DWDP: A Double Warning Thresholds with Double Preemptive Scheduling Scheme for Wireless Rechargeable Sensor Networks

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***Abstract*—Wireless power transfer technique provides new alternatives for solving the limited power capacity problem for so many popular mobile wireless devices, and makes wireless rechargeable sensor networks (WRSNs) promising. However, mainly due to the underestimate of the unbalanced influences of spatial and temporal constraints posed by charging requests, traditional scheduling strategies for on-demand WRSNs architecture achieve rather low charging request throughput or successful rate, posing as a major bottleneck for further improvement. In this paper, we propose a Double Warning Thresholds with Double Preemption (DWDP) charging scheme, in which double warning thresholds are used when residual energy levels of sensor nodes fall below certain thresholds. By introducing specific comparison rules, warning thresholds can be used to adjust charging priorities of different sensors, warn the upcoming recharge deadlines, as well as support preemptive scheduling. We perform extensive simulations to manifest the advantages of DWDP. Simulation results reveal that DWDP can achieve better scheduling performance, in guaranteeing the scheduling success of the high-priority task and improving stability of the system.**

***Index Terms*—Wireless Rechargeable Sensor Networks; Charging Scheduling; Warning Thresholds; Charging Efficiency**

I. INTRODUCTION

Wireless Sensor Networks (WSNs) are composed of a large number of cheap micro-sensor nodes, which can be deployed in the specific area to form a multi-hop and self-organized networks for monitoring. The functionality of WSNs include synergistically sensing, information collecting and processing perceived objects. Potential applications include: military, aviation, explosion, disaster relief, environmental, and so on.

However, WSNs are suffering from a severe problem of constrained power supply in batteries, which yields to short network lifetime and limited application. Recent breakthrough in Wireless Power Transfer(WPT) provides new alternatives for solving this problem [1]. The basic principle of WPT based on magnetically coupled resonance is that two self-resonators that have the same resonant frequency can transfer energy efficiently over midrange distances. Nowadays WPT has been broadly used in body sensor networks, mobile phones, transportation systems and so on. With the help of WPT, the concept of Wireless Rechargeable Sensor Networks (WRSNs) has been proposed.

In WRSNs, one or more Mobile Charging Vehicles (WCVs) are responsible for replenishing energies for all rechargeable sensors. Therefore, it is necessary for WCVs to charge nodes before they exhaust their battery power, otherwise, the dead nodes can no longer be replenished with energy by WCV and continue operating. This issue can be solved by developing appropriate scheduling algorithm. Hence, the scheduling strategies for charging has become a prominent issue.

In literature, scheduling methods can be divided into two categories: deterministic methods and non-deterministic methods. In deterministic methods, charging for individual nodes is carried out in a periodic and deterministic manner. Such methods usually require explicit system information such as, exact node location, channel status, and so on, which are difficult or sometimes even impossible to be obtained in practical application. Therefore, the deterministic methods can become infeasible.

On the contrary, non-deterministic methods, are usually on-demand, in which sensors send their energy charging requests to WCVs when their energy levels run below a threshold. Upon the reception of request, WCV will immediately rearrange the order of recorded charging tasks, select a candidate sensor, and proceed. Nearest-Job-Next with Preemption (NJNP) for the on-demand mobile charging problem [2], which schedules the charging of individual nodes based on spatial and temporal properties is one of the most typical non-deterministic methods. NJNP allows the mobile charger to switch to a spatially closer target node if the new requesting node is closer to the mobile charger.

Although the non-deterministic schemes are more feasible, there are still some prominent drawbacks that cannot be overlooked.

- The travel time of WCV during each task is divided into some time slots in NJNP. Preemption can only occur at each time slot once. Preemption may occur frequently, leading to disturbances in finding ideal paths for charging, disstablizing the system due to the too small time slot.
- Since preemption can originate at any time (except the last time slot) while WCV is executing task, preemption originated in the last few time slots will cause the travel time to become useless, which reduces the charging efficiency of the system.
- Many schemes, such as NJNP, in which charging requests are only ranked based on spatial priority, tend to weigh

heavilier on spatial relations and thus can leave some far-away nodes eventually running out of battery energy.

In this paper, we design a non-deterministic charging scheduling method called Double Warning Thresholds with Double Preemption (DWDP) for on-demand charging architecture in WRSNs. In DWDP, two kinds of warning thresholds are used when remaining energy of sensor nodes falls below certain thresholds. By introducing specific comparing rules, warning thresholds can be used to adjust charging priorities of different sensors, warn the upcoming recharge deadlines, as well as support preemptive scheduling. Simulation results show that, our proposed methods greatly improve the charging efficiency of WCV and the performance in terms of throughput, charging success rate and so on.

II. LITERATURE REVIEW

In 2011, Yang et al [3] proposed the prototype of WRSNs, which laid a foundation for application and popularization of WRSN. In recent years, researchers conducted a comprehensive study of WRSN charging method, some important progress has been made. In general, charging methods can be divided into three categories: 1) periodic charging methods, 2) collaborative charging method and 3) performance evaluation

(1) Periodical charging [6-11] combines node distribution model and energy consumption model, and transforms the charging problem into Traveling Salesman Problem (TSP) by calculating the Hamiltonian cycle as a traveling path for the WCV. Periodically charging solution is mainly divided into single-node charging and multiple-node charging. In single-node charging solution, WCV can only charge one node every time and thus the charging efficiency is low [6]. However, in multiple-node charging solution, WCV can charge multiple neighboring nodes within its charging range simultaneously, which greatly improves the charging efficiency [7, 8]. Based on the multiple-node charging solution, Xie et al researches path planning problem when WCVs are regarded as the mobile base station [9, 10] by establish Smallest Enclosing Dist (SED) [12]. And a SED covers all the sensor nodes in the network. With the node position as the center of a circle and charge loss rate as the radius, they set up concentric circle structure and regard the overlap part of concentric circles as the resting spot of WCV. Similarly, Fu et al [11] proposes the discretization of wireless charging planning theory which sets up the concentric circles structure in the SED and searches of the resting spot of WCV from the overlapping area. But, in reference [13], the researchers point out that the amount of calculation based on SED is large and its not suitable for large-scale wireless sensor networks.

(2) Collaborative charging method requires that the charging process should be collaboratively accomplished by sensors and WCV. He et al pointed out that periodical charging methods have impractical requirements, such as certainty and periodicity. The non-deterministic factors in network will cause immeasurable affects for both of energy demand and energy supply. So it is necessary to adopt collaborative charging mechanism [15] to meet the heterogeneous demands for non-deterministic factors, dynamic topology and node properties[14]. In WCV charging schedule and routing strategy, they proposed WCV charging scheduling method based on tree structure to reduce charging consumption and charging delay [16]. Li et al [17] proposed a J-RoC method combining routing protocol with charging policy. WCV will update global energy status information and then schedule to charge. At the same time, nodes use rechargeable awareness routing protocol to select a path of low energy consumption for transmission. In that way, the energy consumption will be balanced and the lifetime of network will be prolonged. Although collaborative charging method can effectively solve the impact of uncertainty factors in WRSNs, it still neglects the reliability of charging demand information and real-time transmission requirements. Failure or delay of charging demand information may lead to disability for WCV to arrive at charging position before it is out of energy. It will affect the reliability of the network. So the real-time and reliability for demand information transmission needs to be focused, along with hybrid scheduling problem of demand information and gathering information.

(3) Besides periodical charging and collaboratively charging, performances analysis and optimizations of WRSNs are still deserved to be mentioned. Jiang and Cheng et al [19, 20] analyze optimization scheduling problem of WRSN in detail under the condition of random events. And they establish the performance evaluation criteria on the basis of Quality of Monitoring (QoM) [21,2] in network. They optimize the performance of the system from WCV behavior, data transfer protocol, coordination control and so on. Angelopoulos et al posed the charging decision problem and prove its complexity. In order to optimize the performance of the system, they lucubrate how to weigh path of WCV, charging decision of WCV and charging amount of WCV.

III. OUR SCHEME

A. Problem Statement

The on-demand charging architecture is depicted in Figure 1. We consider a set of sensor nodes distributed over a circular area with radius L.All sensor nodes are homogenously implemented with the same battery capacity and energy consumption rate Vd.When the remaining power of a sensor node falls at a warning threshold, the sensor node will immediately send a charging request to the mobile WCV who is responsible for replenishing energy for rechargeable sensors. In addition, we borrow the same assumption as [2]: sensor nodes can posit the location of WCV in real time.

For simplicity, we consider the case where only one mobile WCV is available in the network. The WCV collects all charging requests and saves them in a service pool. As shown in Figure 1, currently, the service pool records location information of node A, K and E. As the charging requests are real-time constrained, which have real-time deadlines for charging tasks, the charging scheduling problem can be considered as a real-time task scheduling problem, which needs to rank charging requests based on urgency and priority in a queue. Once a request is selected to be responded, WCV will instantly

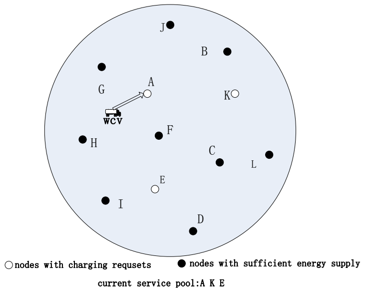

Fig. 1. On-demand Charging Architecture

proceed to charge it. Hence, the traveling path of WCV directly relates to the ordering of tasks in the queue. In the on-demand architecture, the WCV travels at a constant speed. As the charging time is too short compared with traveling time, we neglect such effects of charging.

B. Algorithm Infrastructure

As charging tasks in WRSNs are spatial and temporal related, the scheduling algorithm should pay close attention to both of them. In our algorithm, two different warning thresholds are used to distinguish the time priority of the charging requests.

Denote N as the remaining power of the first warning threshold and M as the remaining power of the second warning threshold. Whenever the remaining power decreases to any warning threshold, a charging request will be sent to WCV. This message contains location of the sensor and the remaining power. We denote tw as the waiting time of charging requests in the queue. As on-demand task scheduling must satisfy different requirements such as: spatial-temporal dependent, preemption, priority adjudication and so on. In the following, corresponding methods are introduced to meet the requirements for each of them

C. Determination of the First Warning threshold

DWDP consists of two warning thresholds. We firstly illustrate how to calculate the remaining power of the first threshold N. We define L and Vm as the radius of the network and the speed of WCV respectively.$T1$ is denoted as the maximum traveling time from one location to another of WCV in the circular area , which can be obtained by equation (1).

$$T1 = \frac{2 * L}{Vm} \tag{1}$$

To ensure all nodes stay alive, the lifetime of the nodes at the first warning threshold should equal to $T1$, so that the WCV can charge nodes before they exhaust their battery power. At the same time we must take into account the length of the queue because not all charging requests will be immediately responded. Therefore, N can be calculated as equation (2).

$$N = T1 * Vd * Lq \tag{2}$$

D. Time Priority adjudication

In this section, we show how to adjust priority of charging requests in the queue. Only determining priority of requests based on the first threshold is not enough, because the situation that nodes run out of battery energy due to long waiting time still exists.

Therefore we need to increase the time priority of charging requests sent by the nodes at the first warning threshold when tw increases to a critical value $t0$. The key question is how to determine the value of $t0$. Denote $Pcur$ as the current remaining power of nodes:

$$Pcur = N - Vd * tw \tag{3}$$

We also can calculate the current remaining lifetime of nodes at first warning threshold. Denote $Tcur$ as the current remaining lifetime of nodes, so we can have equation (4).

$$Tcur = \frac{Pcur}{Vd} \tag{4}$$

Therefore, we can determine the value of $t0$:

$$t0 = T1 - Tmax \tag{5}$$

Where $Tmax$ is average maximum service time for all requests in the service pool,which we can get by queue theory.

E. Preemption

In this section, we analyze temporal preemption. As the remaining energy of nodes, waiting time of charging requests are changing all the time. Moreover, at any time, a new charging request may be added into the service pool. Therefore, we should design preemption mechanisms so as to re-arrange the charging behavior for WCV to enhance the charging throughput.

As we know, the time priority of charging request will become greater when tw increases to $t0$. Although events such as a node that satisfies the first threshold or tw increases to $t0$ may happen at different time. We only need to determine whether the value of tw of each charging request is no less than $t0$, while it is not necessary to worry about when it happens. This manner makes time priority change and there will always be tw increasing to $t0$ after every $t0$. Therefore, the time interval of preemption should be $t0$.

F. Determination of the Second Warning Threshold

In this section, we discuss the reason for designing the second warning threshold and how to determine the second warning threshold M. It is quite possible that a node nearby WCV with medium remaining energy cannot be immediately charged because of low temporal priority. This kind of nodes may cause a long-term traveling after the WCV moves far away. If such nodes can be replenished before WCV leaves, it will greatly improve the charging efficiency. Taking these special nodes into account, we propose the second warning threshold M so that WCV can charge them early.

Next, how can we determine the value of M. Since the remaining power satisfying the second warning threshold is greater than that of the first warning threshold, we denote tc as time difference.tc is calculated based on the following three principles.

1)The time priority of the charging request sent by the nodes at the second warning threshold will become the time priority of the charging request sent by the nodes at the first threshold after tc, so tc should be the time interval of preemption as well. In order to simplify preemption mechanism, $t0$ should be an integer multiple of tc to unified two kinds of preemption. So we can have:

$$t0 = n * tc, n \geq 2 \tag{6}$$

2) In order to prevent preemption from occurring too frequently, we should make tc greater than the average minimum service time, so we can have:

$$tc > Tmin \tag{7}$$

Otherwise preemption occurs during the execution of each task. 3) tc should be small enough not to influence the time priority of other nodes, so tc should be less than the average service time, so we can have:

$$tc < Et \tag{8}$$

We can determine the value of the tc based on the above three principles. And we already know that the remaining lifetime of the nodes at the first warning threshold is $T1$. So we can calculate the lifetime of of the nodes at the second warning threshold. Denote $T2$ as the remaining lifetime of the nodes at the second warning threshold :

$$T2 = T1 + tc * Lq \tag{9}$$

Then, according to the energy consumption rate of nodes Vd, we can determine the value of M:

$$M = Vd * T2 \tag{10}$$

G. DWDP Algorithm

In this section we will described how to compare the priority of two charging requests in details. Related symbols and their definitions used in this paper are listed in Table 1.

TABLE I

Symbols	Definitiond
$tw(A)$	The waiting time for request A
$T(A)$	The temporal priority of A.
$D(A)$	The spatial priority of A.
$P(A)$	The scheduling priority of A.

It is obvious that the time priority of the charging requests can be divided into three classes.

$First\_Class$: The time priority of the charging requests at the first warning threshold, meeting $tw > t0$.

$Second\_Class$: The time priority of the charging requests at the first warning threshold, meeting $tw < t0$.

$Third\_Class$: The time priority of the charging requests at the second warning threshold.

The spatial priorities of the charging requests are determined by the distance between the nodes and WCV, the closer distance with WCV, the greater priority will be.

Firstly, we aim at classifying tasks based on the value of tw, which is shown in Algorithm 1. Then we should compare the spatial priority of requests as Algorithm 2.

Algorithm 1 Time Priority Criterion

```
INPUT: $tw(A)$
Output: $T(A)$
if A charging request A at the sencond warning threshold then
    $T(A) = Third\_Class$
else if $tw(A) < t0$ then
    $T(A) = Second\_Class$
else
    $T(A) = First\_Class$
end if
Return $T(A)$
```

Algorithm 2 Spatial Priority Comparison

```
INPUT: $L(A)$,$L(B)$
Output: Comparison of $D(A)$ and $D(B)$
if $L(A) > L(B)$ then
    $D(A) < D(B)$
else
    $D(A) > D(B)$
end if
```

At last, algorithm for comparing spatial and temporal priority is given in Algorithm 3.

Algorithm 3 proceeds as follow:

Algorithm 3 Spatial & Temporal Priority Comparison

```
INPUT: $T(A)$,$T(B)$,$L(A)$,$L(B)$,$D(A)$,$D(B)$
Output: Comparison results: $P(A)$ and $P(B)$
if $T(A) > T(B)$ then
    if $D(A) > D(B) || D(A) = D(B)$ then
        $P(A) > P(B)$
    else if $T(A)$ is $First\_Class$ then
        $P(A) > P(B)$
    else if $L(B) > L0$ then
        $P(A) > P(B)$
    else if $L(B) > Lc$ then
        $P(A) > P(B)$
    else if $L(A) > Lc$ then
        $P(A) < P(B)$
    else
        $P(A) > P(B)$
    end if
else if $T(A) = T(B)$ then
    if $D(A) > D(B) || D(A) = D(B)$ then
        $P(A) > P(B)$
    else
        $P(A) < P(B)$
    end if
end if
```

1) When the temporal priority and the spatial priority of A are both greater than B's, then it is obvious that the priority of A is greater than the priority of B.

2) When the time priority of A is equal to B, higher spatial priority will yield higher scheduling priority.

3) When the temporal priority of A is greater than Bs whereas the spatial priority of A is less than B's. It will be difficult to compare the scheduling priority of A and B. We need to use two distance values to discuss: $L0$ and Lc. We can know whether preemption will occur during the process

of response to A and B by comparing $L(A)$, $L(B)$, $L0$ and Lc. $L0$ and Lc are defined as follows.

$$L0 = Vm * t0 \tag{11}$$

$$Lc = Vm * tc \tag{12}$$

There are the following conditions.

1) When the temporal priority of A is $First\_Class$, no matter which time priority of B's is, the priority of A is higher. Because, it is very likely that nodes sending A will run out of battery energy if it is not responded.

2) When the temporal priority of A is $Second\_Class$ and the temporal priority of B is $Third\_Class$. We need to compare $L(A)$, $L(B)$, $L0$ and Lc to discuss. Four situations should be discussed.

a. If $L(B) > L0$, then the service time of A and B are both greater than the time interval of preemption $t0$, so no matter which charging request WCV responds ,the time priority of A will become the highest, so the priority of A is greater.

b. If $L0 > L(B) > Lc$, then the service time of A and B are both greater than $t0$, so no matter which request WCV responds, the time priority of B will become $Second\_Class$, and as a result, the waiting queue will be re-sorted and the priority of A will be greater.

c. If $L(A) > Lc > L(B)$, then the service time of B is less than the minimum time interval of preemption tc. Rigorous time will be left to respond to B.So the priority of B is greater.

d. If $Lc > L(A) > L(B)$, then the service time of A and B are both less than tc. So the charging request whose time priority is greater will have higher scheduling priority.

IV. SIMULATION RESULTS

In this section, we evaluate the performance of our algorithms through extensive simulations. We compare our scheme with NJNP, which is comprehensively regarded as a classic scheduling algorithm in on-demand charging architecture.

A. Simulation Setup

TABLE II

Parameters	Values
Network Size	$500m * 500m$
Node Number	300
Energy Consumption Rate Vd	0.02
Moving Velocity of WCV Vm	$4m/s$
First Warning Threshold N	25
Second Warning Threshold M	35

As shown in Table II, in our simulations, 300 nodes are randomly deployed in a 500m500m area. Without loss of generality, we set $Vd = 0.02$ as the energy consumption rate,and the mobile charger travels at $Vm = 4m/s$. We set $N = 25$ and $M = 35$ as the first threshold and the second warning threshold. WCV will sort charging requests according to our algorithms and travel to charge nodes following the sequence of waiting queue.

B. Throughput of Charging Requests

Fig. 2 shows that, with the increasing of time, the throughput of DWDP is gradually increases while the throughput of NJNP is unstable. The throughput of DWDP is much greater than that of NJNP, which is even only half of the throughput of DWDP. This obviously shows that great improvement has been made to enhance the charging efficiency, which means that the sensor nodes will have enough energy to keep operational for a long time, and thus the survival time of WRSN will be prolonged.

C. Successful charging rate

Then we investigate the comparison of charging success rate of WCV between DWDP and NJNP. As shown in Fig.2 we note that although the charging success rate of WCV in DWDP and NJNP are both increasing, the charging success rate of DWDP is higher than NJNP. This shows that WCV can basically meet the needs of sensor nodes' charging requests which results from efficient completion of charging task by WCV. We can conclude that DWDP can enhance the successful charging rate.

D. Average service time

We then compare the average service time (the average traveling time of executing a task of WCV) between two methods.As shown in Fig.2, it is apparent that the average service time of WCV in NJNP is four or five times as much as DWDP. In other words, WCV in NJNP spends about 3.16 minutes more on completing each task than WCV in DWDP on average. So we can conclude that the path planning of WCV has been greatly optimized in DWDP. Large number of charging tasks can be responded in very short time in turn the charging efficiency of WCV is significantly improved.

E. Average response time

Next, we measure the average response time, which is defined as the delay between the time when a request is sent and the time when WCV responds this request. Fig.2 demonstrates that the average response time in DWDP is slowly falling and gradually stabilizes at a low value while the average response time in NJNP is rapidly falling due to amount of nodes running out of battery energy firstly and stabilizes at a high value which is approximately 4.59 minutes more than the average response time in DWDP, which still indicates DWDP has a higher charging efficiency compared with NJNP

F. Average length of waiting queue

We finally study the average length of waiting queue, which expresses the number of charging requests per second in the waiting queue. This factor is used for indicating the working condition of WCV and the power condition of sensor nodes.

As shown in Fig. 2, it is obvious that the average length of waiting queue in DWDP is always stabilized at 4 while the average length of waiting queue in NJNP is much greater. Short waiting queue indicates fast completion of charging task and higher level of remaining energy of nodes, which comprehensively illustrates high efficiency of WCV. In conclusion, this validates the advantages of our algorithm.

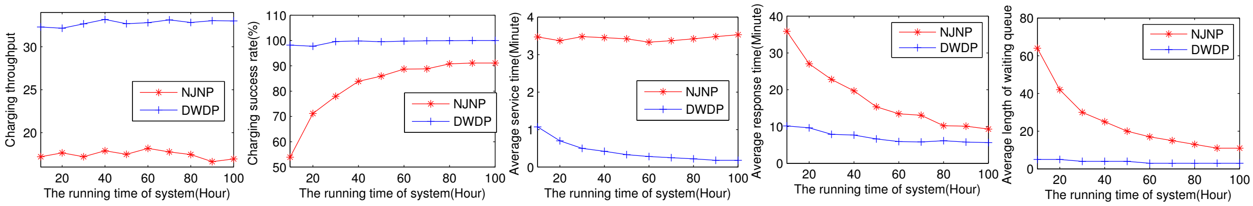

Fig. 2. Simulation Results

V. CONCLUSION

In this paper, we have proposed a scheduling algorithm DWDP for on-demand charging architecture in WRNSs. We formulated two warning thresholds and comparing rules to determine scheduling priority for charging requests. Besides, two preemption mechanisms are designed to deal with real-time characteristics of WRSN. Finally, we evaluated the performance of the proposed algorithms through experimental simulation, and provided numerical results to validate the efficiency of the proposed algorithms. Simulation results that our algorithm outperforms a state-of-the-art scheme, NJNP, in terms of throughput, charging success charging rate and so on.

In the future, we will work on multiple charging vehicles and the potential coordinations among them in improving charging efficiency.

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