PAPER

Wireless Recharging Sensor Networks Cross-Layer Optimization Based on Successive Interference Cancellation*

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SUMMARY In wireless sensor networks (WSN), communication interference and the energy limitation of sensor nodes seriously hamper the network performance such as throughput and network lifetime. In this paper, we focus on the Successive Interference Cancellation (SIC) and Wireless Energy Transmission (WET) technology aiming to design a heuristic power control algorithm and an efficient cross-layer strategy to realize concurrency communication and improve the network throughput, channel utilization ratio and network lifetime. We realize that the challenge of this problem is that joint consideration of communication interference and energy shortage makes the problem model more complicated. To solve the problem efficiently, we adopt link scheduling strategy, time-slice scheduling scheme and energy consumption optimization protocol to construct a cross-layer optimization problem, then use an approximate linearization method to transform it into a linear problem which yields identical optimal value and solve it to obtain the optimal work strategy of wireless charging equipment (WCE). Simulation results show that adopting SIC and WCE can greatly improve communication capability and channel utilization ratio, and increase throughput by 200% to 500% while prolonging the network lifetime.

key words: *concurrency communication, successive interference cancellation, power control, charging strategy, cross-layer optimization*

1. Introduction

With the growing maturity of wireless communication, sensing and microelectronic technology, wireless sensor networks (WSN) are widely used in environmental monitoring, target tracking, medical care and so on [1]–[5]. However, widespread communication interference limits the network throughput, which seriously affects the performance of communications in WSN. In addition, each sensor node is usually powered by its battery, but the energy of the battery is severely restricted by the size and cost of the node. Thus, communication interference and energy issues seriously affect the performance and development of WSN.

In traditional wireless network transmission, collisions occur when multiple nodes transmit data to the same node simultaneously. This will lead to the discard or retransmission of conflict packets, which will affect the efficiency and real-time performance of communication. Successive Interference Cancellation (SIC) [6] is one of the most commonly used methods of interference management technology, which can effectively alleviate interference and achieve concurrency communication. It breaks through the restraint of traditional wireless communication technology for alleviating interference and increasing channel utilization and network throughput. Unfortunately, this greatly increases the energy consumption of nodes, and may cause more significant energy problems.

Solving the energy supply problem relies on two main solutions: energy conservation and energy acquisition. For energy conservation, scholars have done some preliminary work to save energy to prolong the lifetime of WSN, such as reducing the sensor nodes' energy consumption [7]–[9]. Energy acquisition [10], [11] is to harvest energy from the environment, such as sunlight, tides and winds. However, the energy converter may not be applicable to some specific work scenarios due to its large size. In recent years, Wireless Energy Transmission (WET) technology is a new direction to solve energy issues. A major breakthrough in WET technology based on strongly coupled magnetic resonance provides an improved approach for long distance wireless transmission [12]. Therefore, some scholars propose that wireless energy supply equipment should be employed to charge nodes in WSN.

The wireless charging equipment (WCE) has already been applied to wireless rechargeable sensor networks (WRSN) in recent years, freely moving inside the networks to charge nodes within its proximity [13]–[15]. Shi et al. [16] consider employing a mobile charger (MC) with sufficient energy to replenish energy for nodes periodically along the shortest Hamiltonian path, and introduce renewable energy cycle to study the working scheme of MC. As the charging strategy is one of the most important functions of WRSN, it has been studied by many researchers in different network scenarios [17]–[19]. Guo et al. [20] propose a framework of joint wireless energy replenishment and anchor-point with mobile data gathering. Ref. [21] studies a balanced charging strategy by minimizing the total service cost of limited energy MC. Chang et al. [22] firstly introduce the conception and requirements of cyclic energy conservation in conditions of WRSN and enhance the utility of charging achieved by Cuckoo Search. Wei et al. [23] design a Clustering Hierarchical Routing Algorithm for WRSN based on K-means method (K-CHRA) to reduce the energy consumption and the data transmission delay.

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The above studies just consider the energy issues and overlook interference management. Therefore, this paper will further study the charging problem on the basis of considering interference management. The introduction of SIC can further improve communication efficiency, but it will also greatly increase the complexity of the original problem. Time-slice scheduling scheme and energy consumption optimization protocol are adopted to solve this complexity. The main contributions of this paper are listed below:

- We discuss the multi-node concurrency communication conditions in single base station and single hop network and design a power control algorithm based on SIC to realize concurrency communication with less energy.
- By analyzing the working mode of wireless sensor nodes and WCE, we discuss the corresponding dynamic network model and constraints, then propose a cross-layer optimization problem with the objective of maximizing the vacation time ratio of WCE.
- Then we transform the original problem into a linear model which yields the same objective value by using a near-optimal method. Subsequently, we obtain the charging strategy of WCE and then evaluate the communication performance in the WRSN while prolonging the network lifetime.

The remainder of this paper is organized as follows. Section 2 describes the network scenario and designs the power control algorithm and the cross-layer optimization charging model. Section 3 constructs an optimization problem, then reformulates and solutes it by a near-optimal method, followed by construction of initial charging cycle in Sect. 4. In Sect. 5, we verify the performance by experimental simulations and obtain the controlled power and charging strategy. Section 6 concludes this paper.

2. Problem Description

2.1 System Model

The structure model of the single-hop WRSN in this paper is shown in Fig. 1. We consider n sensor nodes randomly distributed over a two-dimensional area and denote the set of nodes as $\mathcal{N} = \{1, 2, 3, \cdots, n\}$. A fixed base station (B) and a fixed service station (S) both with known location are placed in the area [16], [19]. B is the sink node for all data generated by the nodes, and S is a place where the WCE is maintained after travelling all nodes and finishing a round of energy replenishment. Denote $\mathcal{D} = \{d_{i,j} = (i, j) \mid i, j \in \mathcal{N}\}$ as a set of distance, where $d_{i,j}$ represents the Euclidean distance of nodes from node i to node j.

In the network, each node is equipped with the same type of wireless rechargeable battery with the maximum capacity of E_{max} and fully charged initially. Denote the minimum energy at a sensor node as E_{min} (for it to be operational). The mobile WCE starts from the service station S and travels all sensor nodes with speed of V (in m/s). When it arrives at a sensor node, say i, it will spend the time of τ_i to charge its battery wirelessly. After τ_i, WCE leaves node i and travels to the next node. Suppose that the power of each node and the charging power of WCE are invariable. WCE has enough energy to recharge all sensor nodes. WCE will return to S to be served after visiting all the nodes. We call this resting period *vacation time*, denoted as τ_{vac}. After this vacation, WCE will start the next trip. Denote τ the time for a trip cycle of WCE. Moreover, each node i sends data directly to B with a rate of R_i (in b/s).

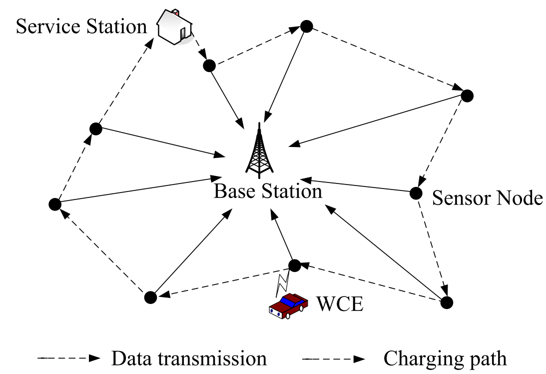

Fig. 1 Structure model of the WRSN with WCE.

The communication channel is AWGN channel. The channel capacity between B and nodes is large enough. And the farthest node can communicate with the base station normally. If multiple nodes could send data to B successfully with SIC, the transmission power of each node must fulfil certain conditions.

2.2 Principle of SIC

2.2.1 Basic Idea

SIC is a powerful physical layer technique based on signal processing. In order to separate the signals transmitted by nodes, the base station with the function of SIC always resolves and eliminates the strongest power signal from the received mixed signals according to the power level, then reorders the remaining mixed signals and starts a new iteration until the remaining signals fail to meet the certainly analytical conditions or all signals are completely decoded.

SIC technology can be employed by the base station to decode and receive each node's signal according to its power level. Each transmission power should be configured so that all signals satisfying certain conditions can be resolved simultaneously. Consequently, this brings about a large amount of energy consumption for nodes, which means the higher requirement for energy.

Network paralysis may occur when most nodes fail due to low energy. This can be avoided by using WCE to supplement energy for nodes. The charging time of each node depends on its energy consumption which is related to power in WRSN. The smaller the power, the shorter the charging time. If the node sends data to the base station successfully, it must have enough sending power. The sending power depends on its transmission rate and the distance from the base station. The minimum sending power of the node can be obtained when the transmission rate and the distance from the base station are known.

For SIC technology, it is difficult for each node to satisfy the threshold condition of simultaneous analysis without power control. Based on this characteristic, a heuristic algorithm is designed to classify and receive signals in time sharing, which is descried in detail below.

2.2.2 Power Control Algorithm

Considering the actual situation, only a small proportion of nodes can transmit data to base station B successfully simultaneously. Thus, the nodes are divided into clusters. All nodes in the same cluster can send data to B simultaneously by controlling their power. In this part, the following three points should be taken into consideration.

1. The power of node affects energy consumption and further affects charging time. To save energy of the sensor node, the power should be as small as possible.
2. The transmitting power of the nodes should be large enough to ensure that the base station successfully detects the signals sent by sensor nodes.
3. Data transmission failure can be caused by transmission conflicts when multiple nodes send data to the base station simultaneously. To avoid this situation, the power of each node should satisfy certain constraints.

Each node consumes energy during the process of data collection, processing and transmission. Compared with the data transmission process, the energy consumption of data collection and processing is negligible. Suppose the data generation rate of node i is $f_i (i \in \mathcal{N})$, and its energy consumption only for transmitting data. The actual sending rate of the node i is R_i. There has $R_i \geq f_i$. Denote the energy consumption rate of node i as P_i. In this paper, we use the following energy consumption model [24]. Then we have the relationship as follows:

$$P_i = C_i * R_i \tag{1}$$

where C_i is a power factor indicating the energy consumption rate for transmitting a unit of data form node i to B. Further, in the model, $C_i = \psi_1 + \psi_2 \cdot d_{i,B}^{\lambda}$, where $d_{i,B}$ is defined as the distance between node i and B, λ is the path loss index, ψ_1 is a distance-independent constant term, and ψ_2 is a coefficient of the distance-dependent term. When node i sends data with power of P_i, the receiving power at B for node i is $g_i P_i$, where g_i represents the power attenuation between the node i and B when transmitting data. Then,

$$g_i = a * d_{i,B}^{-\lambda} \tag{2}$$

where a is a constant term associated with transmitting antennas and it is normalized to facilitate discussion, that is, $a = 1$.

Suppose each node sends data by single hop with the same channel bandwidth W. When multiple nodes send data to B simultaneously, the signal to interference plus noise power ratio of node $i(SINR_i)$ must satisfy the following relation to be correctly decoded and received. Denote the signal to interference plus noise power ratio of node i $(SINR_i)$ as σ_i. When multiple nodes send data to B simultaneously, σ_i must satisfy the following relation to be correctly decoded and received. Based on the principle of SIC, the constraint can be computed as

$$\sigma_i = \frac{g_i P_i}{N_0 + \sum_{g_j P_j < g_i P_i} g_j P_j} \geq \beta \quad (i \neq j; i, j \in \mathcal{N}) \tag{3}$$

where N_0 is noise power, the sum portion indicates the aggregate receiving power of all nodes like node j that transmitting data together with node i simultaneously, but the receiving power is less than the receiving power of node i at B. The receiving power larger than $g_i P_i$ will be priority decoded by the base station B based on SIC. In other words, only nodes whose receiving power at B more than $g_i P_i$ will cause interfere to the reception of signals which transmitted by node i at B. At this point, if and only if $\sigma_i \geq \beta$, the transmitted data can be decoded by B, where β is the threshold of the signal to interference plus noise power ratio. For threshold β, it is required that $\beta > 1$ in most coding and decoding schemes.

If the node i sends data successfully, the channel capacity of node i is $W \log_2(1 + \sigma_i)$, where σ_i can be obtained by Eq. (3), and R_i should be less than or equal to the maximum channel capacity during the whole transmission process. Because of $\sigma_i \geq \beta$, R_i has the following constraint:

$$R_i \leq W \log_2(1 + \beta) \leq W \log_2(1 + \sigma_i) \tag{4}$$

Receiving power at the base station B depends on g_i and P_i, where g_i depends on the distance between the node and base station, and P_i is the transmission power of node i, so we stipulate that the order of analysis of received signals at B is determined by distance.

Theorem 1. *Assuming that the distance from node i and node j to base station is d_i and d_j respectively, node i is known to send data to base station at time t with the power of P. If node j sends data to base station simultaneously with the same transmission power as node i, combining with Eq.* (2)*, then:*

1. *If $d_j < [\beta(g_i + \frac{N_0}{P})]^{-\frac{1}{\lambda}}$, node j can transmit data to the base station at time t, and the data of node j must be decoded before the data decoding of node i.*
2. *If $d_j > (\frac{g_i}{\beta} - \frac{N_0}{P})^{-\frac{1}{\lambda}}$, node j can transmit data to the base station at time t, and the data of node j must be decoded after the data decoding of node i.*
3. *If $[\beta(g_i + \frac{N_0}{P})]^{-\frac{1}{\lambda}} \leq d_j \leq (\frac{g_i}{\beta} - \frac{N_0}{P})^{-\frac{1}{\lambda}}$, node j cannot transmit data to the base station and be decoded*

successfully at time t.

From Theorem 1 we can draw a conclusion: the signal near B is decoded first, and the signal far away from B is decoded later. For example, suppose node i and node j send data to B simultaneously, if $d_i \geq d_j$, the data sent by node j must be decoded by B before decoding the data sent by node i. The proof is described as follows.

Proof. (1) If $d_i \geq d_j$, there is $g_j \geq g_i$. Assuming that base station decodes the data of node i before decoding the data of node j at time t. And the data from node j is regarded as part of the interference when calculating $SINR_i$. Then there is $SINR_i \leq \frac{g_i P}{N_0 + g_j P} < \frac{g_i P}{g_j P} \leq 1 < \beta$. Therefore, the data from node i cannot be decoded, which is contradictory, so the hypothesis is not valid. □

We find that if the receiving power at the base station is sorted according to the size: $g_1 P_1 \leq g_2 P_2 \leq \cdots \leq g_i P_i \leq \cdots \leq g_n P_n (i \in \mathcal{N})$, the relationships between the different receiving power under the SIC conditions are listed as follows:

$$\begin{cases} g_1 P_1 & \geq \beta N_0 \\ g_2 P_2 & \geq \beta (N_0 + g_1 P_1) \\ & \geq \beta (N_0 + \beta N_0) = \beta (1+\beta) N_0 \\ & \vdots \\ g_n P_n & \geq \beta (1+\beta)^{n-1} N_0 \end{cases} \tag{5}$$

Therefore, the minimum value of the received power $g_1 P_1$ can be obtained to satisfy SIC conditions. To consume as little energy as possible, we consider both minimum sending power in Eq. (1) and minimum received power in Eq. (5), then take the minimum power which meets Eq. (1) and Eq. (5) as the actual power. From Eqs. (1)–(5), the sending power of each node within the same cluster can be determined sequentially.

On the premise of the above, a heuristic clustering power control algorithm based on SIC is proposed. First, all nodes in the network are sorted according to the distance from the base station. Then the base station is taken as the center of the circle, and the region is divided circle regions according to different radius sizes, so that the node falls in each circle area. And then searches the nearest node which is not clustered to the base station by traversing each area. If this node satisfies certain conditions, add it to the cluster and recording the real transmission power(calculated by Eqs. (1)–(5)). If no node can satisfy the concurrent communication conditions, a round of traversal is terminate. After terminating a round of search, the next cluster is searched according to the same rules, and the algorithm terminates when all nodes are assigned to the cluster. Notice that each node can only belong to one cluster. When all the sensors nodes are clustered, the control power of each clustered node is also obtained.

As is shown in Fig. 2, there are 6 nodes named from A to F, and the distance from each node to the base station

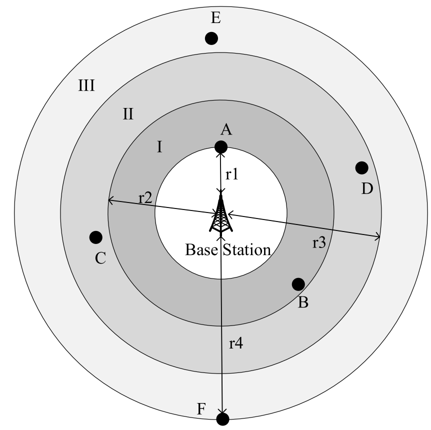

Fig. 2 Clustered node power control algorithm.

follows the relationship: $d_A \leq d_B \leq \ldots \leq d_F$. The region is divided into 3 areas named area I, II and III. In the area I, the nearest node A meet the conditions so set it as the first node of the first cluster, then calculate its transmission power by Eqs. (1)–(5) and record it. Next find in area II, if the nearest node C satisfies the conditions of concurrent communication with node A, add node C to the first cluster as the second node. Then finding the nearest node in area III, if node E satisfies the conditions of sending data to the base station at the same time with node A and node C, add it to the first cluster as the third node. But if node E does not meet the conditions, the search for the first cluster's nodes ends because area III is the farthest area from the base station. Similarly, searching the nodes for the second cluster in the left nodes. Add the nearest node B in area I and the nearest node D in area II to the second cluster if they meet the conditions. Then the same method is used to inspect the node F in area III. If node F cannot be added to the second cluster, it will be the first node in the third cluster. When all nodes are clustered, the control power of each clustered node is also obtained by Eqs. (1)–(5).

Clustering nodes can only ensure that the nodes in the same cluster can send data at the same time. If multiple clusters send at the same time, it is likely that conflicts will occur. Therefore, time slice scheduling mechanism is adopted in the data link layer. That is to say, each cluster has an exclusive time slice. It is advisable to divide the time period T into k time slices according to the number of clusters, and the transmission of each cluster takes up one time slice. The length of time slice is $t_1, t_2, \ldots, t_k$, respectively. The time slices for nodes communicating to the base station are determined by the total transmission rate of all nodes in each cluster. In order to make nodes to send more data, time slices for each sensor node can be set as follows:

$$t_1 : t_2 : \ldots : t_k = \frac{\sum_{i \in \mathcal{N}_1} R_i}{\sum_{i \in \mathcal{N}} R_i} : \frac{\sum_{i \in \mathcal{N}_2} R_i}{\sum_{i \in \mathcal{N}} R_i} : \ldots : \frac{\sum_{i \in \mathcal{N}_k} R_i}{\sum_{i \in \mathcal{N}} R_i} \tag{6}$$

where t_k indicates the time slices of the kth cluster, and $\mathcal{N}_k$

is the set of all sensor nodes in the kth cluster.

The heuristic clustered power control algorithm based on SIC realizes clustering and multi-nodes concurrent communication, and achieves higher network throughput with smaller power. It is implemented as follows.

Algorithm 1 Power Control Algorithm Based on SIC

Require: the number of areas divided w and related parameters
Ensure: the controlled power of clustered node P_v^k
  Initialize each area lists $AList_u$ $(u = 1, 2, \cdots, w)$
  $interval \leftarrow [max(d_i) - min(d_i)]/w$
  $mindistance \leftarrow min(d_i)$
  while $i \le N$ **do**
    $u = \lceil (d_i - mindistance)/interval \rceil$
    if $u = 0$ **then**
      Add the node i into the first area list $AList_1$
    else
      Add the node i into the uth area list $AList_u$
    end if
  end while
  while all the area list $AList_u$ are not null **do**
    Construct the kth cluster
    while $AList_u$ is not null and the neatest node meet the conditions of Eq.1– Eq.4 **do**
      Add the node into the area list $CList_k$, delete this node in $AList_u$ and record the power as P_v^k. (v represents it is the vth node in $CList_k$)
      Find the next area list $AList_{u+1}$
    end while
    Start constructing the next cluster $CList_{k+1}$
  end while

However, compared with no concurrent communication, the demand for energy of sensor nodes is greatly improved. Then we can combine wireless charging technology to design a specific working strategy in this WSN to prolong the network lifetime.

2.3 Charging Model

The period of the charging cycle is the length of the completion of a complete energy supply, consisting of three parts:

(i) the length of the WCE staying in service station τ_{vac};

(ii) the length of WCE moving in the network τ_p;

(iii) the sum of the charging time of the sensor nodes deployed in all networks $\Sigma\tau_i$.

There are two types of charging cycle: the general charging cycle and the initial charging cycle [16]. The initial charging cycle will be discussed later. If the length of the initial charging cycle is τ, the start time of the first general charging cycle is τ and the end time of this cycle is 2τ. We formally define a general charging cycle as follows.

Definition 1. Each node has the same energy curve of its any general charging cycle. The energy level of a sensor node i $(i \in \mathcal{N})$ exhibits a general charging cycle if it meets the following two conditions:

(i) At the end of the general charging cycle, the energy of node i is equal to the energy at the start of the charging cycle over a period of τ;

(ii) The dump energy of any time cannot be less than E_{min}.

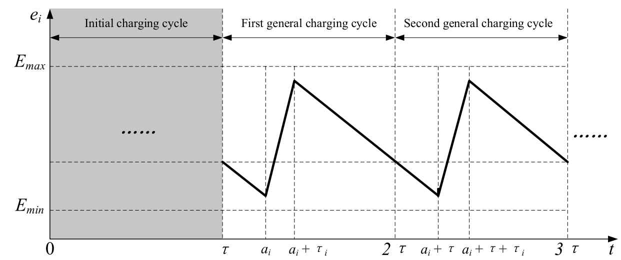

Fig. 3 Complete charging cycle of partially recharged.

Charging cycle of partially recharged is illustrated in Fig. 3. If the periodic working mode can be determined, the rest of the cycles can be regarded as the extension of the first charging cycle. So we only need to consider the case of the first general charging cycle, which is also within $t \in [\tau, 2\tau]$.

Suppose the WCE traverses all nodes by the physical path $p = (\pi_0, \pi_1, \cdots, \pi_N, \pi_0)$, which starts from and ends at the service station (i.e., $\pi_0 = S$). Denote the ith node traversed by the WCE along path p as π_i, $i \in \mathcal{N}$. Denote the Euclidean distance between the service station and the first sensor node visited along p as d_{π_0,π_1}, and the Euclidean distance between the kth and $(k+1)$th sensor nodes as $d_{\pi_k,\pi_{k+1}}$, respectively. The arrival time of WCE at ith sensor node a_i on the traversal path in the first general charging cycle can be obtained by

$$a_{\pi_i} = \tau + \sum_{k=0}^{i-1} \frac{d_{\pi_k,\pi_{k+1}}}{V} + \sum_{k=1}^{i-1} \tau_k \tag{7}$$

Denote D_p the physical distance of path p, so $\tau_p = D_p/V$. τ_{vac} is the vacation time of WCE. The complete charging cycle τ is computed as

$$\tau = \tau_p + \tau_{vac} + \sum_{i \in \mathcal{N}} \tau_i \tag{8}$$

Each node only consumes power in its own time slices and is dormant in the remaining time. Denote $\overline{P_i^k}$ the relative power of node i in the kth cluster and P_i^k the real power, then the constraint on them can be written as

$$\overline{P_i^k} = \frac{t_k}{\sum_{m=1}^{k} t_m} \cdot P_i^k \tag{9}$$

In Definition 1, the amount of energy consumed by node i is equal to the energy supplied by WCE. If the charging power of WCE is U and the charging time is τ_i. Therefore,

$$\tau \cdot \overline{P_i^k} = \tau_i \cdot U \quad (i \in \mathcal{N}) \tag{10}$$

Note that when the WCE visits the node i at time a_i, it does not have to recharge node's battery to E_{max}. Denote the starting energy of node i as E_i and the energy level at

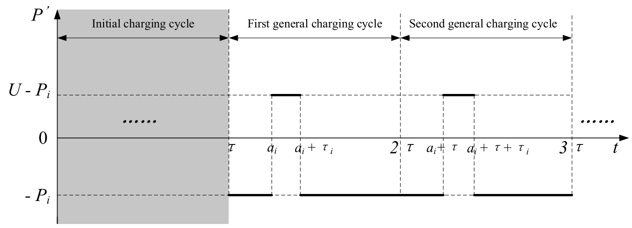

Fig. 4 Energy consumption rate-time diagram in charging cycle.

time t as $e_i(t)$, respectively. The residual energy of the node is always increasing during the energy replenishment stage, and the residual energy in other phases will decrease all the time.

Therefore, the energy level has only two approximate slopes within a cycle $[\tau, 2\tau]$: (i) a slope of $-\overline{P_i}$ when the WCE is not at this node during non-charging period, and (ii) a slope of $(U - \overline{P_i})$ when the WCE is charging this node at a rate of U during charging period. The energy consumption rate is shown in Fig. 4.

Because the energy level cannot be less than E_{min} and more than E_{max} within $t \in [\tau, 2\tau]$, we have $e_i(t)$ within $t \in [\tau, 2\tau]$ must satisfy

$$E_{min} \leq e_i(a_i) \leq e_i(t) \leq e_i(a_i + \tau_i) \leq E_{max} \tag{11}$$

where $e_i(a_i)$ represents the residual energy of node i when WCE arrives at it, which is the lowest energy level over the whole general charging cycle. Also, $e_i(a_i + \tau_i)$ represents the residual energy of node i when WCE leaves it, which is the highest energy.

When the battery energy is charged to E_{max} during the WCE's traversal, the optimal objective maximizing the ratio of the WCE's vacation time over the cycle time is equally good as the battery is partially recharged [16]. Thus, we can only consider the situation of fully recharged. In Fig. 3, $E_i = e_i(2\tau)$. To ensure the second requirement in Definition 1, $e_i(a_i)$ and E_i can be represented as

$$\begin{aligned} E_i &= e_i(a_i + \tau_i) - (2\tau - (a_i + \tau_i)) \cdot \overline{P_i^k} \\ &= E_{max} - (2\tau - (a_i + \tau_i)) \cdot \overline{P_i^k} \\ &= E_{max} - (2\tau - (a_i + \tau_i)) \cdot \overline{P_i^k} \end{aligned} \tag{12}$$

For $e_i(a_i)$ is the residual energy after consumed energy during non-charging period, we have From Fig. 3 the residual energy constraint of node i at each time point of the charging cycle can be derived. From Fig. 3, $e_i(a_i)$ can be represented as From the energy level diagram in reference [16], $e_i(a_i)$ can be represented as

$$\begin{aligned} e_i(a_i) &= E_i - (a_i - \tau) \cdot \overline{P_i^k} \\ &= E_{max} - ((2\tau - ((a_i + \tau_i)) \cdot \overline{P_i^k} - (a_i - \tau) \cdot \overline{P_i^k} \\ &= E_{max} - (\tau - \tau_i) \cdot \overline{P_i^k} \\ &\geq E_{min} \quad (i \in \mathcal{N}) \end{aligned} \tag{13}$$

2.4 Cross-Layer Optimization Problem Construction

To make the WCE stay at the service station as long as possible, naturally, taking the percentage of time that WCE takes a vacation over a cycle $\frac{\tau_{vac}}{\tau}$ as the optimization objective. The optimization problem is formulated as follows.

OPT 1

$$\begin{aligned} &max && \frac{\tau_{vac}}{\tau} \\ &s.t. && (8) \sim (13) \\ & && \tau_i, \tau_p, \tau_{vac}, \tau, P_i^k \geq 0 \quad (i \in \mathcal{N}) \end{aligned}$$

In this problem, τ_p, τ_{vac} are optimization variables; P_i^k can be obtained by the power control algorithm; U, V, E_{max}, E_{min} are constants. This problem is a nonlinear optimization problem and cannot be solved directly in polynomial time since it contains nonlinear objective ($\frac{\tau_{vac}}{\tau}$) and product terms in constraints. In the next section, we will discuss how to simplify the formulations and transform the problem OPT 1 into an equivalent linear problem.

3. Model Optimization and Solution

Theorem 2. *The WCE must move along the shortest Hamiltonian cycle that crosses all the nodes and the service station in an optimal solution with the maximal* $\frac{\tau_{vac}}{\tau}$.

Theorem 2 can be proved by contradiction [16]. In addition, any shortest Hamiltonian cycle and traverse direction can achieve the same optimal objective. The shortest Hamiltonian cycle can be obtained by solving the well-known Travelling Salesman Problem (TSP).

Denote D_{TSP} as the total traversal path distance and $\tau_{TSP} = D_{TSP}/V$ as the traversal time. With the optimal traversal path, Eq. (8) is reformulated as

$$\tau = \tau_{TSP} + \tau_{vac} + \sum_{i \in \mathcal{N}} \tau_i \tag{14}$$

We can observe that there are nonlinear terms in OPT 1 where the target function contains ratio term. Then we use change-of-variable technique to replace the optimization variables in the objective function and constraints to simplify the formulation. For the nonlinear objective $\frac{\tau_{vac}}{\tau}$, we define

$$\eta_{vac} = \frac{\tau_{vac}}{\tau} \tag{15}$$

For Eq. (10), we can remove nonlinear terms $\frac{1}{\tau}$ and $\frac{\tau_i}{\tau}$ by defining

$$\begin{cases} \tau_0 = \tau_{TSP} + \tau_{vac} \\ \eta_0 = \frac{\tau_0}{\tau} \\ \eta_i = \frac{\tau_i}{\tau} \end{cases} \quad (i \in \mathcal{N}) \tag{16}$$

Then Eq. (8) is reformulated as

$$\sum_{m=0}^{n} \eta_m = 1 \tag{17}$$

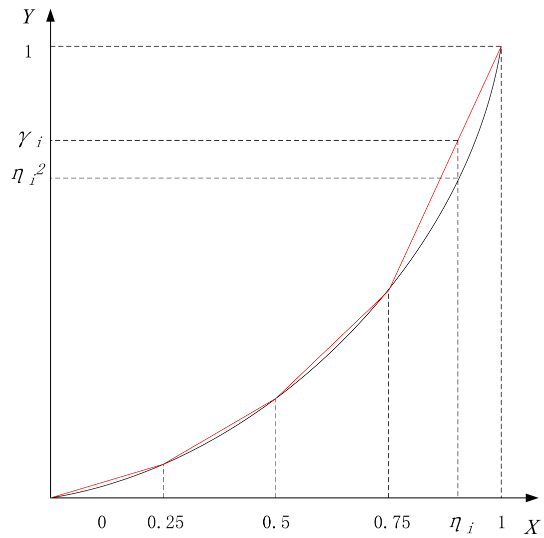

Fig. 5 An illustration of piecewise linear approximation method (with $m = 4$).

or equivalently $\tau = \tau_{TSP}/(\eta_0 - \eta_{vac})$. Similarly, Eq. (10) and Eq. (11) can be reformulated (by dividing both sides by τ) as

$$\overline{P_i^k} = U \cdot \eta_i \quad (i \in \mathcal{N}) \tag{18}$$

$$\overline{P_i^k}(1-\eta_i) \cdot \tau_{TSP} \le (E_{max} - E_{min})(\eta_0 - \eta_{vac}) \tag{19}$$

By Eq. (16) and Eq. (18), constraint Eq. (19) can be rewritten as

$$\eta_{vac} \le \eta_0 - \frac{U \cdot \tau_{TSP}}{E_{max} - E_{min}} \cdot (\eta_i - \eta_i^2) \quad (i \in \mathcal{N}) \tag{20}$$

There is a quadratic term η_i^2 in Eq. (20). An approximate linearization method is adopted to solve this problem, in which the line between two points is used to replace the quadratic curve so that the optimization problem is transformed into a linear programming problem. The key idea is to use m piecewise linear segments to approximate the quadratic curve (see Fig. 5).

Specific steps are as follows. Within the η_i definition domain, the chord approximation of a series of points $\{(\frac{k}{m}, \frac{k^2}{m^2})\}$ $(k = 0, 1, 2, \cdots, m)$ on the line $y = \eta_i^2$ characterizes the curve $y = \eta_i^2$. Then any point (η_i, η_i^2) on the curve can find a corresponding point (η_i, γ_i) on the chord. Then we define

$$\eta_i = \mu_{i,k-1} \cdot \frac{k-1}{m} + \mu_{i,k} \cdot \frac{k}{m} \tag{21}$$

$$\gamma_i = \mu_{i,k-1} \cdot \frac{(k-1)^2}{m^2} + \mu_{i,k} \cdot \frac{k^2}{m^2} \tag{22}$$

where $\mu_{i,k-1}$ and $\mu_{i,k}$ are two weights and satisfy the following constraints. And

$$\mu_{i,k-1} + \mu_{i,k} = 1 \tag{23}$$

$$0 \le \mu_{i,k-1}, \mu_{i,k} \le 1 \tag{24}$$

That is to say, (η_i, γ_i) must be a point on a chord whose endpoints are $(\frac{k-1}{m}, \frac{(k-1)^2}{m^2})$ and $(\frac{k}{m}, \frac{k^2}{m^2})$. Since $y = \eta_i^2$ is a convex function, (η_i, γ_i) must be above (η_i, η_i^2), and $\gamma_i - \eta_i^2 \le \frac{1}{4m^2}$. The equation can be proved by the maximum value of $\gamma_i - \eta_i^2$, so it is not necessary to elaborate.

Denote $\theta_{i,k}$ $(1 \le k \le m,\ i \in \mathcal{N})$ a binary variable indicating whether η_i falls within the kth segment. (i.e., if $\frac{k-1}{m} \le \eta_i \le \frac{k}{m}$, then $\theta_{i,k} = 1$; otherwise, $\theta_{i,k} = 0$). Obviously, $\theta_{i,k}$ can only fall in one of the m segments, so $\theta_{i,k}$ is constrained as

$$\sum_{k=1}^{m} \theta_{i,k} = 1 \tag{25}$$

and (η_i, γ_i) on the kth chord is equivalent to

$$\begin{cases} \mu_{i,0} \le \theta_{i,1} \\ \mu_{i,k} \le \theta_{i,k} + \theta_{i,k+1} \quad (1 \le k < m) \\ \mu_{i,m} \le \theta_{i,m} \end{cases} \tag{26}$$

The constraints from Eq. (26) ensure that there are at most two adjacent positive μ's for each η_i, Eq. (21), Eq. (22) and Eq. (23) can now be rewritten for the entire piecewise linear curve as follows.

$$\begin{cases} \eta_i = \sum_{k=0}^{m} \mu_{i,k} \cdot \frac{k}{m} \\ \gamma_i = \sum_{k=0}^{m} \mu_{i,k} \cdot \frac{k^2}{m^2} \\ \sum_{k=0}^{m} \mu_{i,k} = 1 \end{cases} \tag{27}$$

By replacing η_i^2 with γ_i in Eq. (20), we have

$$\eta_{vac} \le \eta_0 - \frac{U \cdot \tau_{TSP}}{E_{max} - E_{min}} \cdot (\eta_i - \gamma_i) \quad (i \in \mathcal{N}) \tag{28}$$

Now the problem OPT 1 is reformulated as follows.

OPT 2

max $\quad \eta_{vac}$

s.t. $\quad (15) \sim (17), (21) \sim (28)$

$\quad 0 \le \eta_i, \eta_{vac} \le 1 \quad (i \in \mathcal{N})$

In this problem, η_i, η_{vac}, γ_i, $\mu_{i,k}$ and $\theta_{i,k}$ are optimization variables. P_i^k can be obtained by the power control algorithm. $U, V, E_{max}, E_{min}, \tau_{TSP}$ are constants. Once we solve problem OPT 2, the solution to problem OPT 1 (i.e., calculate the values for τ, τ_i, and τ_{vac} by Eqs. (14)–(17)). And m is an approximate coefficient. $m = \left\lceil \sqrt{\frac{U \cdot \tau_{TSP}}{4\epsilon(E_{max} - E_{min})}} \right\rceil$, where ϵ is the performance gap and is usually required $0 < \epsilon \le 1$. This can be proved that the solution constructed by the optimal solution of OPT 2 is the ϵ-suboptimal solution of OPT 1 [16].

After reformulation, the optimization problem becomes a linear problem which can now be solved quickly by a solver such as CPLEX or LINDO in polynomial time. Based on the solution we can construct a feasible solution to problem OPT 1.

4. Initial Cycle Construction

The initial energy replenishment is the first stage in which all sensor nodes receive energy replenishment after the wireless sensor network is completed. In Sect. 3, we skipped the discussion on how to construct the initial charging cycle before the first general charging cycle. In this section, we will discuss how to design corresponding strategies for devices in sensor networks in the initial energy replenishment stage. Now with the optimal traveling path p (the shortest Hamiltonian cycle) and the feasible near-optimal solution (τ_i, τ_{vac}, ...) obtained in Sect. 3, we are ready to construct the initial charging cycle.

It is obvious that at the beginning of the initial charging stage, the residual energy value of the sensor node i is E_{max} higher than the residual energy value $e_i(\tau)$ that is the residual energy at the beginning of each general charging cycle. Then, the initial charging stage cannot be combined with the general charging cycle. At the end of the initial charge stage, the residual energy value of the sensor node is equal to the residual energy value of the sensor node at the beginning of the first general charging cycle. Only in this way can the transition from the initial charging stage to the first general charging cycle be completed. Now we formally define an initial charging cycle as follows.

Definition 2. The energy level of a sensor node $i \in \mathcal{N}$ exhibits an initial energy cycle if it meets the following two requirements: (i) it starts with the energy level of E_{max} and ends with E_i, respectively; and (ii) it never falls below E_{min} for $t \in [0, \tau]$.

The purpose of the initial energy replenishment phase is to ensure that the remaining energy of the sensor node meets certain requirements at the end of this phase, and can be successfully assigned to the first general energy replenishment cycle, as shown in Fig. 6. The first general energy replenishment cycle is the first cycle in the general energy replenishment stage. In the initial energy supply phase, the working mode of sensor nodes and WCE is guaranteed to be the same as the normal energy supply cycle. The purpose of phase connection can be achieved by adjusting the power supply power.

Initial charging cycle is different from the general charging cycle at node i, which starts and ends with the same energy level E_i. Suppose that the initial charging cycle starts with E_{max} and ends with E_i. When the WCE starts to recharge the node at the general charging cycle, the residual energy of the node is $e_i(a_i)$. In the initial energy replenishment cycle, when WCE begins to recharge the sensor node, the remaining energy of the node is

$$e_i(a_i^*) = E_{max} - (E_i - e_i(a_i)) \tag{29}$$

If we adopt the same working strategy in the initial charging stage as the general charging cycle, that is, in the initial energy supply cycle use the same method of full energy supply to make the energy of the sensor node is up to E_{max} when the energy replenishment is completed by WCE, and adjust the energy recharge power of WCE to make sure that energy level satisfies the Definition 2. For a solution $\varphi = (P_i, R_i, \tau, \tau_i, \tau_p, \tau_{vac}, U)$ corresponding to a general charging cycle for $t \geq \tau$, we can construct $\varphi^* = (p^*, P_i^*, R_i^*, \tau^*, \tau_i^*, \tau_p^*, \tau_{vac}^*, U_{\pi_i}^*)$ for the initial charging cycle for $t \in [0, \tau]$ by letting $p^* = p$, $P_i^* = P_i$, $R_i^* = R_i$, $\tau^* = \tau$, $\tau_i^* = \tau_i$, $\tau_p^* = \tau_p$ and $\tau_{vac}^* = \tau_{vac}$, the only difference is $U_{\pi_i}^*$. Thus, in the initial energy replenishment period, the power $U_{\pi_i}^*$ of WCE for energy replenishment can be obtained from the following formula.

$$e_i(a_i^*) = E_{max} - \tau_i \cdot \overline{P_i^k} + U_{\pi_i}^* \cdot \tau_i \tag{30}$$

there is,

$$e_i(a_i) = E_{max} - \tau_i \cdot \overline{P_i^k} + U \cdot \tau_i \tag{31}$$

then, we have

$$U_{\pi_i}^* = U - \frac{E_{max} - E_i}{\tau_i} \tag{32}$$

where $U_{\pi_i}^*$ is the charging rate at ith node on the traversal path during the initial charging cycle. And the value of $E_i, i \in \mathcal{N}$ can be calculated by Eq. (7) and Eq. (12) in Sect. 2. Obviously, $U_{\pi_i}^* \leq U$ because the starting energy $e_i(0) \geq e_i(\tau)$ while they end with the same energy level. In this way, we can construct the initial charging cycle (see Fig. 6).

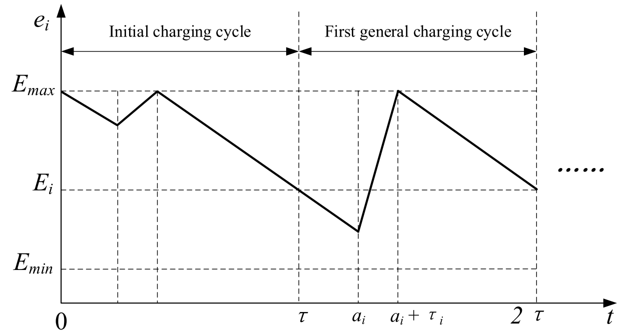

Fig. 6 The connection between the initial charging cycle and the first general charging cycle.

5. Simulation and Analysis

In this section, we will give simulation results of controlled power of nodes and charging strategy of WCE to show the advantage of using SIC in WRSN compared with without SIC.

5.1 Simulation Platform

- The traversal path of WCE is the shortest Hamilton cycle connecting the service station and all sensor nodes. The solution of the shortest traversal path is similar to the TSP traveler problem, which can be obtained by the Concorde TSP Solver.
- The linear programming problem OPT 2 can be solved by IBM WebSphere ILOG CPLEX toolkit.

5.2 Simulation Parameter Setting

We consider a randomly generated single hop wireless sensor

Table 1 Location and data rate R_i for each node in a 20-node network.

Node Index	Location	R_i (Kb/s)	Node Index	Location	R_i (Kb/s)
1	(19, 43)	44	11	(7, 22)	22
2	(46, 62)	20	12	(60, 57)	47
3	(65, 45)	72	13	(40, 93)	86
4	(24, 80)	75	14	(32, 63)	79
5	(40, 24)	27	15	(53, 24)	79
6	(20, 12)	55	16	(80, 47)	81
7	(33, 69)	54	17	(69, 25)	39
8	(12, 69)	60	18	(55, 8)	98
9	(83, 32)	83	19	(73, 68)	63
10	(75, 6)	13	20	(31, 8)	35

network consisting of 20 ~ 50 sensor nodes respectively. The sensor nodes are deployed over a square area of 100 m×100 m ~ 500 m×500 m with the data rate randomly generated within [10, 100] kb/s. The base station is located at (50, 45) (in 100 m × 100 m single-hop network). The service station is at (0, 0). The travelling speed of the WCE is $V = 5$ m/s. The WCE's supply power for the nodes is $U = 10$ W. Other parameters of energy consumption coefficients for transmitting data are $\psi_1 = 5 \times 10^{-8}$ J/b, $\psi_2 = 1.3 \times 10^{-15}$ J/(b·m^4), $\lambda = 4$ and $\beta = 3$. We consider a regular battery whose nominal cell voltage is 1.2 V and quantity of electricity is 2.5 Ah. Let $E_{max} = 1.2 \times 2.5 \times 3600 = 10800$ J, $E_{min} = 0.05 \times E_{max} = 540$ J. In 100m×100m, the location information and the data generation rate of each node are shown in Table 1.

5.3 Results Analysis

The shortest traversal path found by using the Concorde Solver is shown in Fig. 7. For this optimal cycle, $D_{TSP} =$ 380m and $\tau_{TSP} = 76$s. Then we obtain the cycle time $\tau = 124950$s, and the objective $\eta_{vac} = 57.21\%$. Table 2 shows the transmission power of nodes after adopting the power control strategy. The nodes are divided into 5 groups. By solving the optimization problem, the WCE's working strategy over the general energy cycle can be obtained in the single base station and single hop WSN. (See Table 2)

By using the time-slice scheduling strategy designed by Eq. (6), the cluster with high transmission rate is allocated longer working time slices. The throughput can be obtained by calculating the relative transmission rate of each cluster. We have the whole average data rate $\bar{R} = 246.62$Kb/s. If SIC is not used, the average data rate is: $\bar{R}^* = 56.6$Kb/s. After employing SIC, the average data rate can be increased by about 4.36 times.

To verify the reliability of the experimental results, the network size and number of nodes are changed in the simulation environment. Several experiments are done to verify the applicability and scalability of WRSN using SIC and wireless energy supply technology. (See Table 3). With the increase of network scale, the distance between sensor nodes and base station is generally increased, and the power of a single node is also generally increased and closer to the upper limit of power obtained by Eq. (1). According to the conditions of concurrent communication (Eq. (5)), fewer nodes can send data at the same time, and the number of clusters is also relatively increased. There are fewer nodes sending data at the same time, so the average data transmission rate will become smaller. Consequently, $\bar{R}$ and the throughput improvement decrease as the network size increase.

The simulation results with more nodes show that multiple node concurrency communication and wireless energy supply scheme can also be used in broader coverage and denser node deployment networks and can achieve the desired station time. The employment of interference management strategy and wireless energy supply technology can greatly improve the network throughput and channel utilization ratio of the WSN while compensating the energy for all sensor nodes to extend the network life cycle.

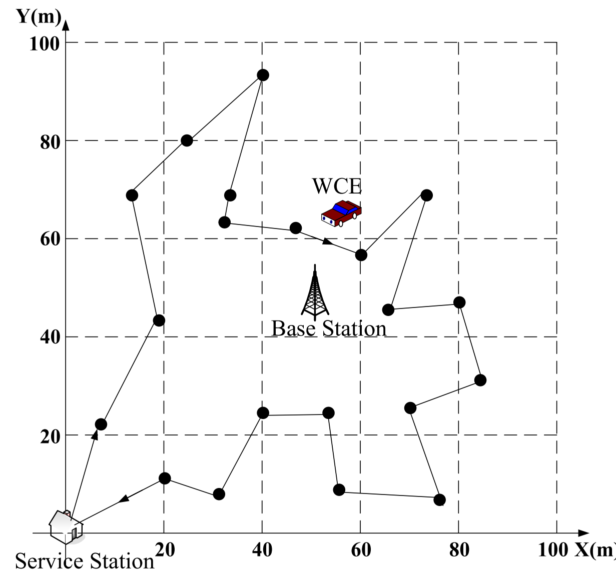

Fig. 7 Optimal traversal path of the WCE.

Table 2 Power and recharging time for each node in a 20-node network.

Cluster	Location	Power(J/s)	Recharging Time(%)
1	(65, 45)	0.0036	0.008
	(53, 24)	0.0434	0.097
	(69, 25)	0.4961	1.109
	(73, 68)	3.8444	8.592
2	(60, 57)	0.0024	0.004
	(40, 24)	0.0348	0.065
	(33, 69)	0.3551	0.662
	(83, 32)	3.0121	5.614
3	(46, 62)	0.0010	0.003
	(32, 63)	0.0136	0.038
	(80, 47)	0.1064	0.294
	(55, 8)	1.0086	2.789
	(31, 8)	6.2207	17.20
4	(19, 43)	0.0023	0.005
	(24, 80)	0.0272	0.060
	(20, 12)	0.1191	0.260
	(12, 69)	0.4918	1.073
	(75, 6)	2.2212	4.847
5	(7, 22)	0.0017	0.002
	(40, 93)	0.0069	0.007

Table 3 The simulation results in different networks.

Network Size	Number of Nodes	η_{vac} (%)	$\bar{R}$ (Kb/s)	Throughput Improvement
100 m×100 m	30	38.47	244.54	435%
100 m×100 m	40	58.35	252.27	484%
200 m×200 m	30	60.64	192.13	358%
200 m×200 m	40	32.38	219.08	408%
300 m×300 m	30	51.83	188.07	374%
300 m×300 m	40	33.91	193.59	382%
400 m×400 m	30	53.61	146.15	283%
400 m×400 m	40	36.16	157.54	300%
400 m×400 m	50	38.43	156.48	305%
500 m×500 m	30	53.99	146.24	260%
500 m×500 m	40	42.80	157.97	280%
500 m×500 m	50	58.10	151.65	263%

6. Conclusion

In order to alleviate the problem of communication interference and energy shortage at nodes in WSN, this paper employed interference management to achieve concurrency communication and WET to supply energy for sensor nodes, which yields a more complicated problem model. To overcome this challenge, we jointly discussed the communication characteristics of nodes and the working mode of WCE in single hop network, then proposed a cross-layer optimization problem and transformed it into a linear problem which yields the same optimization results to get the working strategy. Simulation results demonstrated that the channel utilization ratio was greatly improved and throughput could be increased by 200% to 500% while prolonging the network lifetime by using SIC and wireless energy supply technology. Given this significant performance improvement, we will further study more complex network scenarios with multi-hop transmission and multi base station in our future work.

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References

[1] A. Mainwaring, D. Culler, J. Polastre, R. Szewczyk, and J. Anderson, "Wireless sensor networks for habitat monitoring," Proc. 1st ACM International Workshop on Wireless Sensor Networks and Applications, pp.88–97, ACM, 2002.

[2] L. Song and D. Hatzinakos, "A cross-layer architecture of wireless sensor networks for target tracking," IEEE/ACM Trans. Netwo. (TON), vol.15, no.1, pp.145–158, 2007.

[3] V. Potdar, A. Sharif, and E. Chang, "Wireless sensor networks: A survey," Proc. International Conference on Advanced Information Networking and Applications (AINA 2009), pp.636–641, Bradford, UK, May 2009.

[4] M.Z.A. Bhuiyan, G. Wang, J. Cao, and J. Wu, "Deploying wireless sensor networks with fault-tolerance for structural health monitoring," IEEE Trans. Comput., vol.64, no.2, pp.382–395, 2013.

[5] N. Sghaier, A. Mellouk, B. Augustin, Y. Amirat, J. Marty, M.E.A. Khoussa, A. Abid, and R. Zitouni, "Wireless sensor networks for medical care services," 2011 7th International Wireless Communications and Mobile Computing Conference, pp.571–576, IEEE, 2011.

[6] M. Kontik and S. Coleri Ergen, "Distributed medium access control protocol for successive interference cancellation-based wireless ad hoc networks," IEEE Commun. Lett., vol.21, no.2, pp.354–357, Feb. 2017.

[7] J.A. Haqbeen, T. Ito, M. Arifuzzaman, and T. Otsuka, "Joint routing, MAC and physical layer protocol for wireless sensor networks," TENCON 2017 - 2017 IEEE Region 10 Conference, pp.935–940, Penang, Malaysia, Nov. 2017.

[8] Y. Zhu, E. Li, and K. Chi, "Encoding scheme to reduce energy consumption of delivering data in radio frequency powered battery-free wireless sensor networks," IEEE Trans. Veh. Technol., vol.67, no.4, pp.3085–3097, April 2018.

[9] Z. Cai and X. Zheng, "A private and efficient mechanism for data uploading in smart cyber-physical systems," IEEE Trans. Netw. Sci. Eng., vol.7, no.2, pp.766–775, 2020. http://dx.doi.org/10.1109/TNSE.2018.2830307

[10] P. Kamalinejad, C. Mahapatra, Z. Sheng, S. Mirabbasi, V.C. Leung, and Y.L. Guan, "Wireless energy harvesting for the internet of things," IEEE Commun. Mag., vol.53, no.6, pp.102–108, 2015.

[11] V. Shakhov, "On efficiency improvement of energy harvesting wireless sensor networks," 2016 39th International Conference on Telecommunications and Signal Processing (TSP), pp.56–59, IEEE, 2016.

[12] A. Kurs, A. Karalis, R. Moffatt, J.D. Joannopoulos, P. Fisher, and M. Soljacic, "Wireless power transfer via strongly coupled magnetic resonances," Science, vol.317, no.5834, pp.83–86, July 2007.

[13] G. Jiang, S.-K. Lam, Y. Sun, L. Tu, and J. Wu, "Joint charging tour planning and depot positioning for wireless sensor networks using mobile chargers," IEEE/ACM Trans. Netw., vol.25, no.4, pp.2250–2266, Aug. 2017.

[14] Z. Ma, J. Wu, S. Zhang, and S. Lu, "Prolonging WSN lifetime with an actual charging model," 2018 IEEE Wireless Communications and Networking Conference (WCNC), pp.1–6, Barcelona, Spain, April 2018.

[15] Z. Wei, F. Liu, Z. Lyu, X. Ding, L. Shi, and C. Xia, "Reinforcement learning for a novel mobile charging strategy in wireless rechargeable sensor networks," Proc. International Conference on Wireless Algorithms, Systems, and Applications (WASA), pp.485–496, Tianjin, China, 2018.

[16] Y. Shi, L. Xie, Y.T. Hou, and H.D. Sherali, "On renewable sensor networks with wireless energy transfer," Proc. IEEE INFOCOM 2011, pp.1350–1358, Shanghai, China, 2011.

[17] L. Xie, Y. Shi, Y.T. Hou, W. Lou, H.D. Sherali, and S.F. Midkiff, "Bundling mobile base station and wireless energy transfer: Modeling and optimization," Proc. IEEE INFOCOM 2013, pp.1636–1644, Turin, Italy, 2013.

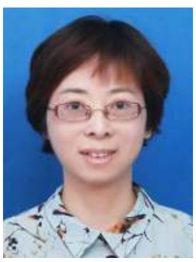
[18] W. Xu, W. Liang, X. Ren, and X. Lin, "On-demand energy replenishment for sensor networks via wireless energy transfer," 2014 IEEE 25th Annual International Symposium on Personal, Indoor, and Mobile Radio Communication (PIMRC), pp.1269–1273, Washington, DC, USA, 2014.

[19] X. Ding, J. Han, and L. Shi, "The optimization based dynamic and cyclic working strategies for rechargeable wireless sensor networks with multiple base stations and wireless energy transfer devices," Sensors, vol.15, no.3, pp.6270–6305, March 2015.

[20] S. Guo, C. Wang, and Y. Yang, "Joint mobile data gathering and energy provisioning in wireless rechargeable sensor networks," IEEE Trans. Mobile Comput., vol.13, no.12, pp.2836–2852, 2014.

[21] J. Xu, X. Yuan, Z. Wei, J. Han, L. Shi, and Z. Lyu, "A wireless sensor network recharging strategy by balancing lifespan of sensor nodes," 2017 IEEE Wireless Communications and Networking Conference (WCNC), pp.1–6, San Francisco, CA, USA, 2017.

[22] H. Chang, J. Feng, C. Duan, Z. Xu, and M. Yin, "Research of recharging scheduling scheme for wireless sensor networks based on cuckoo search," 2018 International Joint Conference on Neural Networks (IJCNN), pp.1–7, Rio de Janeiro, Brazil, 2018.
[23] Z. Wei, F. Liu, X. Ding, L. Feng, Z. Lyu, L. Shi, and J. Ji, "K-CHRA: A clustering hierarchical routing algorithm for wireless rechargeable sensor networks," IEEE Access, vol.7, pp.81859–81874. http://dx.doi.org/10.1109/ACCESS.2018.2885789
[24] Y.T. Hou, Y. Shi, and H.D. Sherali, "Rate allocation and network lifetime problems for wireless sensor networks," IEEE/ACM Trans. Netw., vol.16, no.2, pp.321–334, 2008.



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