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A Smart Collaborative Charging Algorithm for Mobile Power Distribution in 5G Networks

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ABSTRACT The issues of energy supply had been widely investigated to upgrade the network lifetime, power utilization, and system stability of communication networks. However, the deployable charging solution for massive mobile terminals in 5G is still lack. Although prior studies in wireless rechargeable sensor networks focused on the energy usage effectiveness, the charging time was frequently overlooked in most schemes. In this paper, we propose a novel distributed mobile charging (DMC) algorithm to optimize the charging time and charger quantity. The traditional policies are first analyzed based on the energy source. We noticed that the location of base station is extremely significant for charging performance. Then, the details of the DMC algorithm are illustrated through the main process of energy transfer, formula deductions, and performance optimization. To further promote the network capacity, an improved algorithm named adaptive dynamic energy transfer is proposed by introducing linear node sleeping mechanism. The simulation results demonstrate that the algorithms are able to improve the charging time and charger quantity in multiple scenarios.

INDEX TERMS 5G, WRSN, charging time, mobile charging algorithm, node sleeping mechanism.

I. INTRODUCTION

Many attractive features such as ultra-large bandwidth, ultra-high capacity, ultra-dense sites and ultra-reliability are proposed in 5G. All of them cannot be achieved without the high efficient energy supply. However, the current provision mode is facing great challenges. Specifically, the issues of energy supply hinder the development of Internet of Things (IoT). Moreover, the diversity of connecting approaches is also obvious, such as NB-IoT, Zigbee, and virtual peripherals [1]. All components in IoT have a unique tag and physical property to achieve seamless integration with the information network. Although the IoT has been widely deployed in multiple areas [2], the energy problem remains unresolved completely. As the most representative member of IoT, Wireless Sensor Network (WSN) can be described by a three-tier structure (shown in Fig. 1). The bottom layer consists of a large number of scattered sensor nodes. The middle layer includes wireless access nodes (Sink), common access nodes (AP) and high-end sensor nodes. The top layer is converged by WSN-related applications. The availability of wide range parameters, such as temperature, air quality, pressure, light, etc. enables WSN to serve as a general platform for many domains [3]. Coupled with the promising technologies (SDN, ICN, NFV, etc.) [4]–[9], the data collection and processing are further developed. However, with the increase of industrial and environmental data, the energy problem has been become an important bottleneck that constrains the evolution of WSN [10]. It is unrealistic for sensor nodes to replenish energy by changing batteries in most cases. The challenge is to use energy efficiently and charge the nodes quickly.

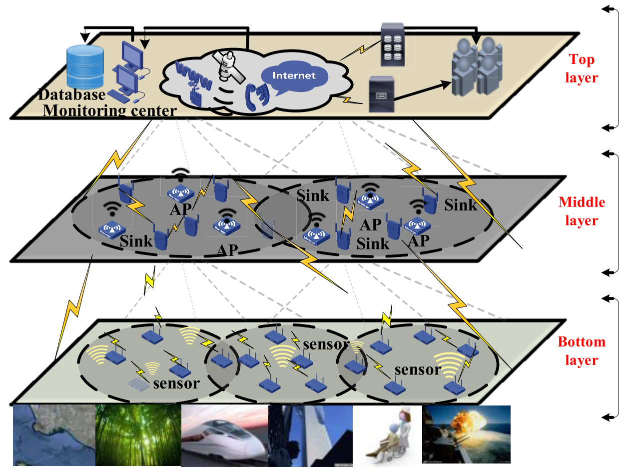

FIGURE 1. The architecture diagram of WSN.

Therefore, finding an appropriate solution in energy supply is crucial for 5G.

Recently, the emergence of WRSNs greatly unfreezes the energy limitation. A large number of charging algorithms and energy supply methods have been proposed. Normally, they can be divided into two categories: environmental energy acquisition and mobile charger charging. For the first case, sensor nodes can obtain energy from the solar, wind, vibration, etc. The basic operation principle is that the external energy sources provide power for the wireless sensor nodes through the voltage regulator circuit, while storing excess energy into the lithium-ion batteries. Thus, the methods of power supply greatly enhance the time duration for wireless sensor nodes. However, the harvest of environmental energy is often uncontrollable and unstable. Furthermore, since a variety of obsolete sensor nodes and circuit boards can trigger pollution, the numerous deployments of nodes may not be environment-friendly. For the second case, the sensor nodes can acquire energy through mobile chargers. This process promotes the time duration of battery and prolongs the network life. However, most charging algorithms mainly focused on the optimization of Charger Quantity (CQ) and energy usage effectiveness without considering the Charging Time (CT) issues. Therefore, an efficient, deployable and energy-saving algorithm is urgent needed.

Motivated by previous discussions, we focus on the CQ and CT aspects to optimize charging performances. First, a Distributed Mobile Charging (DMC) algorithm is proposed based on PSB (Push Shuttling Back). The Base Station (BS) is set in the middle of one-dimensional space. The whole network performs distributed block processing. In order to achieve the energy supply of sensor nodes, the chargers used in each part depart from BS at the same time. Finally, all chargers move back to the starting point simultaneously. Although, the charging time is optimized, the problem of node overlap is still unresolved. Therefore, the Adaptive Dynamic Energy Transfer (ADET) algorithm is proposed by combing Linear Node Sleeping Mechanism (LNSM) with DMC. Based on the simulation results, we prove that the proposed algorithm is able to improve the CQ and CT.

The contribution of this paper is as follows:

- A primary charging algorithm DMC is proposed based on PSB to shorten the charging time and decrease charger quantity.
- An improved collaborate mobile charging algorithm ADET is presented by combining the LNSM with DMC.

The rest of paper is organized as follows. In Section II,we detailed the state of the art research progress of node charging algorithms and power supply methods from different perspectives. Section III presents the principle of primary algorithm DMC and relevant mathematic proofs. In Section IV, the improved algorithm ADET is introduced by combining LNSM and DMC. We theoretically analyze the algorithm flow and performance improvement as well. Section V illustrates the simulation results. Section VI summarizes the whole paper.

II. RELATED WORK

The amount of environmental information in 5G era grows exponentially. The energy consumption of nodes has become an increasingly important issue, which restricts the development of WSN. Therefore, more scholars are attracted to investigate the energy problem of sensor nodes. Generally, the relevant works can be divided into energy supply from the natural environment, wireless charging supply by using mobile chargers and node sleeping mechanisms.

A. ENERGY SUPPLY IN THE NATURAL ENVIRONMENT

The Energy-Harvesting (EH) WSN is a distributed sensing system that consists of a number of low-cost sensor nodes. These nodes combine energy harvesting, data exploration, information aggregation, and packets transfer capabilities. By introducing the energy acquisition technology, an energy acquisition module is attached to each node in the sensor network for converting the natural power (such as wind, water, sunlight) into electrical energy and storing them in the battery. Thereby, the EH WSN receives more and more attention from academia and industry.

For the traditional heterogeneous wireless sensor networks, an efficient EH routing algorithm is considered as the key technology. In the vibration environment, a piezoelectric energy harvesting device with low and resonant frequency was designed to provide a power solution of intently self-powered WSN [11], where the authors developed an energy management module by combining a Full-Bridge Rectifier (FBR) with a voltage controller and a logic-level protection circuit for regulating the voltage of WSN. Finally, the transfer efficiency of FBR was promoted. In the solar energy environment, Mustapha and Djenouri [12] proposed an adaptive approach based on normal distribution for energy harvesting and consumption. The proposed method can accelerate fast broadcast between sensor nodes and base stations. The authors also presented a greedy policy for calculating the optimal set of time slots. Cammarano *et al.* [13] proposed an energy prediction model for providing precise estimations of future energy availability by studying the past energy observations. Voigt *et al.* [14] raised two protocols for solar-aware routing in solar energy environment, the protocols can optimize the energy-saving problems from solar power. In the radio frequency (RF) energy harvesting environment, Nguyen *et al.* [15] proposed an adaptive MAC algorithm for energy efficiency and Quality of Service (QoS). This algorithm was formed by improving the RF-AASP algorithm, where the sensor nodes can harvest RF energy from surrounding eNodeB by adjusting the sleeping period. The result showed a dramatic improvement in network throughput and energy efficiency. In other cases, an effective EH routing protocol inspired by EHARA was proposed for EH network [16], which is improved by combining a new parameter called "extra backoff." The authors focused on prolonging the lifetime of sensor nodes and solving QoS problems under the three energy harvesting techniques (i.e., solar-based EH, RF-based EH and moving vehicle-based EH). Besides that, an energy prediction model was designed for harvesting energy in sensor nodes. The energy efficiency and QoS were improved by the proposed algorithm. Michelusi and Zorzi [17] proposed a decentralized access schemes to optimize the network operation in EH WSN, the sensor nodes randomly access the channel to transmit random utility packets to a common fusion center, according to the energy level. Chen *et al.* [18] developed a HTC protocol to solve the energy supply problems between source and relay in traditional WSN, which includes three parts (AP, source and relay). Then the protocol was extended to multi-relay. Gong *et al.* [19] presented a novel EH routing protocol (AODV-EHA) for improving the energy efficiency of conventional routing protocols. Omairi *et al.* [20] mainly discussed on existing renewable energy in WSN, and analyzed MPPT and SPC-FOCV frameworks. The results of comparisons with traditional MPPT methods were also provided.

Generally, although the EH technologies from environments offer broad prospects for solving large-scale energy problems, it is uncontrollable for the changes in external factors. Therefore, adopting this method may be unreliable and unstable in some special circumstances.

B. WIRELESS CHARGING SUPPLY USING MOBILE CHARGERS

The wireless charging technology is considered as a promising solution to address the problems of limited energy in WSNs. A Mobile Charger (MC) equipped with an energy constrained battery can be applied to wirelessly charging the sensor nodes [21], [22]. Therefore, a large number of charging algorithms have been proposed in order to prompt the sensor nodes to quickly harvest energy from the mobile chargers and charge nodes efficiently.

Peng *et al.* [23] introduced a novel wireless charging system including three parts (MC, mobile robot carrying chargers and sensor nodes equipped wireless receivers) for WRSN. The experiments of the proposed scheme was validated. Two specific algorithms (i.e., Greedy algorithm and GreedyPlus algorithm) were proposed to address the specific problems. Zhang *et al.* [24] proposed a new charging scheme, named collaborative mobile charging, to improve the ratio of payload energy and overhead energy. The chargers can not only charge the sensor nodes, but also charge each other among them. Inspired by the collaborative mobile charging, the authors subsequently introduced a novel charging algorithm, i.e., PushWait in [25]. Although it can reduce the charging loss, the algorithm needs too many chargers. Therefore, Liu *et al.* [26] introduced a novel charging concept called ISC, which utilized the least number of chargers. A selection algorithm was presented for determining the priority of sensors recharging in WRSN [27], which enabled network energy utility maximization. He *et al.* [28] proposed an on-demand mobile charging algorithm by introducing the Nearest-Job-Next with preemption disciplines. The sensor nodes should initiatively send a charging request to the charger when their energy is low. This algorithm is more efficient comparing with previous approaches. In [29], a Dynamic Path Generation Scheme (DPG-Scheme) was introduced to control the traveling path of wireless charging vehicles. The lifetime of WSN was prolonged and energy consumption was optimized. Similarly, Chen *et al.* [30] proposed a geometric routing protocol, i.e., GR-Protocol, to arrange the traversing path of wireless charging vehicles. Compared with DPG-Scheme, this scheme not only optimizes the energy consumption, but also reduces the computation time during the optimal path finding. Xu *et al.* [31] designed a partial energy charging algorithm by scheduling the mobile chargers to charge life-critical sensors without charging a sensor to full energy capacity. The sum of sensor lifetime was maximized in WSN. In [32], a primary and passer-by scheduling algorithm (P^2S) was proposed in on-demand charging architecture to improve energy utility ratio by scheduling problem of spatial and temporal tasks.

In general, most of algorithms focused on energy efficiency, energy consumption, charger quantity and route planning, without considering the CT problem. Therefore, the algorithms of node charging are not comprehensive enough.

C. NODE SLEEPING MECHANISM

Since the sensor nodes are randomly distributed in unattainable areas, the effective management is hard to be guaranteed. In most cases, the node sleeping mechanism can enhance the energy utilization and reduce unnecessary losses by closing the redundant components.

Li *et al.* [33] focused on the pollution source positioning and water quality monitoring based on the GAF routing algorithm in WSN system. Through the use of GAF algorithm which is a clustering algorithm according to the geographical locations of nodes, the environment pollution is prevented and the water resources are protected. Tan and Viet [34] introduced a sleep scheduled and tree-based clustering approach routing algorithm (SSTBC) to improve energy efficiency and remove redundant data by turning off radio of superfluous nodes, where the BS was used for sleep scheduling and cluster division. A novel partial coverage algorithm (PCLA) was proposed based on learning automata to find the minimum number of sensors for prolonging the lifetime of WSN [35]. The proposed method utilized the learning automata to schedule the sensors into active or inactive state. Pradeebaa and Lavanis [36] focused on two algorithms (ENS_OR and GeRaF) to improve network lifetime by using the node sleeping mechanism, where the concept of wakeup alarm was inserted into the sleep node concept for controlling the dormant time. From [37], we noticed that a geographical adaptive routing algorithm based on overlapping area (GAOA) was raised to monitor the uranium tailings radioactive pollution. The optimal next hop can be selected to transmit data. In [38], the author introduced an energy-saving optimization coverage algorithm by using the nodes sleep scheduling mechanism. The proposed algorithm improved the energy efficiency according to network coverage ratio, residue energy and redundant degree.

III. PRIMARY DMC ALGORITHM

According to the previous discussions, we found that the proposed algorithms, such as PushWait, ISC, PSB, DBP-PSB, prefer to start the charger from the leftmost BS. Therefore, when the number of sensor nodes increases exponentially, the round trip time of chargers will be longer. This mechanism will lead to the inefficient charging process in WSN. More seriously, when the energy of sensors is used up, the charging signal will be generated. Due to the long round trip time, the node had been shut down when the charger approaches to it, which will definitely affect the data collection of WSN.

In this section, we mainly introduce the primary charging algorithm DMC. First, we briefly analyze the heuristic algorithm PSB. Then the DMC algorithm is presented and the optimization of charging time is theoretically proved.

A. PUSH-SHUTTLING-BACK ALGORITHM

Previous researchers have proven that it's contradictory to reduce the charger number and energy consumption simultaneously. To handle this challenge, PSB algorithm selects similar actions with the ISC algorithm [26]. The sensor nodes are charged to $b/2$ (b is the battery capacity of each sensor node) respectively during the Push and Back process. Finally, the authors concluded that the number of chargers is relatively small, the moving distance of chargers is relatively short, and the energy consumption was optimized. Accordingly, the value of L (L is where the chargers exchange energy) was changed dynamically. The PSB algorithm can be divided into three steps (Push, Shuttling and Back).

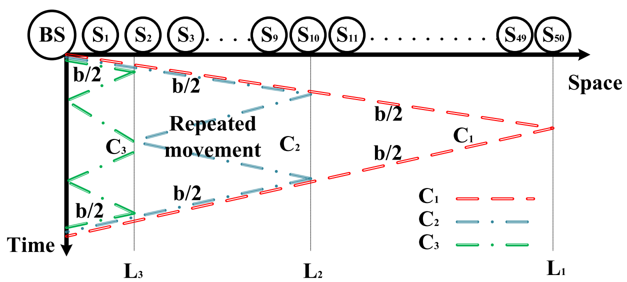

FIGURE 2. The flowchart of PSB algorithm.

As shown in Fig 2, we consider a sensor network scenario including N nodes evenly distributed along a one-dimension straight line. We assume that the distance between two sensors is one unit. The sensors are labeled as $S_1 \ldots S_N$. The chargers are labeled as $C_1 \ldots C_k$. The chargers exchange power at L_i. The algorithm defines that the charger C_i charges $C_{i-1} \ldots C_1$ at L_i and C_i charges the sensor nodes at $L_i \ldots L_{i+1}$. The specific process is as follows:

- 'Push' phase: all sensor nodes are scattered over a one-dimensional space. All chargers start at BS with full power, charger C_i consumes b/2 power to charge the sensor nodes at $L_i \ldots L_{i+1}$, then charges $C_{i-1} \ldots C_1$ at L_i for pushing other chargers to further distance.
- 'Shuttling' phase: The charger C_i makes circular reciprocating motion at $L_i \ldots L_{i+1}$ to charge other chargers returning back L_i.
- 'Back' phase: when other chargers return to L_i, the power of them is 0. The charger C_i makes circular reciprocating motion at $L_i \ldots L_{i+1}$ like Shuttling phase, which makes other chargers have enough power to return to L_{i+1}. Finally, all chargers back to BS.

By the final calculation, the authors gave the farthest distance that each charger can move away from the BS is

$$\begin{cases} L_K = \dfrac{B}{(K+1)c + b/2} \\ L_i = \sum_{j=i}^{K} \dfrac{B}{(j+1)c + b/2} \\ L_1 = \sum_{j=2}^{K} \dfrac{B}{(j+1)c + b/2} + \dfrac{B}{2c+b} \end{cases} \tag{1}$$

The number of shuttling for C_i between L_i and L_{i+1} can be calculated as follows:

$$\begin{cases} NS_1 = 0, \\ NS_2 = 1, \\ NS_i = \left\lceil \dfrac{NS_{i-1} \cdot B}{B - 2c(L_i - L_{i+1})} \right\rceil + 1, \quad 2 < i < K \\ NS_k = \left\lceil \dfrac{NS_{k-1} \cdot B}{B - 2cL_k} \right\rceil + 1. \end{cases} \tag{2}$$

However, the PSB algorithm did not consider the CT problem. As sensors continue to grow in scale, CT may severely impact the charging performance of system. While the proposed primary algorithm (DMC) aims to solve this issue.

B. DISTRIBUTED MOBILE CHARGING ALGORITHM

In order to optimize the charging time, we propose the DMC algorithm. Our basic idea is to place the BS in the center of the one-dimension space, which divides the space into two areas. According to the needs of the sensor nodes, the two regions are assigned corresponding chargers. The same-capacity chargers at the BS are fully charged, then start from BS for charging sensor nodes. The general process of charging is the same as PSB algorithm. Finally, all chargers return to the BS simultaneously. This DMC algorithm changes the original serial charging time to parallel charging time, which saves the costs by approximately fifty percent, improves the energy efficiency and reduces the number of chargers.

In this part, we assume that the charging process is fully exchanged without loss. We theoretically set the parameters of WRSN and the prerequisites are similar to the PSB algorithm. We consider the N sensor nodes are distributed along the one-dimension straight line. The BS is located at the center of line (show as in Fig 3), the distance between two adjacent nodes is one unit. There are K chargers, the C_i is denoted as the ith mobile charger, the S_i is labeled as the ith sensor node, b is denoted as the total power of sensors, and B stands for the total power of chargers, the two areas of one-dimension space is divided into a number of segments, as labeled by $L_m, L_{m-1} \ldots L_1$, L_i is the farthest distance that

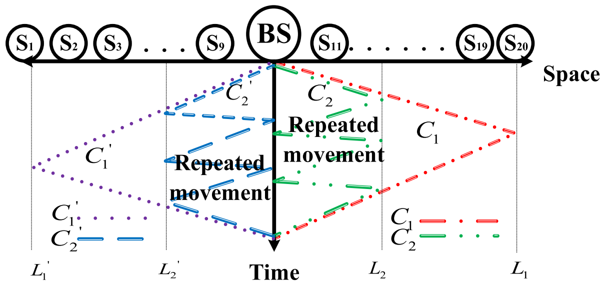

FIGURE 3. The flowchart of DMC algorithm.

C_i moves away from BS, c is denoted as the unit path loss of charger moving. The ultimate goal of the DMC algorithm is to use the fewest chargers, achieve the least charging time and improve the charging efficiency. The process of the proposed algorithm includes three phases:

- 'Push' phase: the chargers in both areas start from BS with the full power. Take one side as an example, the charger C_i can also get charged at $L_m \ldots L_{i+1}$, by chargers $C_k \ldots C_{i+1}$. The charger C_i is responsible for charging the sensor nodes between L_i and L_{i+1}. In order to achieve the optimization of the number of chargers and path consumption, C_i only charges the sensors with $b/2$ power. The remaining energy is used for charging the other chargers at L_i, nodes and chargers in 'Back' phase. The half-charging approach has been proved that the charger quantity and path loss are optimized. When C_i reached L_i, it will charge $C_{i-1} \ldots C_1$ at L_i, so that they can be pushed further to the $L_{i-1} \ldots L_1$. The remaining power of them can be enough to return to L_i.

  As we all know, the position of L_i is very important for improving performances, which is related with the number of chargers. During the 'Push' phase, the charger C_i can get fully charged at L_{i+1}. When arriving at L_i, the energy consumption of C_i includes the following parts: the energy loss for travelling from L_{i+1} to L_i, the energy for charging other chargers at L_i, the energy for half-charging sensor nodes between L_{i+1} and L_i. We assume that $k/2$ chargers are used for each part of the two areas. Therefore, the charger capacity B is expressed as follows:

$$\begin{cases} B = 2c\left(L_1 - L_2\right) + b\left(L_1 - L_2\right), \\ B = (1+i)\,c\left(L_i - L_{i+1}\right) + (b/2)\left(L_i - L_{i+1}\right), \\ B \geq \left(1 + \dfrac{K}{2}\right) c\left(L_m - 0\right) + (b/2)\left(L_m - 0\right). \end{cases} \tag{3}$$

  or

$$\begin{cases} B = 2c\left(L_1' - L_2'\right) + b\left(L_1' - L_2'\right), \\ B = (1+i)\,c\left(L_i' - L_{i+1}'\right) + (b/2)\left(L_i' - L_{i+1}'\right), \\ B \geq \left(1 + \dfrac{K}{2}\right) c\left(L_m' - 0\right) + (b/2)\left(L_m' - 0\right). \end{cases} \tag{4}$$

  In addition, the maximum distance which each charger can move away from the BS should be calculated. We assume that there are $k/2$ chargers in each part of both areas, we can calculate the energy consumption of the unit length, and then the farthest distance from BS can be given by using the formula (5) and (6).

$$\begin{cases} L_{\frac{K}{2}} = \dfrac{B}{(\dfrac{K}{2}+1)c + b/2} \\ L_i = \sum_{j=i}^{\frac{K}{2}} \dfrac{B}{(j+1)c + b/2} \\ L_1 = \sum_{j=2}^{\frac{K}{2}} \dfrac{B}{(j+1)c + b/2} + \dfrac{B}{2c+b} \end{cases} \tag{5}$$

  or

$$\begin{cases} L_{\frac{K}{2}}' = \dfrac{B}{(\frac{K}{2}+1)c + b/2} \\ L_i' = \sum_{j=i}^{\frac{K}{2}} \dfrac{B}{(j+1)c + b/2} \\ L_1' = \sum_{j=2}^{\frac{K}{2}} \dfrac{B}{(j+1)c + b/2} + \dfrac{B}{2c+b} \end{cases} \tag{6}$$

- 'Shuttling' phase: After the charger C_i charges other chargers $C_{i-1} \ldots C_1$ at L_i, C_i needs to return to L_{i+1} for getting recharged by C_{i+1}. When C_i carries more energy back to L_i, it also consumes some energy for travelling. Since it will not be one-time charging for C_i, C_i needs to do reciprocating multiple motion between L_i and L_{i+1} until C_{i-1} is fully charged. After C_i charges C_{i-1}, it leaves enough energy to go back to L_{i+1}. In the 'Back' phase, C_i also needs to do the same process so that the other chargers can return to L_{i+1} at the same time. Because of the reciprocating motion for charging, the number of the chargers used in WRSN will be reduced accordingly.

  In the 'Shuttling' phase, the total energy which C_i gets from L_{i+1} through reciprocating movement consists of four parts: the energy for path consumption of shuttling, the energy for C_{i-1} being charged at L_i, the energy for $C_{i-1} \ldots C_1$ to back to L_{i+1} and the energy for half-charging sensor nodes. Therefore, we can get the number of shuttling based on formula (3), which is shown in formula (7).

$$\begin{cases} NS_1 = 0, \\ NS_2 = 1, \\ NS_i = \left\lceil \dfrac{NS_{i-1} \cdot B}{B - 2c\left(L_i - L_{i+1}\right)} \right\rceil + 1, \quad 2 < i < \dfrac{K}{2} \\ NS_{\frac{K}{2}} = \left\lceil \dfrac{NS_{\frac{K}{2}-1} \cdot B}{B - 2cL_{\frac{K}{2}}} \right\rceil + 1. \end{cases} \tag{7}$$

or

$$\begin{cases} NS'_1 = 0, \\ NS'_2 = 1, \\ NS'_i = \left\lceil \dfrac{NS'_{i-1} \cdot B}{B - 2c\left(L'_i - L'_{i+1}\right)} \right\rceil + 1, \quad 2 < i < \dfrac{K}{2} \\ NS'_{\frac{K}{2}} = \left\lceil \dfrac{NS'_{\frac{K}{2}-1} \cdot B}{B - 2cL'_{\frac{K}{2}}} \right\rceil + 1. \end{cases} \tag{8}$$

It can be proved that although the number of chargers is decreased, the path loss also increases due to the greater number of reciprocations. So, it is crucial to balance the relationship between the number of chargers and the path loss.

- 'Back' phase: when $C_{i-1} \ldots C_1$ return to L_i, the energy of them is zero. C_i will charge these chargers by reciprocating movement to make them back to L_{i+1}, and half-charge the sensor nodes. Similarly, for C_i, it will get recharged at $L_m \ldots L_{i+1}$ to have enough power back to BS.

In short, the 'Push' process means that charge other chargers to move further, the 'Shuttling' process means that the chargers make reciprocating movement to charge other chargers, the 'Back' process means that the chargers get recharged in the corresponding location to return back to the BS.

C. PERFORMANCE OPTIMIZATION

Through the theoretical analysis of the DMC algorithm, we can estimate that the proposed algorithm improves two parameters, i.e., the charging time of mobile chargers and the number of chargers. We suppose that all the sensor nodes in the WRSN are identical and have the equal energy, the distance between the two adjacent sensor nodes is one unit. In addition, the energy conversion time between the chargers is much less than between the charger and sensor nodes.

Compared with PSB algorithm, the DMC algorithm reduces the charging time by approximately half and decreases the number of chargers. In the PSB algorithm, L_1 is the longest distance that charger C_1 moves for charging the sensor nodes, and the largest scale in the one-dimension network. The average moving speed of mobile chargers is v. Therefore, the total charging time by using the PSB algorithm is:

$$t = \frac{2L_1}{v} \tag{9}$$

However, the DMC algorithm divides the network range into two parts. The required charging time for the whole process is equal to the time for parallel unidirectional charging time. The charging round-trip time of the DMC algorithm is half of the time by utilizing the PSB algorithm, namely:

$$t_1 = \frac{t}{2} \tag{10}$$

Therefore, the DMC algorithm reduces the charging time of the WRSN by about half.

Additionally, for the number of chargers, we only have to consider the number of single-side chargers when the network range is divided equally. From the formula (1), we can see that the charging distance of one side is:

$$L'_1 = \frac{L_1}{2} = \frac{1}{2}\left(\sum\nolimits_{j=2}^{K} \frac{B}{(j+1)c + b/2} + \frac{B}{2c+b}\right) \tag{11}$$

After transformation:

$$L'_1 = \frac{L_1}{2} = \frac{1}{(2K+2)\,c+b} + \frac{1}{2Kc+b} + \frac{1}{(2K-2)\,c+b} + \cdots + \frac{B}{4c+2b} \tag{12}$$

Next, we calculate the distance that $k/2$ mobile chargers can move:

$$L''_1 = \frac{B}{\left(\frac{K}{2}+1\right)c + b/2} + \frac{B}{\frac{K}{2}c + b/2} + \frac{B}{\left(\frac{K}{2}-1\right)c + b/2} + \cdots + \frac{B}{2c+b} \tag{13}$$

By comparing the formula (12) and (13), we can see:

$$\frac{B}{\left(\frac{K}{2}+1\right)c + b/2} + \cdots + \frac{B}{2c+b} \succ \frac{1}{(2K+2)\,c+b} + \cdots + \frac{B}{2c+b} \tag{14}$$

Namely:

$$L''_1 \succ L'_1 = \frac{L_1}{2} \tag{15}$$

Therefore, the charging distance by using $k/2$ chargers is greater than $L_1/2$, in other words, the number of sensors to transmit $L_1/2$ length is less than $k/2$. The number of sensors by using DMC algorithm is satisfied:

$$K_1 \prec K \tag{16}$$

In summary, the DMC algorithm compared with other charging algorithms shortens the charging time, reduces the number of chargers and lowers energy consumption. However, there are a variety of redundant nodes, which require charging for them. Therefore, a node sleeping mechanism is urgently found to solve above problems. The improved DMC algorithm (ADET algorithm) will be introduced in the next section.

IV. IMPROVED ADET ALGORITHM

For the shortage of DMC algorithm, we propose an improved DMC charging algorithm called ADET algorithm (i.e., adaptive dynamic energy transfer algorithm) that combines the proposed linear node sleeping mechanism and DMC algorithm. In this algorithm, the sensor nodes can dynamically adjust their working status to form a new network topology according to the network state.

In this part, we first introduce the linear node sleeping mechanism (LNSM) based on GAF algorithm and briefly discuss the principle of LNSM. Afterwards, we analyze the working process of ADET algorithm in detail, and finally we prove the performance optimization through the theoretical analysis.

A. LINEAR NODE SLEEPING MECHANISM

Although there are many node sleeping algorithms, few researchers have considered the combination with the charging algorithms. The existing sleeping algorithms contain GAF, GeRaF, RS, LDS, RPA and ASCENT algorithms.

We propose a linear node sleeping mechanism inspired by the two-dimension sleeping algorithm GAF, it is an adaptive clustering algorithm based on the geographical location of the sensor nodes. The adaptive mechanism affects the network topology by turning on or off certain nodes in the network. When an event occurs, the node turns off the radio frequency module to sleep. The main aim is to solve the switching problem between sleeping and active of nodes. A sensor node can sense its own position in the network and deploy itself in corresponding segments of the network according to their own geographical location information. At the same time, the final topology must ensure that any two nodes can communicate with each other.

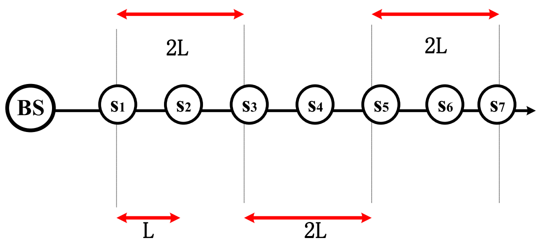

FIGURE 4. The schematic diagram of Linear Sleep algorithm.

As shown in Fig 4, we only consider one side of the scenario. We assume that the sensing range of the nodes is L. So, the ultimate distance between any two sensor nodes in a one-dimension space is $2L$, that is, within a distance of $2L$, two sensors can collect the maximum of data in this range. The algorithm considers that the nodes in the same segment are equivalent and mutually redundant, and the information they collect is similar. Therefore, two nodes with the largest distance value in the range of $0 \leq l \leq 2L$ are selected as active nodes. All sensor nodes between the two nodes are automatically hibernated. Thus, the LNSM saves the power of sensor nodes and improves network efficiency.

In a sensor network, turning off redundant nodes and only retaining partial nodes are an energy-saving method. From the level of protocol, redundant nodes have no special effect in future network applications. They are neither data source nodes nor sink nodes. From the level of routing, the adjacent nodes are identical and can replace each other. So, we only utilize part of nodes. Turning off equivalently redundant nodes is necessary for conserving energy. At the same time, the LNSM reduces unnecessary energy loss, indirectly decreases the number of chargers. Therefore, it is crucial to incorporate sleeping mechanisms in the charging algorithm.

B. ADAPTIVE DYNAMIC ENERGY TRANSFER ALGORITHM

In this section, we propose ADET algorithm based on DMC algorithm, which combines the DMC algorithm with the LNSM. The sensor nodes can dynamically change its own state according to the network conditions. Thus flexibly changing the topology of the network can avoid unnecessary waste of resources. After the nodes are automatically distributed, the network nodes can periodically learn their positions and determine whether they need to sleep according to their own geographical position. After that, the chargers charge the network devices according to the DMC algorithm. The results show that the proposed algorithm optimizes the CT and CQ problems.

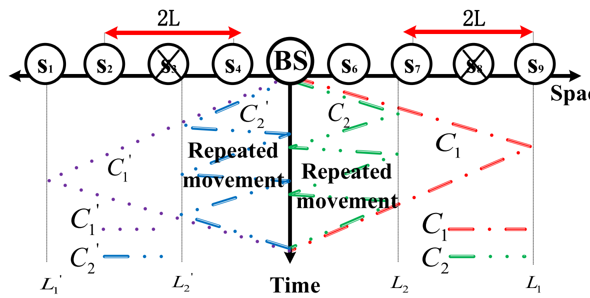

FIGURE 5. The schematic diagram of ADET algorithm.

In this part, we assume that the energy is fully exchanged without loss. We set the parameters of WRSN, the prerequisites are similar to the DMC algorithm. We consider that the N sensor nodes are distributed along the one-dimension straight line. The BS is located at the center of line (show as in Fig 5), the distance between two adjacent nodes is one unit. There are K chargers, then the C_i is denoted as the ith mobile charger, the S_i is labeled as the ith sensor node, b stands for the total power of sensors, and B is denoted as the total power of chargers, the two areas of one-dimension space are divided into a number of segments, as labeled by $L_m, L_{m-1} \ldots L_1$, L_i is the farthest distance that C_i moves away from BS, c is denoted as the unit path loss of chargers. The object of the ADET algorithm is to use the fewest chargers, decrease the CT. We only consider one side of the situation. The general process of the proposed algorithm contains four parts, i.e., 'Nodes Sleeping', 'Push', 'Shuttling' and 'Back'.

- 'Nodes Sleeping' phase: after the network is initialized, the nodes announce their locations and IDs by sending a message. The the nodes learn the information of other nodes in the same scope by collecting the information. After some nodes are randomly distributed in the initial network, the sensor nodes can dynamically adapt to the network and judge whether the sleeping operation is required. The redundant nodes are shut down in the same line segment, as shown in Fig 6. Finally, the DMC algorithm is used for forming a low-redundancy and efficient network topology to reach a steady state.
- 'Push' phase: this process is similar to the DMC algorithm. The mobile charger C_i charges other chargers to

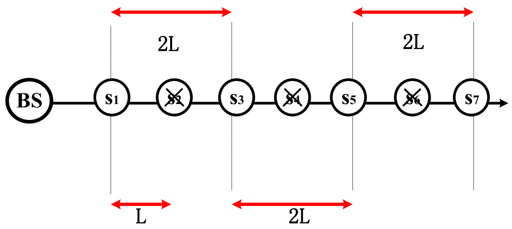

FIGURE 6. The state diagram of closing the redundant nodes.

move further at L_i and half-charges the sensor nodes between L_i and L_{i+1}. Part of the energy is used for the path loss. In addition, the energy consumption of C_i still include the three parts: the energy loss for travelling from L_{i+1} to L_i, the energy for charging other chargers at L_i, the energy for half-charging sensor nodes between L_{i+1} and L_i. Therefore, the total power of chargers B is expressed as follows:

$$\begin{cases} B = 2c\left(L_1 - L_2\right) + b\dfrac{\left(L_1 - L_2\right)}{2L}, \\ B = (1+i)\,c\left(L_i - L_{i+1}\right) + (b/2)\,\dfrac{\left(L_i - L_{i+1}\right)}{2L}, \\ B \geq \left(1 + \dfrac{K}{2}\right)c\left(L_m - 0\right) + (b/2)\,\dfrac{\left(L_m - 0\right)}{2L}. \end{cases} \tag{17}$$

or

$$\begin{cases} B = 2c\left(L'_1 - L'_2\right) + b\dfrac{\left(L'_1 - L'_2\right)}{2L}, \\ B = (1+i)\,c\left(L'_i - L'_{i+1}\right) + (b/2)\,\dfrac{\left(L'_i - L'_{i+1}\right)}{2L}, \\ B \geq \left(1 + \dfrac{K}{2}\right)c\left(L'_m - 0\right) + (b/2)\,\dfrac{\left(L'_m - 0\right)}{2L}. \end{cases} \tag{18}$$

So, the farthest distance from chargers to BS can be calculated. We similarly assume that there are $k/2$ chargers in each part of both areas, we can calculate the energy consumption of the unit length, and then the farthest distance from BS can be given, as the formula shows:

$$\begin{cases} L_{\frac{K}{2}} = \dfrac{2LB}{(\frac{K}{2}+1)2Lc + b/2} \\ L_i = \sum_{j=i}^{\frac{K}{2}} \dfrac{2LB}{(j+1)2Lc + b/2} \\ L_1 = \sum_{j=2}^{\frac{K}{2}} \dfrac{2LB}{(j+1)2Lc + b/2} + \dfrac{2LB}{4Lc + b} \end{cases} \tag{19}$$

or

$$\begin{cases} L'_{\frac{K}{2}} = \dfrac{2LB}{(\frac{K}{2}+1)2Lc + b/2} \\ L'_i = \sum_{j=i}^{\frac{K}{2}} \dfrac{2LB}{(j+1)2Lc + b/2} \\ L'_1 = \sum_{j=2}^{\frac{K}{2}} \dfrac{2LB}{(j+1)2Lc + b/2} + \dfrac{2LB}{4Lc + b} \end{cases} \tag{20}$$

Therefore, we can easily see that the ADET algorithm is more efficient than the DMC algorithm.

- 'Shuttling' phase: the charging process of ADET algorithm is similar to the DMC algorithm in this phase, i.e., the chargers make reciprocating movement to charge other chargers and half-charge the sensor nodes from L_i to L_{i+1}. The total energy which C_i gets from L_{i+1} consists of four parts: the energy for path consumption, the energy for C_{i-1} being charged at L_i, the energy for $C_{i-1} \ldots C_1$ backing to L_{i+1} and the energy for half-charging sensor nodes. Therefore, we can have:

$$NS_i \cdot B = NS_i \cdot 2c\left(L_i - L_{i+1}\right) + NS_{i-1} \cdot B + (i-1)\,c\left(L_i - L_{i+1}\right) + \frac{(b/2)\left(L_i - L_{i+1}\right)}{2L} \tag{21}$$

Next:

$$NS_i = \frac{NS_{i-1} \cdot B}{B - 2c\left(L_i - L_{i+1}\right)} + \frac{\left((i-1)\,2Lc + b/2\right)\left(L_i - L_{i+1}\right)}{\left(B - 2c\left(L_i - L_{i+1}\right)\right) \cdot 2L} \tag{22}$$

From formula (17), we can see:

$$B = (1+i)\,c\left(L_i - L_{i+1}\right) + (b/2)\,\frac{\left(L_i - L_{i+1}\right)}{2L} \tag{23}$$

Then, we can get:

$$\begin{cases} NS_1 = 0, \\ NS_2 = 1, \\ NS_i = \left\lceil \dfrac{NS_{i-1} \cdot B}{B - 2c\left(L_i - L_{i+1}\right)} \right\rceil + 1, \quad 2 < i < \dfrac{K}{2} \\ NS_{\frac{K}{2}} = \left\lceil \dfrac{NS_{\frac{K}{2}-1} \cdot B}{B - 2cL_{\frac{K}{2}}} \right\rceil + 1. \end{cases} \tag{24}$$

or

$$\begin{cases} NS'_1 = 0, \\ NS'_2 = 1, \\ NS'_i = \left\lceil \dfrac{NS'_{i-1} \cdot B}{B - 2c\left(L'_i - L'_{i+1}\right)} \right\rceil + 1, \quad 2 < i < \dfrac{K}{2} \\ NS'_{\frac{K}{2}} = \left\lceil \dfrac{NS'_{\frac{K}{2}-1} \cdot B}{B - 2cL'_{\frac{K}{2}}} \right\rceil + 1. \end{cases} \tag{25}$$

It is a fact that NS_i, L_i and other parameters involved in this part are completely different from the formula (7) and (8). Their inferences are based on different formulas. Thus, what they represent is different.

- 'Back' phase: the responsibility of charger C_i mainly includes two aspects, i.e., half-charging the sensor nodes from L_i to L_{i+1} and charging the other chargers for backing to L_{i+1}. The specific process is similar to the DMC algorithm.

In summary, the overall performances of the ADET algorithm are better than the DMC algorithm. As the number of sensor nodes decreases, the number of chargers is lowered, which avoids the redundant charging process.

C. PERFORMANCE OPTIMIZATION

The basic principle of ADET algorithm is to promote the CT and CQ problems by introducing the node sleeping mechanism. Compared with the DMC algorithm, the ADET algorithm mainly enhances the CQ. The specific proof is shown as follows.

In terms of CQ, we only need to validate the performance based on the one side of network. We similarly assume that there are $k/2$ chargers in single side of area. From the formula (19), we can get:

$$L_i = \sum_{j=i}^{\frac{K}{2}} \frac{2LB}{(j+1)2Lc + b/2} \tag{26}$$

Thus, we have

$$L_i = \sum_{j=i}^{\frac{K}{2}} \frac{B}{(j+1)c + b/4L} \tag{27}$$

We assume that the farthest distance that C_i moves away from BS in DMC algorithm is L_i'', we can get the value of L_i'' from the formula (5)

$$L_i'' = \sum_{j=i}^{\frac{K}{2}} \frac{B}{(j+1)c + b/2} \tag{28}$$

By comparing the formula (27) and (28), we can see

$$\sum_{j=i}^{K} \frac{B}{(j+1)c + b/4L} \succ \sum_{j=i}^{K} \frac{B}{(j+1)c + b/2} \tag{29}$$

Namely

$$L_i \succ L_i'' \tag{30}$$

Thus, we can conclude that the ADET algorithm requires the least number of chargers for the same network scale.

In conclusion, we can see that, the DMC algorithm compared with PSB, ISC and other algorithms saves more time and reduces the number of chargers. However the ADET algorithm incorporating the LNSM utilizes less mobile chargers than DMC algorithm.

For the Coverage Efficiency (CE) problem, since two or more sensor devices in a target area are close to each other, the data they perceive will be very similar. In addition, as each of them conveys data to the BS, this results in a variety of redundant data in BS. We define the CE formula as

$$CE(i,j) = \frac{r}{kd_{i,j}} \tag{31}$$

In the formula (31), $d_{i,j}$ represents the Euclidean distance between s_i and s_j, r stands for the perceiving distance of the sensor nodes, and k means the controlling parameter to adjust the value of CE in the range of (0,1).

In terms of DMC algorithm, r is $2L$ and $d_{i,j}$ is the unit distance. While, for the ADET algorithm, r is $2L$, $d_{i,j}$ becomes $2L$. Therefore, according to the theoretical analysis, the ADET algorithm is $2L$ times better than the DMC algorithm in terms of CE, i.e.,

$$CE_{ADET}(i,j) = \frac{1}{2L} CE_{DMC}(i,j) \tag{32}$$

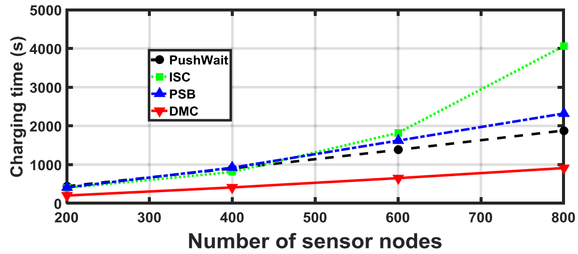

FIGURE 7. The result graph of CT between DMC and other three algorithms.

In summary, the ADET algorithm optimizes the CQ and CE, which performs better than the DMC algorithm due to incorporate the linear node sleeping mechanism. This section is only a theoretical proof of the optimization algorithm, then we will further discuss the optimal characteristics of the ADET algorithm based on the actual simulation.

V. PERFORMANCE EVALUATION

In this section, the experimental topology is established by simulation tools, and the proposed algorithms are evaluated and verified. We firstly set the parameters of the simulation, then analyze the results on CT and CQ problems respectively.

A. SIMULATION SETUP

The experimental topology is divided into four network scenarios. All sensor nodes are evenly distributed in a one-dimension network environment. The chargers travel uniformly when charging the sensor nodes, and there exists time delay when the power is converted between the chargers. The specific parameters are set as shown in Table 1.

TABLE 1. Simulation parameters.

Symbol	Parameter	Value
N	Sensor nodes quantity	200/400/600/800
$b\ (J)$	Total power of nodes	10
$B\ (J)$	Total power of chargers	1000
$V\ (m/s)$	Moving speed of chargers	1
$c\ (J/m)$	Unit path loss	1
$\varepsilon\ (m)$	Redundancy of ISC algorithm	200
t (s)	Energy transfer time between chargers	10
$l\ (m)$	Perceiving range of sensor nodes	10

B. RESULTS OF DMC AND PREVIOUS ALGORITHMS COMPARISON

In this section, we compare the DMC algorithm with PushWait, ISC and PSB algorithms in terms of the CQ and CT. In the four different network scales (i.e., 200, 400, 600, 800 sensor nodes). As shown in Fig 7, comparing with the other three algorithms, the simulation results reveal that the proposed DMC algorithm consumes the shortest charging time, i.e., 200s, 410s, 650s, 910s. The charging time is almost half of the other charging algorithms. The DMC algorithm coverts the original serial charging time into parallel processing time. In other words, the original method of calculating time is changed to parallel calculation. While the ISC algorithm utilizes the least number of chargers, the moving distance is increased exponentially and charging time is longer due to the a large number of repeated 'Shuttling' processes. Therefore, the performance of ISC is the worst. For PushWait algorithm, it also has the weak performance on charging time because of the vast waiting time. In addition, as the network scale continues to enlarge, the charging time of other algorithms increases exponentially. In contrast, the growth rate of charging time for DMC algorithm is relatively stable.

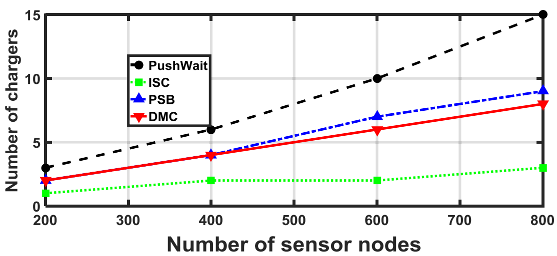

FIGURE 8. The result graph of CQ between DMC and other three algorithms.

For charger quantity, the ISC uses the least number of chargers, as shown in Fig 8. However, the results reveal that the ISC algorithm is not the best choice for charging sensor nodes due to its long charging time. If the ISC algorithm is not available, the DMC algorithm utilizes the least chargers for WRSN than PushWait algorithm and PSB algorithm. When values in X axis are smaller than 400, the DMC and PSB utilize the same number of changers. Considering the CT and CQ, the DMC algorithm is practical and feasible to deploy. The number of chargers is decreased by 33% compared with the PushWait algorithm, and 11% compared with PSB algorithm. It is ineffective and impractical for PushWait to be considered to charge sensor nodes in WRSN. In fact, the number of chargers continues to exponentially grow with increasing sensor nodes by using PushWait algorithm.

In summary, the DMC algorithm is better than the PushWait algorithm, ISC algorithm and PSB algorithm in terms of CT and the CQ. This distributed approach is effective and feasible, in terms of improving charging efficiency, promoting the system stability, and attaching a positive effect on the development of WRSN.

However, as we mentioned earlier, the distribution of sensor nodes is random, and the coverage of a large number of nodes is overlapped. The introduction of node sleeping mechanism decreases the unnecessary waste of energy, improves the charging efficiency on the basis of the previous algorithms, and increases the energy availability. Therefore, we will further analyze the advantages and performance of the ADET algorithm through the simulation results.

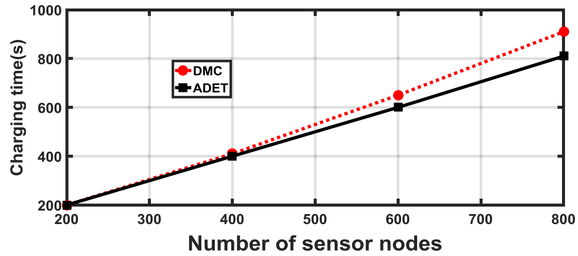

FIGURE 9. The comparison of CT between ADET and DMC.

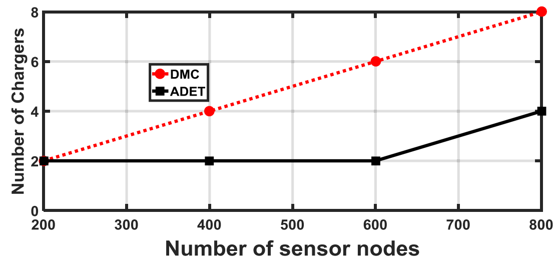

FIGURE 10. The comparison of CQ between ADET and DMC.

C. RESULTS BETWEEN ADET ALGORITHM AND DMC ALGORITHM

Based on DMC algorithm, we combine the LNSM mechanism with original procedures. The concrete results are shown in Fig 9. Compared with DMC algorithm, the charging time of ADET algorithm is 200s, 400s, 600s, 810s, which is approximately 7.3% lower. The ADET algorithm consumes the least charging time among the five algorithms. In different scales of WRSNs, with the increasing number of sensor nodes and energy consumption, the number of dormant nodes is also increasing. Therefore, the ADET saves the charging time and the performance of ADET algorithm is optimal.

TABLE 2. Simulation results.

Method	CQ	CT
PUSH-WAIT	H++	L
ISC	H+	L++
PSB	H	L+
DMC	S	F
ADET	S+	F+

H++=extremely high, H+=very high, H=high, S+=very small, S=small, L++=extremely long, L+=very long, L=long, F+=very fast, F=fast.

For the CQ validations, since a large number of redundant nodes are dormant, the chargers save a lot of energy, which reduces the charger number by using the ADET algorithm. From Fig 10, the result shows that the CQ of chargers used in ADET algorithm is reduced by about 50% compared with the DMC algorithm. If the network size is between 200 and 600 nodes, the result shows that the CQ of the ADET algorithm is invariable. With the extension of the network, the CQ of ADET algorithm will increase.

In summary, the ADET algorithm we proposed is optimal in terms of CT and CQ comparing with the other algorithms.

We not only adopt the idea of distributed computing, but also introduce the LNSM mechanism to the charging algorithm. We provide the comparison results in Table 2.

VI. CONCLUSION

The 5G era is coming with the urgent needs of effective energy supply. In this paper, we investigated the existing power provision modes (PushWait, ISC, PSB, etc.) of WRSNs in detail. For the CT and CQ issues, we firstly propose a primary charging algorithm DMC. The base station is located at the center of network to divide the space into two areas, which changes the original serial charging time to parallel charging time. Then the specific theoretical deduction and validation are addressed. To further consider the redundancy problem of sensor nodes, the ADET algorithm is introduced by combining the linear node sleeping mechanism with DMC. It is able to save plenty of energy and improve the charging efficiency. Comparing with traditional algorithms, the simulation results show that both the CT and CQ of DMC algorithm are decreased by 50% and 11%, respectively. In addition, these two parameters can be further reduced (about 7.3% and 50% respectively) when the ADET algorithm is utilized.

The power supply issues seriously hinder the development of 5G networks. An excellent charging algorithm plays a vital role in multiple stages of network applications. In the future, the two-dimension charging process will be considered based on the achievement in this paper. We believe that the charging path can be further optimized.

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