network layer to avoid paths including channels in a bad state or depleted nodes [10]. So far, there have been a certain amount of studies on cross-layer algorithm related to wireless sensor networks (WSNs) [11].

However, in typical Leach algorithm, the information in each layer is difficult to share so communication overhead is increased continuously in order to balance energy consumption in whole network. The main idea of this paper is to promote the typical Leach algorithm with a cross-layer optimization model. So we designed a clustering routing algorithm based on cross-layer optimization model. The high-performance links can be selected to forward packets to reduce BER and retransmissions, furthermore, transmitting power can be effectively controlled according to routing information to reduce energy consumption for transmitting packets. Based on this model we proposed a new routing algorithm called Leach-CLO.

The remainder of this paper is organized as the follows: Section II elaborates on related works and our contributions; Section III proposed an improved cross-layer optimization model. Section IV we establish an energy efficient routing algorithm based on cross-layer optimization model. Section V presents the results of our experiments, and Section VI offers a conclusion.

II. RELATED WORK

In wireless sensor networks, sensor nodes are limited by their energy efficiency, lifetime and so on. Because of that, many cross-layer protocols have been proposed to optimize the energy consumption for wireless sensor networks.

Gajjar *et al.* proposed fuzzy and ant colony optimization based mac/routing cross-layer protocol (FAMACRO) [12] for wireless sensor networks with idea that combined energy-efficient hierarchical cluster routing and media access. The operation of FAMACRO included both network setting and steady-state phase. During network setting, nodes in the network were organized into 'layers'. Afterwards, each node broadcast a message using non-persistent CSMA MAC protocol [13] and stored information received in its neighborhood table. In steady-state phase, nodes independently decided to become cluster heads which possessed high residual energy, a mass of neighboring nodes and high quality of communication link using Fuzzy Inference System (FIS) with Mamdani model [14]. Then, cluster heads advertised their role using non-persistent CSMA MAC protocol to send messages within their advertising radius to implement clustering. Finally, using ant colony optimization (ACO) accomplished inter-cluster routing. However, in the proposed optimization algorithm, mac/routing cross-layer protocol is the main research objective and the physical layer is not considered.

A Cross-Layer Energy-Efficient Protocol (CLEEP) for wireless sensor networks is proposed in [15] to improve the energy efficiency. But there were some defects in this protocol such as minimized energy consumption. Based on CLEEP, Fouzi *et al.* proposed an Energy Efficient Cross-layer Protocol (EECP) in [16] for wireless sensor networks to interact between the physical layer, MAC layer and network layer. In EECP, by creating and maintaining neighboring tables, the qualified nodes could be awakened to send the data. Furthermore, a wake-up mechanism is used in MAC layer to prevent the overhearing.

Singh *et al.* came up with an energy efficient cross-layer based adaptive threshold routing protocol for WSN in [17]. In this paper, introducing the steps performed to execute the presented protocol algorithm, they are respectively initialization, deployment, CH selection, cluster creation, and sending aggregated data to the base station.

For optimizing the energy consumption and node placements of WSN, Xenakis *et al.* [18] introduced a cross-layer energy-aware topology control using Simulated Annealing (SA). Firstly, the cross-layer energy aware analysis of ARQ, FEC and HARQ were provided. Then, the energy-aware optimization problem including power control, packet size and sensor placements, was formulated and solved by using the SA algorithm.

In order to save energy, Mahmoud Sami *et al.* [19] presented a cross-layer cooperative MAC protocol. Firstly, this protocol used physical layer network coding (PNC) which could reduce transmission time slots and obtained higher throughput and power-efficiency than conventional network coding. Then, because extending the channel reservation in time and space was the key to coordinate relay transmission, new control frames, RTS, CTS, ATH and DATA were proposed. Subsequently, the protocol employed relay selection and power allocation algorithm to obtain effective transmission and network lifetime enhancement.

Sarvi *et al.* presented a new adaptive cross-layer (NAC) error control protocol to gain reliable and energy efficient multimedia communication over WSN in [20]. Before that, an adaptive cross-layer erasure coding scheme had been introduced to be employed in the application layer and dynamic hybrid FEC/ARQ scheme which dynamically determines redundancy in the wireless link layer. Subsequently, a new cross layer adaptive (NAC) error control protocol was proposed with delay-constrained retransmission and unequal error protection (UEP) strategy. It could adaptively optimize distortion and energy parameters.

Different layers with the same timescale could accomplish cross-layer cooperation. However, there was a difference in layers' timescales. Thus, Quoc-Viet Pham *et al.*designed a multi-timescale rate-effective network utility maximization (MTSRENUM) distributed algorithm with multi-timescale cross-layer [21] to minimize the total link delay and power consumption.

Wang *et al.* proposed a cross-layer mobility support scheme [22] to realize the interaction between the link layer and the network layer in new-type wireless sensor network, the IPv6 over low-power wireless personal area network (6LoWPAN) wireless sensor network (WSN). The 6LoWPAN was composed of low-power nodes with limited resources and had mobility. In this protocol, the scheme could combine the handover in the network layer with the handover in the link layer so that the two could be executed synchronously.

Wireless Sensor Networks had been researched for various applications, especially for tracking, monitoring and assisting rescue operations such as earthquake and fire. However, because of the limited capacity of sensor nodes, image transmission became very difficult. Therefore, Singh and Verma

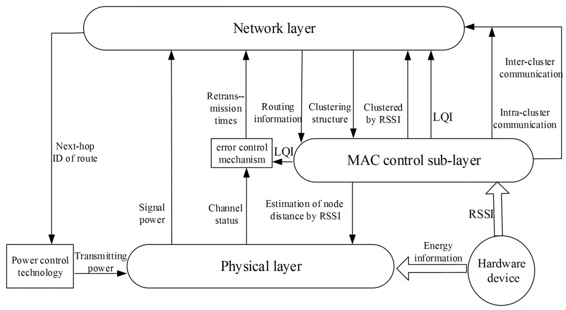


FIGURE 1. Cross-layer optimization model.

proposed an image transfer protocol [23] based on cross-layer interaction between the application, transport, network and MAC layers to help to achieve efficient reliable transfer of images across the network. Niroumand et al. came up with a new geographic cross-layer routing method in WSN [24] to facilitate relief operations in disasters. The geographic cross-layer routing adapted with disaster relief operations (GCRAD) could resolve the problem of the undesirable priority and potential relay node to improve the energy efficiency and reduce the end-to-end delay [25], [26]. The main contributions of this paper are as follows:

- Using the idea of cross-layer optimization of joint design, combining the design of physical layer, link layer and network layer to construct the cross-layer optimization model of wireless sensor network, and the optimization model of each layer is given.
- The ring isomorphism monitoring area is constructed,and the optimal cluster nodes forwarding mechanism is put forward by using the optimized hierarchical strategy,and the research results show that the multiple-hop cluster communication mechanism can save energy more than the single-hop communication under certain conditions.
- The LEACH-CLO routing algorithm is proposed,which is based on how much of the remaining energy is used to control the priority of the node campaign cluster head, to avoid a large number of cluster heads too concentrated, according to the size of the detection range, the number of nodes and the size of the node communication radius to calculate the number of optimal cluster heads, so that the selection of cluster head and the establishment of cluster is more reasonable.

III. CROSS-LAYER OPTIMIZATION ALGORITHM

Physical layer, link layer and network layer play an important role for energy-saving optimization in wireless sensor network, so a cross-layer optimization model in which those three layer are considered as a whole based on a variety of cross-layer protocols is presented as shown in Fig.1.

Here, the specific optimization mechanism of the model is as follows:

- The network layer can design the gradient of the monitoring range through the topological information provided by the physical layer, calculate the distance between each gradient, and divide the nodes into ranks in the monitoring range.
- The network layer selects the nodes with higher residual energy and good distribution position as the cluster head nodes according to the residual energy information and the node density information provided by the physical layer.
- The network layer makes the nodes reasonably clustered according to the signal intensity between the nodes provided by the link layer.
- The link layer can reasonably use the link layer protocol according to the node clustering structure information of the network layer. The inter-cluster communication of the nodes uses the link layer protocol based on competition to improve the channel efficiency. The intra-cluster communication of the nodes uses the link layer protocol based on scheduling to reduce competition within the cluster.
- In routing selection, the network layer uses the residual energy information provided by the physical layer and the link quality information provided by the link layer to make the routing choice and select the best path.
- During routing, if the member node is used as the relay node, when the link layer is allocated the time-slot by the cluster head node, it needs to allocate more time-slots to the member node to reduce the delay of the routing.
- The routing information can only be forwarded when the sensor node obtains the time-slot or acquired the right to use the channel through competition.
- Before forwarding data, the network layer will inform the physical layer of the next hop node's ID through routing, the physical layer calculates the optimal transmission power through the power-control technology and transmits the data using the minimum transmission power on the basis of ensuring the connectivity of the entire network.
- The link layer uses the error-control technology, which refers to the channel state and link quality to ensure the correctness of transmission.

A. PHYSICAL LAYER OPTIMIZATION

MAC layer is mainly responsible for the accurate reception of data, the system can achieve a higher gain in throughput and power saving by using physical layer information to adjust the MAC layer's control mechanism, the network layer uses the information such as channel state information (CSI), residual energy, geographical location, etc., and the transmission power of the physical layer as the basis for its routing, the network layer can transmit different rates and different priorities of data on different channels, according to the channel status information using the routing function to select the best path.

Energy consumption in wireless sensor networks mainly involves sending and receiving channel listener data. A schematic of the data communication process is shown in Fig.1.

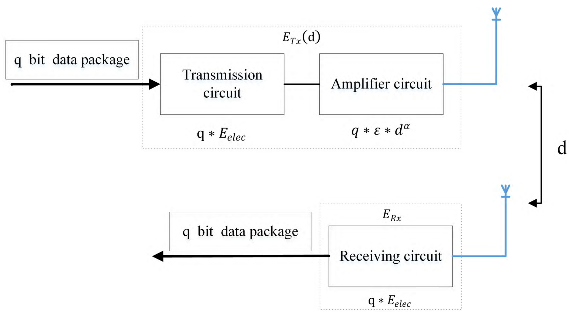


FIGURE 2. Physical layer communication mode.

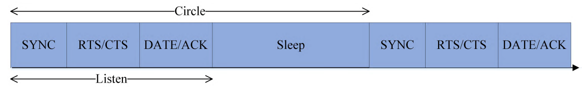


FIGURE 3. S-MAC work and sleep cycle.

We assume that the sending node is u, the receiving node is v, the distance between them is $d(u, v)$, and the q bit node sending energy consumption is as follows:

$$E_{Tx}(u, v) = qE_{elec} + q\varepsilon d(u, v)^{\alpha} = \begin{cases} qE_{elec} + q\varepsilon_{fs} d(u, v)^2 & d(u, v) < d_0 \\ qE_{elec} + q\varepsilon_{mp} d(u, v)^4 & d(u, v) \geq d_0 \end{cases} \tag{1}$$

$$d_0 = \sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}} \tag{2}$$

Where E_{elec} is the consumed energy for circuit transmission unit data, and the threshold value d_0 is a constant. ε is also a constant, and when $d(u, v) < d_0$, ε is ε_{fs}, power amplifiers use the free-space transmission mode; when $d(u, v) \geq d_0$, ε is ε_{mp}, power amplifiers use the using multi-path fading channel transfer mode, as shown in Fig.2. α is the path loss exponent in outdoor radio propagation models, where usually $\alpha \geq 2$(in this study, α is either 2 or 4).

The communication distance between two nodes in the communication range of the threshold d_0 is proportional to the communication energy loss and communication distance squared. Communication distance that is greater than the threshold d_0 is proportional to communication energy loss and the quartic square of communication distance. Thus, communication distance directly affects the loss of communication energy. During practical application, communication distance is generally less than d_0; thus, we assume that $d(u, v) < d_0$.

N sensor nodes are randomly deployed in the $L \times L$ square area, the sensor nodes periodically collect data and send it to the base station. It is assumed that the network has the following properties:

(1) After the deployment is completed, all nodes can not move and each node has a identifier (ID), the location of the base station is fixed and the energy consumption of it is not considered.

(2) All nodes are isomorphic, i.e. the nodes are identical, equal status and without GPS sensors.

(3) Each node has data fusion function. Hardware can sense the RSSI and its own residual energy. Sensor nodes can estimate the distance between the nodes through the signal strength and adjust the transmission power.

(4) The link is symmetric.

B. MAC LAYER OPTIMIZATION

The characteristic of the physical layer can also be improved by the power adjustment information and transmission control from the MAC layer. The error control mechanism of the MAC layer is adjusted according to the state of the current radio channel and the number of the physical layer to reduce the transmission error, and the collision of the data frame is reduced by adjusting the length of the data frame to improve the throughput. The MAC layer can be used as the state of the radio channel reflected by the intermediary. The MAC layer estimates the distance between nodes through RSSI and the network layer is divided by the distance information, LQI, PRR and other link quality information can also be used as bases for the network layer routing. When the condition of channel is poor, the retransmission mechanism of the MAC layer will introduce a long transmission delay which will cause connection timeout for the transport layer, thus starting the retransmission mechanism and reducing the transmission power.

As the member nodes also forward data in the inter-cluster routing, they need to periodically turn on the transceiver to listen to whether there are forwarding data from other nodes. The member nodes use periodic listening method to reduce idle listening time and energy consumption. It is necessary to consider whether the member node becomes a relay node for routing when the cluster head node allocates timeslots to the member nodes. The member node uses an accumulator to record the number of times that it becomes the relay node. The cluster head node will allocate more timeslots to the member node according to the number of accumulator of the relay node, so that the member node as the relay node has more opportunity to communicate with the cluster head node. In this way, we can reduce the delay between the inter-cluster communications and ensure real-time data. In the cluster communication, the base station allocates frames to the cluster head nodes, so that it can better avoid collision and interference to ensure the correctness and integrity of the data when the coverage area of the cluster has cross-channel message.

Inter-cluster communication phase: the cluster head consumes a large amount of energy, and it will cause the whole network topology to change when the energy of node is exhausted or damaged. So the link layer protocol based on the competitive S-MAC protocol, it can adapt to these changes better. In addition, the distance between cluster head nodes is relatively far, the competition of wireless resources is relatively small, and the S-MAC protocol can improve the utilization rate of the channel. The S-MAC protocol working model is shown in Fig.3.

Idle listening is the main aspect of network energy consumption. In order to reduce the power consumption of idle listening in S-MAC protocol, periodic listening/hibernation mechanism is adopted. Each node independently dispatches its own state and enters the dormant state periodically. Each node monitors the channel to determine whether there is a request from other nodes after sleeping for a period of time. In order to ensure that the node can receive data packets and synchronization messages, the node divides the listening state into two parts–the node sends and receives synchronization messages and the node data transmission and reception. Each node maintains a schedule information table and the node uses SYNC message to announce its own scheduling information to maintain the synchronization between each node. According to the SYNC message, the Received Signal Strength Indication (RSSI) between the nodes and the neighbor nodes is obtained. The neighbor node can calculate the optimal transmit power by receiving power, transmitting power, transmitter and receiver distance. Then the neighbor node returns to the node through the ACK frame (includes the optimal transmit power and the inter-node distance), and the node stores d_i and the optimal transmit power P_m in the scheduling table. When the node is found around the node there is control information to send and not sent to itself, the node will randomly generate a NAV value, enter the sleep state.

According to the Friis formula of the wave propagation in the free space, the received power can be obtained.

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \tag{3}$$

P_t is the antenna transmit power of transmit end; G_t and G_r is the transmit and receive antenna gains; λ is the wavelength; d is the distance between the transmitter and the receiver which can be estimated by the RSSI value; L is the system loss factor, $L \geq 1$.

The node determines whether a signal is transmitted in the channel by listening to the Received Signal Strength Indication (RSSI) in the channel. It indicates that there is signal transmission in the channel and the receiving node can receive the data correctly in the channel when the intercepted energy intensity is higher than the node reception threshold R_t. There gives the minimum transmit power required for the sending node

$$P_m = \frac{(4\pi)^2 d^2 L R_t}{G_t G_r \lambda^2} \tag{4}$$

R_t is the receive threshold of the receiving node; P_m is the minimum transmit power required for the sending node; Through the equeation (3), (4),

$$P_{m-free} = \frac{P_t R_t}{P_r} \tag{5}$$

Thus, the minimum transmission power value P_m required for the sending node can be calculated from the known data P_t, R_t and P_r. Considering the attenuation characteristics of channel, P_{m-free} is usually multiplied by an adjustment parameter $c(c > 1)$, so that the signal can be reliably transmitted in the channel.

C. NETWORK LAYER OPTIMIZATION

The physical layer can calculate the optimal transmit power of neighbor nodes according to the neighbor table information in the network layer, can calculate the optimal transmit power for a certain node by routing the next information, and can send data with optimal transmit power to reduce energy consumption. Two channel usage modes of MAC can be reasonably used through the design structure of network layer clustering. The inter-cluster communication can improve the channel utilization by using competition mode. The intra-cluster communication can use slot allocation mode to use channels and reduce the channel SNR and BER. A reasonable routing protocol can also improve the service quality of the application layer and the efficiency of the transport layer.

When communicating between clusters,sensor nodes of the whole network are classified, the base station as the center, respectively d_i, $2d_i$, ..., nd_i for the radius of concentric circles, which d_i determines the width of the two gradient. The energy consumption of inner-ring nodes is faster, and it not only needs to support its own data communication, but also to help forward the data of outer-layer nodes. Thus, the area near the base station needs more nodes to help transmit the data. With the increase of wheel number, the energy consumption of inner-ring nodes increases. While expanding the two gradient, outer-layer nodes can become inner-layer nodes to help transmit data.

Hot spot problems are especially severe in hierarchical routing. Inner-layer nodes frequently help transmit data, causing their energy consumption too fast. In order to reduce the energy consumption of inner-layer nodes forwarding, the forwarding frequency of inner-layer nodes can be decreased, and outer-layer nodes share responsibility for the forwarding task.

Where a, b and c are the distance between the nodes, and C is the base station. Assuming that the residual energy of the node A is E_A, the remaining energy of the inner neighbor node B is E_B,the physical communication mode can be satisfied when nodes communicate. The path, (1) $A- > C$, is that this node communicates directly with the base station, and the path, (2) $A- > B- > C$, is that the node communicates with the base station through inner-layer nodes forwarding.

The energy consumption of $A- > C$ is

$$E_{AC} = kE_{elect} + k\xi b^2 \tag{6}$$

After the communication, the residual energy of node A is $E_A - kE_{elect} - k\xi b^2$, the residual energy of node B is E_B, the average residual energy of A and B is $\frac{E_A+E_B-kE_{elect}-k\xi b^2}{2}$, the variance is $(\frac{E_B-E_A+kE_{elect}+k\xi b^2}{2})^2$.

The energy consumption of $A- > B$ is

$$E_{AB} = kE_{elect} + k\xi c^2 \tag{7}$$

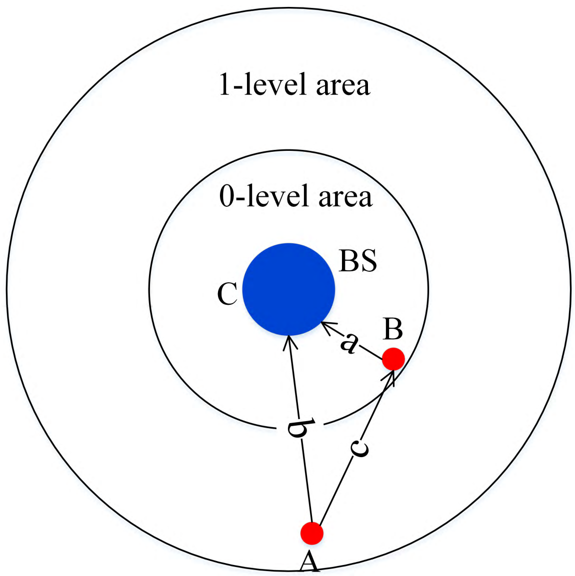


FIGURE 4. Inner layer nodes forwarding model.

The energy consumption of $B->C$ is

$$E_{BC} = kE_{elect} + k\xi a^2 \tag{8}$$

After the communication, the residual energy of node A is $E_A - kE_{elect} - k\xi c^2$, the residual energy of node B is $E_B - kE_{elect} - k\xi a^2$, the average residual energy of A and B is $\frac{E_A+E_B-2kE_{elect}-k\xi a^2-k\xi c^2}{2}$, the variance is $(\frac{E_B-E_A+k\xi(a^2-c^2)}{2})^2$.

In order to ensure that after the communication, the energy of inner neighbor nodes and the node is more balanced, it is necessary to ensure that the energy difference between the node and the forwarding node is small after the communication, that is the variance is as small as possible. This means that the energy consumption is more balanced when communicating through this mode.

(1)path variance-(2)path variance is

$$\left(\frac{E_B-E_A-kE_{elect}+k\xi b^2}{2}\right)^2-\left(\frac{E_B-E_A+k\xi(a^2-c^2)}{2}\right)^2 = \frac{(kE_{elect}+k\xi(b^2+a^2-c^2))(2E_B-2E_A+k\xi(b^2+c^2-a^2))}{4} \tag{9}$$

Because of the multi-hop routing mechanism between clusters, $kE_{elect} + k\xi(b^2 + a^2 - c^2) > 0$ is known. Therefore, When $2E_B - 2E_A + k\xi(b^2 + c^2 - a^2) > 0$, the residual energy of the node and the inner neighbor node is more balanced after path(2) communication, that is necessary to use the inner neighbor node to forward the data. Simplifying $2E_B - 2E_A + k\xi(b^2 + c^2 - a^2) > 0$ is $E_A - E_B < k\xi(b^2 + c^2 - a^2)/2$. In conclusion, if satisfying $E_A - E_B < k\xi(b^2 + c^2 - a^2)/2$ or $E_A < E_B$, the data is transmitted by the inner neighbor nodes, otherwise, the node directly communicates with the base station as shown in Fig.4.

IV. CLUSTERING ROUTING ALGORITHM BASED ON CROSS-LAYER OPTIMIZATION MODEL

In this section based on the design of each layer of the cross-layer optimization model, we propose a Leach-CLO (Leach Cross-Layer Optimization) algorithm. Leach-CLO works in rounds; there are six stages in the main work of each round: the stage of network initialization, the stage of choosing cluster head, the stage of clustering, the stage of inter-cluster communication, the stage of intra-cluster communication, the stage of power control. Specific steps are as follows.

(1) Network initialization

The BS (base station) broadcasts a message to the whole network nodes. Each node calculates the $dBS(i)$ (distance) to the BS according to this information, and stores the $dBS(i)$ and the $E_{residual}(i)$ (residual energy) of the node in the scheduling information table of each node.

(2) Cluster heads election

Definition 1 (Node Waiting Time (T_m)): The node enters the sleep wait time before the campaign cluster head.

$$T_m = t_m \times \frac{E_{initid}}{E_{residual}} \tag{10}$$

Definition 2 (Node Density): Assumed that the communication radius of node k is D, the total number of its neighbors is j, the distance between node k and any node i in neighbors is d_i, then the node density is

$$\rho = \sum_{i=1}^{j} D/d_i \tag{11}$$

In order to extend the entire network lifetime, so that the node's energy consumption balance is necessary, the node with high residual energy becomes the high probability of cluster head. The improved $T(n)$ equation for the LEACH protocol is

$$T(n)=\frac{p}{1-p[r mod(\frac{1}{p})]}\times(z_1\times\frac{E_{residual}(n)}{E_{initid}}+z_2\times(1-\frac{1}{p})) \tag{12}$$

$E_{residual}(n)$ is the residual energy of the node, E_{initid} is the initial energy of the node, $0 < z_1 < 1$, $0 < z_2 < 1$ and $z_1 + z_2 = 1$.

The smaller the value of d_i (the distance between nodes) leads to the higher the value of ρ (node density).

In Equation (11), the smaller the ρ value results in a greater d value. By equation (12), the greater the ρ value leads to the higher $T(n)$ value, indicating that the higher the density of nodes have a higher probability of becoming a cluster head. The larger the value of $E_{residual}$ is, the more surplus energy. When E_{initid} initializes energy, constant value is unchanged. The larger the value of $T(n)$ is, the greater the probability of the cluster head is elected, effectively extending the entire network lifetime.

(3) Clustering

Cluster head node sending the cluster broadcast, member nodes receiving the cluster information, join the cluster head node to complete the establishment of the cluster.

(4) Intra-cluster communication

The members of the cluster need to send the monitored data and the data forwarded by the agent to the cluster head node, and then the data collected by the cluster head node will be data fusion processing, remove the redundant data.

(5) Inter-cluster communication

Since the distance between cluster head nodes and the base station is far away, if the data is sent directly to the base station, the transmission power is so large that will consume a lot of energy, so the inter-cluster is routed through multi-hop routing. Specifically in three steps:

The First step: the base station as the center, respectively d_1, d_2, ...,d_i,..., for the radius of concentric circles, which i determines the width of the two gradient. The equation is as follows,

$$d_i = R/\sqrt{2N \times p} + r_i \times (R/d_{i-1})/m \tag{13}$$

Where R represents the radius of the detection area, N represents the number of nodes, p represents the probability of the cluster head node, r is the current number of wheels, and m is the control parameter. The direction of the routing is from the outer region to the inner region, and the monitoring area is divided into n order regions. The region within d_i is called the 0-level region, $2d_i - d_i$ area is called the 1-level region, $(n+1)d - nd_i$ region called n_i-level region, in which the cluster head called n_i-level cluster head. N is an integer greater than 0 and its value is related to the size of the monitoring range, and the level of each cluster head exists in the scheduling information table. The inter-cluster routing model is shown in Fig.5.

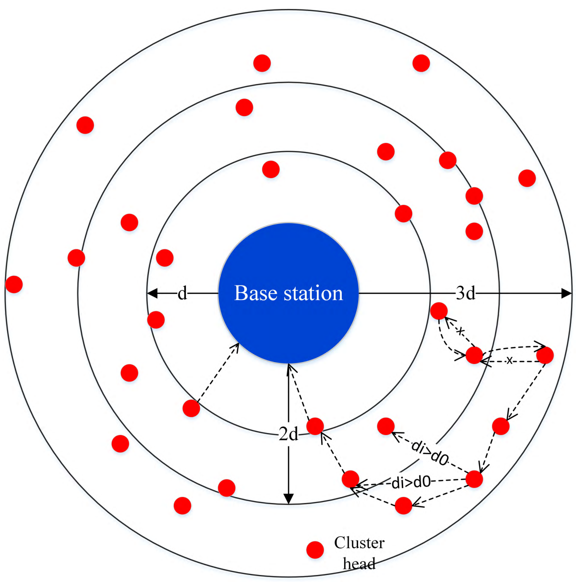


FIGURE 5. Inter-cluster routing model.

The second step: When routing selection, the model according to the priority from high to low order to select the next hop node to better adapt to the deployment of various sensor nodes. The level is divided into four priority levels. When the n_i-level cluster head node needs to forward data, it finds the next hop node from the neighbor node, in which the cluster head node of the upper level area is the first priority, the member node of the upper level area is the second priority. The cluster head node of the same level region is the third priority, and the member node of the same level region is the fourth priority. As shown in Fig.6.

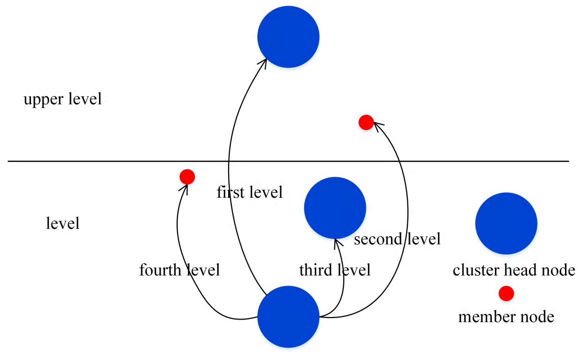


FIGURE 6. Selecting the priority model.

Since the distance between nodes is $d_i > d_0$, the transmit power of the node is greatly increased. Therefore, the node with the distance $d_i < d_0$ between nodes is preferred as the next hop route.

The cluster head node with better link quality should be selected to reduce the data collision and signal interference, and reduce the probability of data retransmission. At the same time, the nodes with higher residual energy are selected as the next hop of the routing to better consume the energy of the balanced network, so the link factor ($E_{efficiency}$) is used as the target of the next hop. $E_{efficiency}$ satisfies the following equation.

$$E_{efficiency} = z \times \frac{LQI}{255} + (1-z) \times \frac{E_{redidual}}{E_{initid}} \tag{14}$$

Where z represents a positive number less than 1.

The third step: When looking for a routing path, a node on the stack storage path is pushed into the stack, as follows.

1) If the node cannot communicate directly with the base station into step (2), if it can communicate with the base station, go to step 5).

2) The node needs to communicate with the base station in a multi-hop forwarding manner. The node looks for the next hop node in the neighbor nodes from the highest priority to the low priority order, and does not look for the nodes in the current stack and the nodes that have been pushed out, thus avoiding the loopback selection. If the next hop nodes are found to enter the step 3), if the nodes cannot be found to enter the step 4).

3) If the node satisfying the condition is found, the node with the largest link factor is the next hop node. If the next hop node is the cluster head node, the node will be pushed into the stack to back to step 1); If the next hop node is the member node of the others cluster, the node is pushed into the stack, the member node is incremented by 1 as the accumulator of the relay node, and the cluster head node is also pushed into

the stack, back to step 1). If the next hop node is found as a member node of this cluster, the node will be pushed to the stack, and the accumulator value will be incremented by 1, return to step 1).

4) If the nodes cannot be found, the node will be pushed out stack to determine whether the current stack is empty. If the stack is not empty back to step 1). If the stack is empty, it is considered that the cluster is an isolated cluster. In this case, it is necessary to use the path closest to the base station to communicate with the base station through power amplification technology.

5) If the node can communicate directly with the base station, then it is judged whether it is a 0-level node. If the node is a 0-level node, it communicates directly with the base station. If the node is not a 0-level node, it is necessary to find the relay node from the inner-node of the neighbor node for data forwarding.

The energy difference between the node and the inner-node of the neighbor is judged whether or not it is balanced. If the energy balance then the inner node forwards the data, the node communicates directly with the base station. Judgment model as shown in Fig.7.

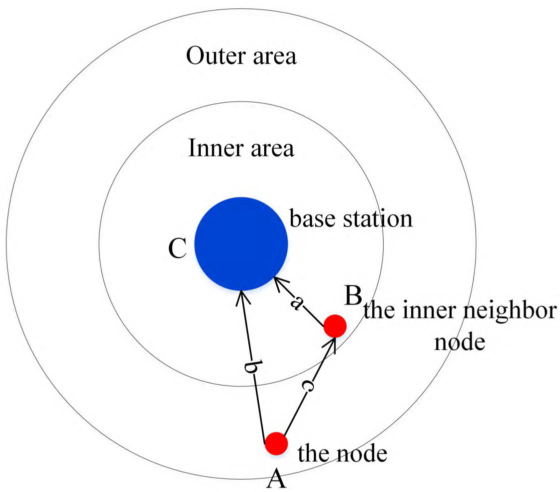


FIGURE 7. Inner layer forwarding model.

In the Figure 7, a, b and c are the distance between nodes, and C is the base station. Assuming that the residual energy of the node A is E_A, the remaining energy of the inner-node of the neighbor B is E_B, the k bit data is transmitted, and ε_{fs} is the communication model parameter. If A or B is satisfied, the data is forwarded through the inter-node of the neighbor, and the neighbor 0-level node is pushed into stack. Otherwise the node communicates directly with the base station.

(6) Power control

After routing, the optimal transmit power is specified by the forwarding distance. The schedule table of nodes is shown in Table 1.

V. SIMULATION AND PERFORMANCE ANALYSIS

In this paper, we compared the Leach-L [27] and Leach-EE [28] routing algorithms with Leach-CLO in order to prove that the Leach-CLO routing algorithm could reduce energy consumption and prolong the lifetime of wireless sensor networks. In the simulation, we set the region size to 250 m * 250 m with 101 nodes (one base station and 100 sensor nodes) distributed randomly throughout. Table 2 lists specific simulation environment parameters.

The relationship between the running rounds and the number of surviving nodes in wireless sensor networks was shown in Fig.8. It was obvious that the first node died after 80 rounds in Leach-L routing algorithm. Furthermore, nodes began to die after 120 rounds in Leach-EE routing algorithm and nodes start to die after 140 rounds in Leach-CLO routing algorithm. This is because that the residual energy and the density of nodes were used parameters to elect cluster heads. This algorithm is more reasonable than the other two routing algorithms. When a node campaigned for the cluster head, it should sleep in some time according to its residual energy. So a node with more residual energy had more opportunities to be elected as a cluster head. In Leach-CLO routing algorithm, not only the cluster head can forward data, but also common nodes can forward too. So common nodes shared the forwarding tasks and reduced the energy consumption of cluster heads. The energy consumption of the whole wireless sensor network is balanced and the lifetime is prolonged.

The average residual energy of nodes in 200 rounds is shown in Fig.9. It can be seen that the average residual energy in Leach-CLO routing algorithm was greater than that in Leach-L or Leach-EE routing algorithm. After 200 rounds, the average residual energy in Leach-CLO was about twice that in Leach-EE routing algorithm. That is because that

TABLE 1. Schedule information.

Attribute Parameter	Attribute
Number of cluster head	15
Simulation time(s)	3600
Ring level	20
Simulator	Cooja
Mote Type	Sky mote
Operating System	Contiki 2.7
Radio medium	UDGRM(Unit Disk Graph Medium):Distance Loss
Mote startup delay (ms)	1000
Transmission range (m)	50

TABLE 2. Simulation parameters.

Parameter	Values
Monitoring	$250m \times 250m$
Number of nodes	100
Location of Sink node	(0,0)
Initial energy E_0	0.02J
E_{elec}	50 $\times 10^{-9} J/bit$
ε_{fs}	10 $\times 10^{-12} J/bit/m^2$
ε_{mp}	$1.3 \times 10^{-15} J/bit/m^4$
d_0	87m
E_{DA}	$5 \times 10^{-9} J/bit$
Packet size	4000bit/s

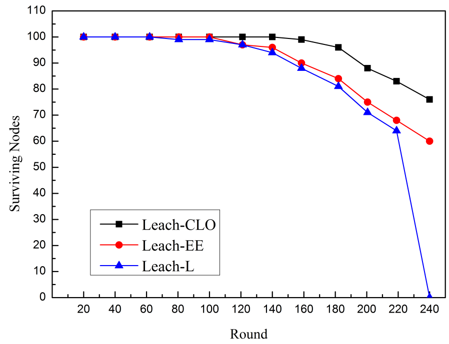


FIGURE 8. Number of surviving nodes.

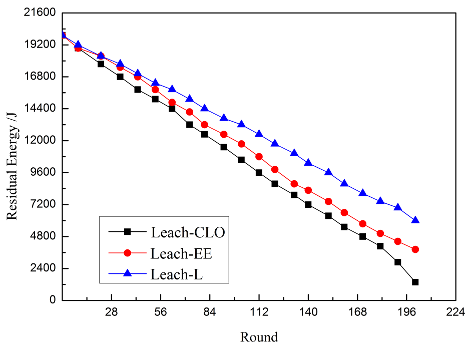


FIGURE 9. Average residual energy of nodes.

the link quality was considered as a control parameter to select the best routing path, so the packet forwarding is more efficient and effective. The number of packet retransmissions was decreased and the energy consumption was reduced.

When the wireless sensor network was running in round 160, a large amount of nodes start to die. So the traffic began to greatly reduce in Leach-EE routing algorithm and Leach-L algorithm. However, because of excellent routing mechanism and connectivity in Leach-CLO algorithm, more packets could be sent from nodes to base station. Based on that, Leach-CLO routing algorithm is more effective than the other two algorithms as shown in Fig.10.

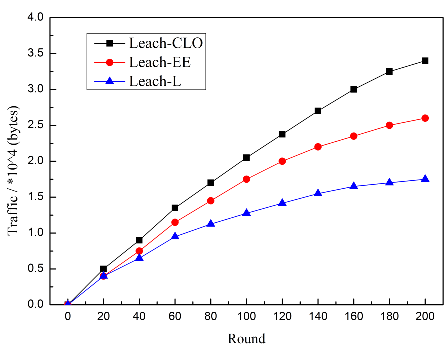


FIGURE 10. Number of packet transmissions.

With the extension of the monitoring range the number of running rounds was decreased. The relationship between the monitoring range and the number of rounds when nodes was found to start dying was shown in Fig.11. When the monitoring range was 150m^2, nodes began to die in the 110th round in Leach-L routing algorithm but nodes start to die later in Leach-EE or Leach-CLO. Furthermore, in the same monitoring range, nodes start to die later in Leach-CLO algorithm than in the other two routing algorithms.

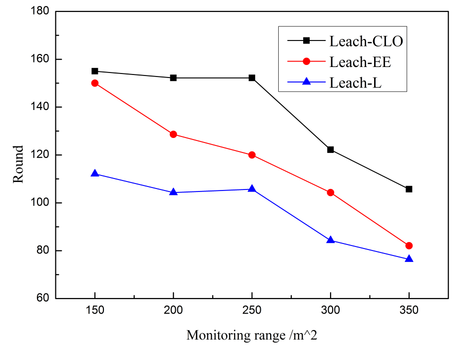


FIGURE 11. Number of rounds when nodes begin to die.

The relationship between the ending rounds and the network lifetime is shown in Fig.12. With the increase of monitoring rage, packet should be transmitted longer distance and more energy is consumed. So the ending round of sensor nodes is decreased and the network lifetime is shorter. Comparing with Leach-L and Leach-EE routing algorithm with Leach-CLO routing algorithm, it is easy to see that wireless sensor networks where Leach-CLO routing algorithm was used had longer lifetime. That is because that in Leach-CLO, not only the cluster head could forward packets, but also the common sensor nodes could forward too. And high quality link could be selected to forward packets, so the energy consumption could be reduced and balanced.

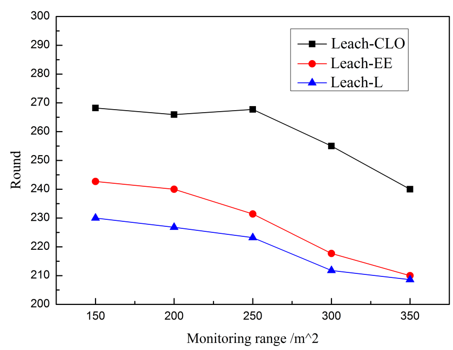


FIGURE 12. Number of ending rounds.

The relationship between the number of nodes and the throughput is shown in Fig.13. With the increase of energy consumption of wireless sensor networks, the number of existing nodes in the whole network is reduced rapidly. So the connectivity of the network was reduced and it was more difficult to forward packets to base station only by cluster heads. However, in Leach-CLO routing algorithm, the common sensor nodes could also forward packets, so this algorithm is

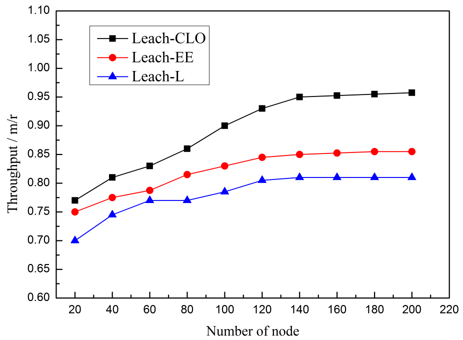


FIGURE 13. Throughput.

more advantageous when the number of nodes is insufficient in wireless sensor networks.

VI. CONCLUSION

The specials of the WSN application environment and the limitations of hardware conditions make the energy problem a major problem that the sensor network faces and needs to be solved, and the protocol stack is optimized to optimize the energy problem to a large extent. The traditional layered optimization plays a certain role in energy problem, but it realizes the local optimization and the difficulty of sharing resources, resulting in the extra communication overhead and information redundancy between peer layers. Therefore, in terms of energy saving, the layers of the physical layer, the link layer and the network layer should be shared. The physical layer provides the underlying support. The link layer combines routing and uses link layer policies to improve resource utilization. The network layer specifies routing to select a more energy-efficient communication path based on the link quality provided by the link layer, thus reducing the energy consumption during communication. The Leach-CLO clustering routing protocol based on the cross-layer optimization model is simulated and verified, and its optimization in energy saving and adaptability is verified to some extent. Cross-layer optimization method considers the energy consumption problem from a global perspective to achieve the information sharing between the layers, so it can better reduce energy consumption and extend the network lifetime.

REFERENCES

[1] Y. Ye, T. Hu, C. Zhang, and W. Luo, "Design and development of a CNC machining process knowledge base using cloud technology," *Int. J. Adv. Manuf. Technol.*, vol. 94, nos. 9–12, pp. 3413–3425, 2016.

[2] Z. Huang, T. Hu, C. Peng, M. Hou, and C. Zhang "Research and development of industrial real-time Ethernet performance testing system used for CNC system," *Int. J. Adv. Manuf. Technol.*, vol. 83, nos. 5–8, pp. 1199–1207, 2016.

[3] W. Zhu, T. Hu, W. Luo, Y. Yang, and C. Zhang, "A STEP-based machining data model for autonomous process generation of intelligent CNC controller," *Int. J. Adv. Manuf. Technol.*, no. 2, pp. 1–15, Jan. 2018, doi: 10.1007/s00170-017-1554-9.

[4] T. Hu, P. Li, R. Liu, and C. Zhang, "Design and application of a real-time industrial Ethernet protocol under Linux using RTAI," *Int. J. Comput. Integr. Manuf.*, vol. 26, no. 5, pp. 429–439, 2013.

[5] H. B. Elhadj, J. Elias, L. Chaari, and L. Kamoun, "A Priority based cross layer routing protocol for healthcare applications," *Ad Hoc Netw.*, vol. 42, no. 5, pp. 1–18, 2016.

[6] G. Han, X. Yang, L. Liu, M. Guizani, and W. Zhang, "A Disaster management-oriented path planning for mobile anchor node-based localization in wireless sensor networks," *IEEE Trans. Emerg. Topics Comput.*, to be published, doi: 10.1109/TETC.2017.2687319.

[7] G. Han, L. Liu, S. Chan, R. Yu, and Y. Yang, "HySense: A hybrid mobile crowdsensing framework for sensing opportunities compensation under dynamic coverage constraint," *IEEE Commun. Mag.*, vol. 55, no. 3, pp. 93–99, Mar. 2017.

[8] A. M. S. Saleh, B. M. Ali, M. F. A. Rasid, and A. Ismail, "A survey on energy awareness mechanisms in routing protocols for wireless sensor networks using optimization methods," *IEEE Trans. Emerg. Telecommun. Technol.*, vol. 25, no. 12, pp. 1184–1207, Dec. 2014.

[9] G. Han, J. Jiang, M. Guizani, and J. J. P. C. Rodrigues, "Green routing protocols for wireless multimedia sensor networks," *IEEE Wireless Commun.*, vol. 23, no. 6, pp. 140–146, Dec. 2016.

[10] S. Ji, T. Hu, S. Sun, and C. Zhang, "A parametric hardware fine acceleration/deceleration algorithm and its implementation," *Int. J. Adv. Manuf. Technol.*, vol. 63, nos. 9–12, pp. 1109–1115, 2012.

[11] M. Khanafer, M. Guennoun, and H. T. Mouftah, "A survey of beacon-enabled IEEE 802.15.4 MAC protocols in wireless sensor networks," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 2, pp. 856–876, 2nd Quart., 2014.

[12] S. Gajjar, M. Sarkar, and K. Dasgupta, "FAMACRO: Fuzzy and ant colony optimization based MAC/routing cross-layer protocol for wireless sensor networks," in *Proc. Int. Conf. Inf. Commun. Technol.*, vol. 46. 2015, pp. 1014–1021.

[13] Y.-W. Kuo and J.-H. Huang, "A CSMA-based MAC protocol for WLANs with automatic synchronization capability to provide hard quality of service guarantees," *Comput. Netw. Int. J. Comput. Telecommun. Netw.*, vol. 46, pp. 1014–1021, 2015.

[14] D. R. Keshwani, D. D. Jones, G. E. Meyer, and R. M. Brand, "Rule-based Mamdani-type fuzzy modeling of skin permeability," *Appl. Soft Comput.*, vol. 8, no. 1, pp. 285–294, 2008.

[15] S. Liu, Y. Bai, M. Sha, Q. Deng, and D. Qian, "CLEEP: A novel cross-layer energy-efficient protocol for wireless sensor networks," in *Proc. Int. Conf. Wireless Commun.*, Oct. 2008, pp. 1–4.

[16] F. Semchedine, W. Oukachbi, N. Zaichi, and L. Bouallouche-Medjkoune, "EECP: A new cross-layer protocol for routing in wireless sensor networks," in *Proc. Int. Conf. Adv. Wireless, Inf., Commun. Technol.*, 2015, pp. 336–341.

[17] R. Singh and A. K. Verma, "Energy efficient cross layer based adaptive threshold routing protocol for WSN," *AEU-Int. J. Electron. Commun.*, vol. 72, no. 2, pp. 166–173, 2017.

[18] A. Xenakis, F. Foukalas, and G. Stamoulis, "Cross-layer energy-aware topology control through simulated annealing for WSNs," *Comput. Elect. Eng.*, vol. 56, no. 11, pp. 576–590, 2016.

[19] M. Sami, N. K. Noordin, F. Hashim, S. Subramaniam, and A. Akbari-Moghanjoughi, "An energy-aware cross-layer cooperative MAC protocol for wireless ad hoc networks," *J. Netw. Comput. Appl.*, vol. 58, no. 12, pp. 227–240, 2015.

[20] B. Sarvi, H. R. Rabiee, and K. Mizanian, "An adaptive cross-layer error control protocol for wireless multimedia sensor networks," *Ad Hoc Netw.*, vol. 56, no. 3, pp. 173–185, 2017.

[21] Q.-V. Pham, H.-L. To, and W.-J. Hwang, "A multi-timescale cross-layer approach for wireless ad hoc networks," *Comput. Netw.*, vol. 91, no. 11, pp. 471–482, 2015.

[22] X. Wang, Q. Sun, and Y. Yang, "A cross-layer mobility support protocol for wireless sensor networks," *Comput. Electr. Eng.*, vol. 48, no. 11, pp. 330–342, 2015.

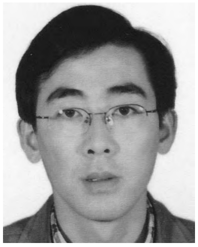
[23] R. Singh and A. K. Verma, "Efficient image transfer over WSN using cross layer architecture," *Optik-Int. J. Light Electron Opt.*, vol. 130, no. 2, pp. 499–504, 2017.

[24] G. Han, L. Zhou, H. Wang, W. Zhang, and S. Chan, "A source location protection protocol based on dynamic routing in WSNs for the social Internet of Things," *Future Generat. Comput. Syst.*, vol. 82, no. 5, pp. 689–697, 2017.

[25] Z. Niroumand and H. S. Aghdasi, "A geographic cross-layer routing adapted for disaster relief operations in wireless sensor networks," *Comput. Elect. Eng.*, vol. 64, no. 11, pp. 395–406, 2017.

[26] G. Han, L. Liu, J. Jiang, L. Shu, and G. Hancke, "Analysis of energy-efficient connected target coverage algorithms for industrial wireless sensor networks," *IEEE Trans. Ind. Informat.*, vol. 13, no. 1, pp. 135–143, Feb. 2017.

[27] Z. Ying and S. Hongliang, "A clustered routing protocol for underwater wireless sensor networks," in *Proc. 34th Chin. Control Conf.*, 2015, pp. 7665–7670.
[28] Q. H. Wang, H. Y. Guo, and Y. H. Ji, "Research and improvement of LEACH protocol for wireless sensor networks," *Microcomput. Appl.*, vol. 562–564, pp. 1304–1308, 2011.



WENBO ZHANG received the Ph.D. degree in computer science from Northeastern University, China, in 2006. He is currently a Professor with the School of Information Science and Engineering, Shenyang Ligong University, China. He has published over 100 papers in related international conferences and journals. His current research interests are ad hoc networks, sensor networks, satellite networks, and embedded systems. He was a recipient of the ICINIS 2011 Best Paper Awards and up to nine Science and Technology Awards including the National Science and Technology Progress Award and Youth Science and Technology Awards from China Ordnance Society. He has served in the Editorial Board of up to 10 journals, including the *Chinese Journal of Electronics* and the *Journal of Astronautics*.

XUANREN WEI received the B.S. degree in computer science and technology from Shenyang Ligong University, China, in 2016, where she is currently pursuing the master's degree with the School of Information Science and Engineering. Her current research interests include node deployment algorithm and MAC protocol for underwater sensor networks.

GUANGJIE HAN (S'01–M'05) received the Ph.D. degree from Northeastern University, Shenyang, China, in 2004. From 2004 to 2006, he was a Product Manager for the ZTE Company. In 2008, he finished his work as a Post-Doctoral Researcher with the Department of Computer Science, Chonnam National University, Gwangju, South Korea. From 2010 to 2011, he was a Visiting Research Scholar with Osaka University, Suita, Japan. He is currently a Professor with the Department of Information and Communication System, Hohai University, Changzhou, China, and also a Distinguished Professor with the Dalian University of Technology, Dalian, China. He has authored over 280 papers published in related international conference proceedings and journals, and is the holder of 110 patents. His current research interests include sensor networks, computer communications, mobile cloud computing, and multimedia communication and security.

Dr. Han is a member of ACM. He was a recipient of the ComManTel 2014, ComComAP 2014, Chinacom 2014, and Qshine 2016 Best Paper Awards. He has served as a Co-chair for over 50 international conferences/workshops and as a Technical Program Committee member of over 150 conferences. He has served on the Editorial Boards of up to 16 international journals, including the IEEE Access, *Telecommunication Systems*, the *International Journal of Ad Hoc and Ubiquitous Computing*, the *Journal of Internet Technology*, and the *KSII Transactions on Internet and Information Systems*. He has guest edited a number of special issues in the IEEE Journals and Magazines. He has served as a Reviewer of over 50 journals.

XIAOBO TAN received the B.E. degree from Liaoning Normal University, and the M.E. degree from Northeast University, China, in 2000 and 2006, respectively. He is currently an Associate Professor with the Communication and Network Institute, School of Information Science and Engineering, Shenyang Ligong University. His research interests include mainly wireless sensor networks and embedded system.