Optimal Scheduling for Quality of Monitoring in Wireless Rechargeable Sensor Networks

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Abstract—Wireless Rechargeable Sensor Network (WRSN) is an emerging technology to address the energy constraint in sensor networks. The protocol design in WRSN is extremely challenging due to the complicated interactions between rechargeable sensor nodes and readers, capable of mobility and functioning as energy distributors and data collectors. In this paper, we for the first time investigate the optimal scheduling problem in WRSN for stochastic event capture, i.e., how to jointly mobilize the readers for energy distribution and schedule sensor nodes for optimal quality of monitoring (QoM). We analyze the QoM for three application scenarios: i) the reader travels at a fixed speed to recharge sensor nodes and sensor nodes consume the collected energy in an aggressive way, ii) the reader stops to recharge sensor nodes for a predefined time during its periodic traveling and sensor nodes deplete energy aggressively, iii) the reader stops to recharge sensor nodes but sensor nodes can adopt optimal duty cycle scheduling for maximal QoM. We provide analytical results for achieving the optimal QoM under arbitrary parameter settings. Extensive simulation results are offered to demonstrate the correctness and effectiveness of our results.

Index Terms—Optimal scheduling; wireless rechargeable sensor networks; stochastic event capture;

I. INTRODUCTION

LAst decade has witnessed the widespread adoption of Wireless Sensor Networks (WSNs) in a variety of fields, including environment monitoring, ecosystem surveillance, physical hazards prevention, and daily activity recognition [2]–[4]. Albeit their great success, most of existing WSNs are confined to short-term applications related to scientific researches or industrial monitoring, as sensor nodes are typically battery powered and replacement of battery or sensor nodes themselves will incur huge management cost. The energy constraint has become the major challenge that holds back the further popularity and maturity of WSNs, while the rapid advances in Micro Electronic Mechanical System (MEMS) and communication technologies have been leading to reduction in manufacture cost during the last several years.

Energy harvesting technologies have been adopted to address the energy constraint in the WSNs. An energy-harvesting WSN can harvest energy from its surroundings and thus have a great potential to yield a perpetual network operation time. Roughly speaking, energy harvesting technologies can be categorized into two folds: i) energy scavenging, and ii) energy distribution. Well known examples of energy scavenging include rechargeable sensor nodes that can be powered by solar, wind, vibration, and biochemical processes [5]–[8]. These energy scavenging sensor nodes are generally expensive and of large size since additional hardware devices are integrated for energy collection, which limits their applications of large scale. Another drawback of energy scavenging sensor nodes is the energy reliance on the surroundings. For example, solar powered sensor nodes will fail to collect energy at night or when sunshine is not available. The most popular approach of energy distribution is harvesting energy from RF signal. The great success in prevailing applications of Radio Frequency Identification (RFID) has demonstrated the stupendous advantages and the bright future of applying RF signal for energy distribution.

Recently, harvesting energy from RF signal has been applied beyond identification to pervasive sensing and computing. Intel Research Center and University of Washington have collaborated to develop a Wireless Identification and Sensing Platform (WISP), where energy from RF signal can be harvested, stored, and used for powering the operation of MCU (Micro Control Unit), directing the computing and sensing. Based on their model, we fabricate a prototype of WISP 4.1DL, which is shown in Fig. 1. With the excellent thin shape and the advantage of getting rid of battery, WISP can be widely applied in fields ranging from individual activity recognition to large-scale urban sensing [9]–[11], opening up a new research area referred to as Wireless Rechargeable Sensor Network (WRSN).

In a WRSN, there are mainly two components: i) a bunch of WISP tags for sensing and computing, and ii) several readers for data collection and energy distribution. WISP tags can be static (e.g., embedded in the infrastructures) or mobile (e.g., carried by humans or attached to vehicles), and...
readers travel around to meet WISP tags in a deterministic or opportunistic way. To guarantee a desired performance, WISP tags have to determine a good on-off sampling scheduling, and readers need path planning to wirelessly recharge WISP tags and retrieve data. Solving the on-off scheduling and path planning problems independently is very challenging. Moreover, these problems are usually coupled as the WISP’s sampling scheduling and data forwarding delay depend on the frequency of readers’ arrival.

In this paper, we make the first attempt to address the scheduling problem in a WRSN consisting of a collection of WISP tags embedded in the infrastructures (e.g., bridges) and one reader deterministically recharging WISP tags. Stochastic events are assumed to occur at these infrastructures, and we aim at jointly scheduling the WISP tags and the reader to maximize the quality of monitoring (QoM), i.e., the ratio of captured events to all occurring events. We consider three application scenarios: i) the reader travels at a fixed speed to recharge WISP tags and WISP tags deplete the collected energy without any duty cycle scheduling, ii) the reader stops to recharge WISP tags for a predefined time during its periodic traveling and WISP tags still use energy without any scheduling, iii) the reader stops to recharge WISP tags as scenario (ii) but WISP tags can adopt optimal duty cycle scheduling to maximize QoM. Note that such three scenarios cover different system complexities in practice. For example, the first scenario does not require exact localization of WISP tags or complicated motion control of reader, while both the first and second scenarios do not require the scheduling ability of WISP tags. We give analytical results of QoM under arbitrary parameter settings for these three scenarios. Our analysis shows that the scheduling of the reader and the WISP tags has a significant impact on the QoM. We also show how to decide the optimal scheduling by jointly addressing the scheduling of both the reader and WISP tags. Extensive simulation results are also provided to validate our results.

The remainder of this paper is organized as follows. We discuss the existing works on stochastic events capture in WSNs and WISP tags in WRSN in Section II. We give some preliminary knowledge about the wireless recharging and formulate our problem in the Section III. The QoM for different application scenarios and optimal scheduling schemes are investigated in the Section IV, followed by the validation via extensive simulation results in the Section V. We conclude the paper in Section VI.

II. RELATED WORK

Recently, wireless sensor networks are widely applied to monitoring applications [12]–[17], where their primary concerns are to capture interesting events occurring in the region of interest. As most of time there is no prior knowledge about when the events occur, it is typical to model events as stochastic processes. Poisson process is one of the most popular ones that are adopted in the existing work to characterize the dynamics of event occurrences [12], [15]. In general, existing works on stochastic event capture can be classified into two folds, identified by whether the deployed sensor nodes are static or mobile. In a static sensor network, an energy-efficient scheduling is proposed in [16], where He et al. for the first time investigate how the periodic sensor scheduling improves the quality of capture (QoC) by exploiting the event dynamics. It is shown that an asynchronous network with the coordinated sleep protocol (CSP) is the best choice in terms of QoC and energy efficiency. In some applications where there are not sufficient sensor nodes, it is an alternative to use mobile sensor nodes, referred to as mobile sensor networks. The mobile sensor nodes patrol in the region of interest, gather information at the points of interest (PoIs), and report it to a data collection center (sink node). Bisnik et al. investigate how the parameters, such as sensor speed, event dynamics and the number of mobile sensors, affect the quality of event capture [13]. They also study how to coordinate the movement of multiple mobile sensor nodes to satisfy the application requirements as well as to achieve energy efficiency. Yau et al. [15] study quality of monitoring of stochastic event capture by using periodic schedule (q, p), where mobile sensors monitor PoIs for q time of every p time. They also consider the heterogeneity of PoIs and adopt utility functions, e.g., Step function, Linear function, to describe the event capture process. He et al. further consider the tradeoff between energy efficiency and QoC in a mobile sensor network [18]. They propose a metric: expected information captured per unit of energy consumption (IPE), to evaluate the overall performance of a mobile sensor network, and systematically analyze the optimal scheduling under different scenarios.

Energy harvesting technologies have emerged in the last several years to address the challenge of energy constraint of battery-powered sensor networks. One approach to design a battery-free system is to scavenge energy from surrounding energy sources. Known examples of energy sources include solar [7], vibration [8], temperature variation [19], wind [20], etc. Another approach of battery-free system design is to distribute energy from energy-rich sources to energy-hungry nodes, which mainly involves two methods: i) through strongly coupled magnetic resonances [21], and ii) through radio frequency (RF) signals [22]. In this paper, we introduce wireless rechargeable sensors for perpetual sensing and computing, by harvesting energy through RF signal. A rechargeable sensor, also referred to as a WISP tag, is a battery-free platform with capability of sensing and computing [23]. Buettner et al. propose a list of potential applications for WISP tags in [24], such as monitoring blood temperature during storage or transportation, recognizing the daily activities of the elderly, etc. Yeager et al. add capacitive sensor into the WISP tags for monitoring the fill percentage of milk carton [22]. In [25], Holleman et al. develop a Neural WISP, which can monitor the neural signal and periodically transmit the spike density to the reader. How to deploy readers to provision enough energy for every WISP tag in the region of interest is investigated recently in [26].

While considerable research efforts have been invested into energy-efficient scheduling for event capture in the traditional battery-powered sensor networks, few works focus on energy-efficient protocol in the wireless rechargeable sensor networks. We for the first time investigate the optimal scheduling problem in WRSN for stochastic event capture, i.e., how to jointly mobilize the reader for energy distribution and to schedule sensor node for efficient event capture. We extensively study
the problem and analyze the quality of monitoring for different application scenarios.

III. PRELIMINARIES AND PROBLEM STATEMENT

Wireless Identification and Sensing Platform (WISP) is mainly composed of four components: i) energy harvesting component, ii) micro-controller component, iii) sensors and iv) communication component [22, 23, 27]. MSP430 micro-controller component with several low-power modes (LPM) is in charge of all the activities in the WISP tag. The energy harvesting component can harvest the RF radio energy and store it in the energy storage capacitor (ESCap). A WISP tag can be integrated with certain lower-power sensors, e.g., accelerometer, light sensor and temperature sensor, and the communication component can upload the ID information and sensory data to an adjacent reader through backscatter modulation.

A. Wireless Recharging Model

Before formulating our problem, we first present a wireless recharging model based on experimental data. In Friis transmission equation, the power $P_{rx}$ at the receiver is $P_{rx} = G_{tx}G_{rx}\frac{\lambda}{4\pi d^2}P_{tx}$, where $P_{tx}$ is the transmission power of the transmitter, $d$ is the distance between the transmitter and the receiver, $G_{tx}$ is the antenna gain of transmitter, $G_{rx}$ is the antenna gain of receiver, and $\lambda$ is the wavelength of the RF wave. In this paper, we adopt the following empirical wireless recharging model, which was proposed and verified in [26],

$$P_{rx} = \frac{G_{tx}G_{rx}\eta}{L_p}\left(\frac{\lambda}{4\pi(d + \beta)}\right)^2 P_{tx}, \quad (1)$$

where $\eta$ is referred to as rectifier efficiency, $L_p$ is the polarization loss and $\beta$ is an adjustable parameter to adapt our equation to room environment. Through extensive experimental tests, [26] has obtained $\eta = 0.125$ and $\beta = 0.2316$ by employing the least square technique to fit the experimental data.

Note that when WISP tag is too far away from the reader, the wireless charging power would be too low to be harvested. Therefore, we assume there exists a threshold of distance denoted by $r$, beyond which the WISP tag cannot be wirelessly charged. Then the empirical recharging model is expressed as

$$P_{rx}(d) = \begin{cases} \frac{\tau}{(d + \beta)^2}, & 0 \leq d < r \\ 0, & \text{otherwise} \end{cases} \quad (2)$$

where $\tau = \frac{G_{tx}G_{rx}\eta}{L_p}\left(\frac{\lambda}{\tau_{\text{reader}}}\right)^2 P_{tx}$ is a constant, $d (d \geq 0)$ is the distance between the reader and WISP tag.

B. Problem Statement

We consider $N$ WISP tags, indexed from 1 to $N$, placed at $N$ points of interest (PoIs) in a 2D plane as shown in Fig. 3. A reader that is capable of mobility can travel to visit the WISP tags at PoIs one by one along a curve ($\Omega$) with a cycle time, where $\Omega$ denotes the traveling path along which the reader will visit all tags subsequently. One typical example may be one shortest path connected all WISP tags in space. Since the reader keeps moving along $\Omega$ periodically, we can focus on the scheduling design within one cycle. Note that the results in this paper does not rely on any specific shape of $\Omega$. The distance between tag $i$ and tag $i+1$ along curve $\Omega$ is $l_i$, $i \in (1, N-1)$, and $l_N$ denotes the distance between WISP tag $N$ and 1. Note that in order to simplify the presentation, here we assume the distance between each two PoIs is not less than $2r$, and for each PoI we employ only one WISP tag. Thus the reader can recharge only one tag at a time. Since the common charging threshold $r$ is around 20m [26], such a setting is feasible for many applications where PoIs are not too intensive. Note that different from traditional RFID tags, each WISP tag can be equipped with various sensing components for different system requirements [27]. In addition, for many applications, it is beneficial to reduce the overlapping sensing area of different tags for reducing the system costs. Extensive works have been devoted to developing techniques for placing sensor nodes so that the system hardware costs can be reduced with guaranteed sensing performance [28].

Once collecting enough energy, each WISP tag turns into active state and gathers the physical information at each PoI. We assume stochastic events occur at each PoI sequentially. When an event occurs, it stays for a while (called event staying time, denoted by $X$), and then disappears. There is a time duration (called event absent time, denoted by $Y$) before new event occurs. We assume $X$ and $Y$ at each PoI $i$ follow the Exponential distributions with means $\frac{1}{\mu_i}$ and $\frac{1}{\alpha_i}$, respectively. For simplicity, we further assume that $\alpha_i = \alpha$ and $\mu_i = \mu$, for $i = 1, ..., N$. 

Fig. 2. Experimental and theoretical receiving power of WISP tag proposed in [26].

Fig. 3. $N$ WISPs placed at PoIs along a curve $\Omega$. 

The wireless charging power would be too low to be harvested.
Suppose the reader patrols along curve \( \Omega \) at a fixed speed denoted by \( v \) \((v > 0)\). We refer to the duration for the reader to complete traveling the curve \( \Omega \) as reader period. Note that \( r \) denotes the maximal distance for recharging a WISP tag. Once the reader is within the range \( r \), the WISP tag will get recharged. All the harvested energy is stored in capacitor ESCap. We assume the capability of ESCap is large enough and the leakage current is negligible. WISP tags cannot work unless the voltage of ESCap is higher than \( V_{reg} \). For each WISP, there are two major states: active and sleep with the power consumption of \( P_{act} \) and \( P_{slp} \), respectively. Another major energy cost comes from transition from different states, e.g., from sleep state to active state, and we call such energy consumption switch cost, denoted by \( E_{wak} \). To facilitate the analysis in the following, we denote the time for transition by \( T_{wak} \), and the average power cost by \( P_{wak} \), thus \( P_{wak} = E_{wak}/T_{wak} \). We assume \( P_{act}, P_{slp}, P_{wak}, T_{wak} \) and \( E_{wak} \) are constants as they all only depend on the hardware design.

We assume each WISP tag works on a periodic scheduling \((q, p)\), where the WISP tag will be active for \( q \) time of every \( p \) time. Assume during time \( T \), there are \( m_i \) stochastic events occurring at PoI \( i \), and WISP tag \( i \) captures \( c_i \) events. The quality of monitoring of the stochastic event is defined as

\[
QoM = \lim_{T \to \infty} \frac{\sum_{i=1}^{N} c_i}{\sum_{i=1}^{N} m_i}
\]

Then our problem can be formulated as how to schedule the movement of the reader and the operation of WISP tags to maximize \( QoM \), i.e.,

\[
\max \ QoM \quad \text{s.t.} \quad E_i \leq \bar{E}_i, \quad i = 1, 2, \cdots, N
\]

where \( E_i \) is the energy consumption of WISP tag \( i \), which depends on the schedule \((q, p)\), and \( \bar{E}_i \) is the average collected energy of node \( i \) within one reader period.

In this paper, in order to simplify the statements, only one WISP tag is placed at one PoI for monitoring the events. However, we can extend the obtained results to handle the case where multiple WISP tags are deployed at each PoI. Specifically, since multiple tags can be wirelessly recharged simultaneously, we can first consider the multiple tags at the same place as one big virtual tag whose charging power is the same as the accumulative charging power of multiple tags. Then we apply the design results in later sections in order to obtain the scheduling scheme for the big virtual tag. After that, we may evenly divide the working period of virtual tag into several parts based on the number of tags, and let each tag take charge of one part under a given order.

### IV. QoM Analysis

As each WISP tag is scheduled to be active periodically, there are two cases for an event to be captured: i) the event happens in WISP’s active period \([0, q]\), and is captured instantaneously, and ii) the event happens during the WISP tag’s inactive state \([q, p]\) but lasts long enough till the next active period \([p, p + q]\). From [15], we get the probability of capturing event for a general \((q, p)\) scheduling as follows.

\[
QoM = \frac{\int_0^q P_r(X = 0) \, dt + \int_q^p P_r(X + t = p) \, dt}{\int_0^p P_r(X = 0) \, dt}
\]

When the event staying time \( X \) follows the Exponential distribution with given parameter \( \alpha \), the QoM can be reduced to [15]

\[
QoM = \frac{q}{p} + \frac{1 - e^{-\alpha(p-q)}}{\alpha p}.
\]

The on-off scheduling \((q, p)\) of each WISP tag depends on the available harvested energy and the scheduling strategies, which is largely related to both the movement of the reader, the way of recharging, and scheduling of WISP tags. It is of great interest to jointly investigate how reader plans its path to provision sufficient energy and how the WISP tags should duty cycle themselves to maximize the QoM. There are mainly three typical cases: i) Independent Aggressive Wake-up (IAW), which means the WISP tags collect energy independently and drain out all the energy at one active state, ii) Joint Aggressive Wake-up (JAW), i.e., the reader would stop at each PoI to recharge WISP tags for a predetermined time, then WISP tags wake up aggressively to capture events, iii) Joint Periodical Wake-up (JPW), which means the reader would stop at each PoI to recharge WISP tags, and WISP tags will rationnally manage the use of energy it collects, and duty cycle to capture events. Note that for both IAW and JPW cases, Joint means the reader will jointly optimize both its patrolling speed and its stationary recharging time at each PoI. We will study the optimal scheduling problem in the following for these three cases. Table I gives a summary of notations commonly used in this paper.

#### A. QoM in Independent Aggressive Wake-up

In this application scenario, the reader can travel along the curve \( \Omega \) periodically, and recharge each WISP tag when the relative distance is less than \( r \). Denote the total energy collected by each WISP tag in each traveling period by \( E_{law} \).
We can get the expression for $E_{iaw}$ as follows,

$$E_{iaw} = 2 \int_0^\tau \frac{\tau}{(v+\beta)} dt = \frac{2\tau r}{v(r+\beta)}. \tag{7}$$

Recall that the capability of capacitor ESCap is assumed to be large enough, and thus we do not consider the energy overflow in the capacitor during recharging process. The WISP tag cannot work unless the voltage of capacitor ESCap is larger than the voltage threshold $V_{reg}$ in WISP tag, $V_{reg}$ is set to be 1.8 V in default, however, we can also change such setting as [29]).

One scheme is that a WISP tag will turn into active state as soon as voltage threshold is satisfied. However, in this case the WISP tag can only work in an instant time, and the switches from active to sleep state or sleep to active state are too frequent. To yield continuous operation of WISP, we design firmware to let WISP tag wake up to work only if the traveler arrives. As soon as voltage threshold is satisfied, the WISP tag cannot work unless the voltage of capacitor ESCap is larger than $V_{reg}$, therefore speed $v$ in IAW has to satisfy the following condition

$$\min \{ P_wak L/v, \frac{2\tau r}{v(r+\beta)} \} \geq E_{wak}. \tag{11}$$

The underlying assumption in this paper is that the hardware WISP tag will wake up in every cycle. Note that such a constraint is necessary but only for simplifying the statements. If the reader speed is larger than the maximal allowable speed, the reader has to patrol several times for supporting one wakeup. Such situation can be transformed into the case in this paper by utilizing the relationship between the charged energy and the traveling speed of reader.

Now we are ready to present the result about how the reader speed affects the QoM for IAW policy.

**Theorem 1**: For Independent Aggressive Wake-up, the maximum value of QoM can only be achieved at the maximum allowable reader speed.

**Proof**: The detailed proof is given in Appendix.

From Theorem 1, it can be observed that if the nodes wake up in an independent aggressive way, it is always better for the reader to move faster unless the constraint (11) is violated. In such result also provides some insights about how the events would be captured. Specifically, the expression of QoM (10) can be divided into two parts, where the first part equals to

$$\frac{T_{iaw}^act}{L/v} = \frac{1}{L} \left( \frac{A - P_{slp} L}{P_{act} - P_{slp}} \right) \frac{\Delta E}{P_{act} - P_{slp} v}$$

corresponding to the events which are captured when they just happen. Note that this part is a decreasing function of $v$ due to the existence of wakeup time $T_{wak}$. Meanwhile, the second part of QoM equals to

$$1 - e^{-\alpha (L/v - T_{iaw}^slp)} \cdot \frac{\Delta E}{P_{act} - P_{slp}}$$

which corresponds to the events which are captured when they last until the nodes activate in the next cycle. This part is an increasing function of $v$ due to that the activation frequency is increasing with the reader speed $v$. And the second part would play an increasingly significant role when $v$ grows.

**B. QoM in Joint Aggressive Wake-up**

In the JAW scenario, the reader would stop at each PoI to recharge WISP tag for a period of $t$ before it moves to the next PoI, and we call such additional charging process as stationary recharging. Note that based on the wireless charging model (2), the charging power during stationary recharging can be maximized if the reader stays at $d = 0$. In order to shorten the statements, we only consider the case when $d = 0$ in the rest of this paper, which means that the reader will stay at each WISP tag for stationary recharging. The results below would also be able to extended to handle the case where $0 < d < r$.

Besides, we denote the period for reader to patrol the curve $\Omega$ in JAW by $T_jaw$, and the amount of energy each WISP tag collects in the period $T_jaw$ by $E_{jaw}$. In JAW, WISP tag uses
energy aggressively, and we denote its active time by $T_{\text{jaw}}^{\text{act}}$, and the sleep time by $T_{\text{slp}}^{\text{jaw}}$. Then $T_{\text{jaw}}$ can be calculated by $T_{\text{jaw}} = L/v + Nt$, where $t$ is the stationary recharging time for each WISP tag.

Different from the previous IAW case, the energy collected by each WISP tag during $T_{\text{jaw}}$ for JAW is composed of two parts: i) energy harvested when the reader stops, and ii) energy harvested when the reader is traveling towards or away from the WISP tag. Thus we can calculate $E_{\text{jaw}}$, i.e., the total energy that each tag collects during every $T_{\text{jaw}}$ as follows

$$E_{\text{jaw}} = \frac{\tau t}{\beta^2} + \frac{2\tau r}{v\beta(r + \beta)}.$$  \hfill (12)

1) Constant Activation: We have shown that for IAW there exists a critical sensor number above which it is impossible to keep the tag constant working. But such a critical value is usually too small to be applicable. Now we prove that by applying JAW policies such a critical value can be enlarged.

**Theorem 2:** For any given reader patrolling speed $v$, all the tags can constantly work if the following conditions are satisfied simultaneously

1) The number of tags $N$ satisfies $N \leq \frac{\tau}{\beta^2} T_{\text{act}}^{\text{jaw}}$, with $A = \frac{2\tau r}{v\beta(r + \beta)}$.

Proof: The proof can be obtained from the fact that in order to support constant working, we must have $E_{\text{jaw}} \geq P_{\text{act}} T_{\text{jaw}}$ i.e., $\frac{\tau t}{\beta^2} + \frac{2\tau r}{v\beta(r + \beta)} \geq P_{\text{act}}(L/v + Nt)$.  

Note that the threshold of tag numbers for JAW can be enlarged $\frac{\tau}{\beta^2} T_{\text{act}}^{\text{jaw}}$ times that for IAW. Meanwhile, the minimal required stopping time $t$ is decreasing along with the speed $v$. However, it should be noted that such a critical tag number is still quite small compared with the usual large number of tags in different applications. For example, in our setting, the reader will be able to support the constant working of 5 tags by JAW. Therefore, in the rest of this section, we would investigate the design for the non-constant activation case, i.e., $N > \frac{\tau}{\beta^2} T_{\text{act}}^{\text{jaw}}$.

2) Non-constant Activation: Denote $T_{\text{jaw}}^{\text{act}}$ as the active time of WISP and $T_{\text{slp}}^{\text{jaw}}$ as its sleep time for JAW scenario. We can establish their relationship in a similar way as (8) and (9). The scheduling of each WISP tag can be expressed as $(T_{\text{jaw}}^{\text{act}}, T_{\text{jaw}}^{\text{slp}})$. Hence we can get the QoM in JAW scenario as follows,

$$QoM = \frac{T_{\text{jaw}}^{\text{act}}}{L/v + Nt} + 1 - e^{-\alpha(L/v + Nt - T_{\text{jaw}}^{\text{act}})} \frac{\alpha(L/v + Nt)}{\alpha(L/v + Nt)},$$  \hfill (13)

where $T_{\text{jaw}}^{\text{act}}$ is also a function of $t$ and $v$, i.e.,

$$T_{\text{act}}^{\text{jaw}} = \begin{cases} \frac{P_{\text{act}} - P_{\text{slp}}}{(\tau/\beta^2)(P_{\text{slp}} N \tau v + A - P_{\text{slp}} L/v) \alpha L/v + Nt)} \\ - E_{\text{wak}} + P_{\text{slp}} T_{\text{wak}} \end{cases}$$  \hfill (14)

Since $T_{\text{jaw}}^{\text{act}}$ and $T_{\text{slp}}^{\text{jaw}}$ in JAW are also nonnegative, we have the following constraints for $v$ and $t$

$$\min\left\{\frac{\tau t}{(d + \beta)^2} + \frac{2\tau r}{v\beta(r + \beta)} \frac{(L + Nvt) P_{\text{wak}}}{v}, \frac{(L + Nvt) P_{\text{wak}}}{v} \right\} \geq E_{\text{wak}}.$$  \hfill (15)

**Remark 2:** From the expression of $T_{\text{jaw}}^{\text{act}}$, it should be noticed that charging of each WISP tag is likely to contribute only when $N < \frac{\tau}{\beta^2} T_{\text{slp}}^{\text{jaw}}$, which means there exists an exact upper bound for the number of WISP tags above which the contribution of reader stopping is always negative. Note that this value is usually considerably large as the sleeping power $P_{\text{slp}}$ is very small in practice, e.g., around 1700 for our system parameters. Therefore, we would only focus on the performance of JAW with $\frac{\tau}{\beta^2} T_{\text{act}}^{\text{jaw}} < N < \frac{\tau}{\beta^2} T_{\text{slp}}^{\text{jaw}}$.

It is natural to ask how to design the moving speed of reader when the stationary charging time $t$ is given, which is answered by the following theorem.

**Theorem 3:** For Joint Aggressive Wake-up with $\frac{\tau}{\beta^2} T_{\text{act}}^{\text{jaw}} < N < \frac{\tau}{\beta^2} T_{\text{slp}}^{\text{jaw}}$, for any arbitrary $t$, the maximal value of QoM can only be achieved at $\bar{v}$.

Proof: The detailed proof is given in Appendix.

By Theorem 3, for an arbitrary $t$, it would be preferable to increase the patrolling speed of reader to its maximum value. On the other hand, it is also of great interest to investigate how the stationary charging time $t$ would affect the monitoring performance when the reader speed is given. In order to facilitate the description, we define notions as follows

$$\Delta E = E_{\text{wak}} - P_{\text{slp}} T_{\text{wak}},$$

$$S = \frac{1}{P_{\text{act}} - P_{\text{slp}}} (P_{\text{act}} N - \frac{\tau}{\beta^2}) > 0,$$

$$U = \frac{P_{\text{act}} L - A}{P_{\text{act}} - P_{\text{slp}} v} + \frac{\Delta E}{P_{\text{act}} - P_{\text{slp}}},$$

$$G(t) = e^{-\alpha(S(t) + U)} + \alpha N v U - \alpha L S - N v \frac{\alpha N v S t + \alpha L S + N v}{\alpha N v S t + \alpha L S + N v}.$$

Then we have the following theorem.

**Theorem 4:** For Joint Aggressive Wake-up, if $v$ is fixed, and $\frac{\tau}{\beta^2} T_{\text{act}}^{\text{jaw}} < N < \frac{\tau}{\beta^2} T_{\text{slp}}^{\text{jaw}}$, then the maximal QoM can only be achieved:

1) at $t \rightarrow \infty$, if a) $\frac{1}{\alpha} < \frac{\Delta E}{P_{\text{act}} - P_{\text{slp}}}$, or b) $\frac{\Delta E}{P_{\text{act}} - P_{\text{slp}}} > \frac{\Delta E}{P_{\text{act}} - P_{\text{slp}}}$

Proof: The detailed proof is given in the Appendix.

From Theorem 4, it is interesting that the optimal staying time depends on both the event dynamics $\alpha$ and the moving speed. Specifically, there exists a critical value for $\alpha$, above which, the staying time should be chosen as large as possible. Additionally, if such a critical value is not satisfied, it would be still better to enlarge the staying time when the speed of reader is less than a constant value (determined by the number of nodes as well as the charging and recharging parameters). Otherwise, the optimal staying time should be chosen from a small set of points including $t = 0$.

Theorem 4 can also be explained from the expression of QoM under JAW policy. By enlarging staying time $t$, it can be expected that the ratio of activation time over total cycle period is increasing to a limitation, which will definitely increase the first part of QoM. Meanwhile, the cycle period will increase linearly with the staying time $t$ which may reduce the second part of QoM. In fact, if the maximal QoM would be achieved
when \( t \) approaches \( \infty \), we have

\[
QoM^n = \lim_{t \to \infty} \left[ \frac{T_{jaw}^n}{L/v + Nt} + 1 - e^{-\alpha(L/v + Nt - T_{jaw}^n)} \right] \alpha(L/v + Nt) \\
= \frac{\tau}{N(P_{act} - P_{slp})}.
\]

where the second part would approach zero quickly when \( t \) approaches \( \infty \). Note that in this paper, \( t \) approaches \( \infty \) does not cover the case where the reader stays at one WISP tag leaving other tags not charged\(^1\). Instead, \( t \) approaches \( \infty \) means that the staying time becomes large enough that the stationary charging plays a major role in the expression of QoM.

Thus, it becomes understandable that it would always be better to enlarge the staying time \( t \) if the second part of QoM is considerably small compared with the first part as guaranteed by the conditions provided by Theorem 4. Note that the capacitor of WISP in practice always owns a limited energy capacity. Therefore, if Theorem 4 proves that under a given setting the optimal reader staying time should be as large as possible, we can design such an optimal \( t \) according to the actual capacitor size. On the other hand, when the staying time becomes larger, the effect of further enlarging \( t \) would become smaller and smaller and the QoM will approach the limitation quickly, which will also be shown in the simulation part. Therefore, we may be able to achieve a better trade-off by taking account of both the theoretical results and the practical costs.

C. QoM in Joint Periodic Wake-up

In the previous two subsections, we investigate how to plan the moving pattern of mobile reader so that the QoM at the sensor side can be maximized. On the other hand, since the random event may stay for a random period of time once it happened, the sensor itself may be able to achieve better QoM by properly scheduling its activation other than aggressively working [16]. However, due to the additional energy and time cost of waking up, it is of great interest to investigate whether sensor scheduling is beneficial and how to design the schedule. In this subsection, we will provide the condition under which the periodic activation would enhance the QoM performance. We will also show how to design the optimal periodic schedule, i.e., Joint Periodic Wake-up (JPW), which maximizes the QoM under practical constraints.

Denote the time for the reader to complete a round of traveling \( \Omega \) by \( T_{jpw} \) and the corresponding collected energy of WISP tag by \( E_{jpw} \). Then we have \( T_{jpw} = T_{jaw} = L/v + Nt \).

Besides, the energy that a WISP tag collects in period \( T_{jpw} \) is the same as that in JAW too, i.e.,

\[
E_{jpw} = E_{jaw} = \frac{\tau t}{(d + \beta)^2} + \frac{2\tau r}{v\beta(r + \beta)}. \tag{17}
\]

Each WISP tag depletes an amount of energy \( E_{wak} \) to switch from inactive state to active state which will cost \( T_{wak} \).

And we assume that each WISP tag will divide \( T_{jpw} \) into \( n \) individual slots for scheduling, i.e., \( T_{slot}^{jpw} = T_{jpw}/n \). Then the energy and time costs in the switch process also increase linearly with the slot number \( n \). And the total time spent in switch process during one reader period is upper bounded by \( T_{jpw} \), and the total energy consumption is upper bounded by \( E_{jpw} \), i.e.,

\[
nE_{wak} \leq \frac{\tau t}{(d + \beta)^2} + \frac{2\tau r}{v\beta(r + \beta)}, \quad nT_{wak} \leq L/v + Nt.
\]

Thus the \( v, t \) and \( n \) in this scenario must satisfy the following inequality.

\[
\min \left\{ \frac{\tau t}{n(d + \beta)^2} + \frac{2\tau r}{nv\beta(r + \beta)}, \frac{(L + Nvt)E_{wak}}{nv} \right\} \geq E_{wak}. \tag{18}
\]

We denote the active time in each slot by \( T_{act}^{jpw} \), the inactive time by \( T_{slp}^{jpw} \). Since all the energy is assumed to be allocated to each slot equally, we have

\[
T_{act}^{jpw} = \frac{E_{jpw}/n - P_{slp}(T_{slot}^{jpw} - T_{wak}) - E_{wak}}{P_{act} - P_{slp}},
\]

\[
T_{slp}^{jpw} = T_{slot}^{jpw} - T_{act}^{jpw}.
\]

Since all the slots are equally divided, we can treat each of them as a scheduling period \( T_{slot}^{jpw} \) in which there is a constant active duration denoted by \( T_{act}^{jpw} \). Then the scheduling can be expressed as \( (T_{act}^{jpw}, T_{slot}^{jpw}) \). According to the Eq. (6), QoM under JPW can be expressed as

\[
QoM = \frac{nT_{act}^{jpw}}{(L/v + Nt)} + \frac{n - n\alpha(L/v + Nt)/n - T_{act}^{jpw}}{\alpha(L/v + Nt)} \tag{19}
\]

where

\[
T_{act}^{jpw} = \frac{1}{n}T_{act}^{jaw} - \frac{n - 1}{n} \frac{\Delta E}{P_{act} - P_{slp}} > 0 \tag{20}
\]

with \( \Delta E = E_{wak} - P_{slp}T_{wak} \). Then the effect of slot number \( n \) is provided by the following theorem.

**Theorem 5:** For Joint Periodic Wake-up with given feasible \( v \) and \( t \),

1) if \( \frac{\alpha}{\beta} \leq \frac{\Delta E}{P_{act} - P_{slp}} \), the maximal QoM can be achieved at \( n = 1 \).

2) if \( \frac{\alpha}{\beta} > \frac{\Delta E}{P_{act} - P_{slp}} \), the maximal QoM can be achieved at the maximum \( n \) satisfying (18) and (20).

**Proof:** The proof is given in the Appendix.

From Theorem 5, it can be observed that when the expected event staying time is less than a critical value, it would be better not to periodically schedule the activation due to the cost of additional energy for waking up. Otherwise it would be better to schedule the activation as frequently as possible.

The results of Theorem 5 can also be explained from the expression of QoM under JPW, we can also see that, the first part of QoM will decrease linearly due to the additional wakeup energy \( \Delta E \). However, the second part is an increasing function for \( n \), and it will play a more significant role if the expected event staying time \( \frac{\alpha}{\beta} \) becomes large. Note that in practical setting the sleeping power \( P_{slp} \) is much smaller than \( P_{act} \) while the additional energy for waking up, i.e., \( E_{wak} \), is usually much larger than \( P_{slp}T_{wak} \). Therefore the critical value for expected event staying time \( \frac{\alpha}{\beta} \) can be well approximated by \( \frac{E_{wak}}{T_{act}^{jpw}} \).
With given reader staying time \( t \) and moving speed \( v \), Theorem 5 tells how to design the duty cycle of WISP tag so that the QoM can be maximized. On the other hand, if the slot number \( n \) has been given in advance, we can also determine the \( v \) or \( t \) in a similar way as the JAW scenario. Since the periodic schedule only add another constant term (when \( n \) is given), the effects of parameters \( v, t \) on QoM with given \( n \) are similar to those in IAW and JAW. The only difference would be some changes of the values in Theorem 4 which can be obtained after direct algebraic manipulations.

D. Summary

In this section, we investigate how to jointly mobilize the reader for distribution and to schedule sensor nodes for efficient event capture. We consider three different scenarios, i.e., Independent Aggressive Wake-up (IAW), Joint Aggressive Wake-up (JAW), and Joint Periodic Wake-up (JPW), which fit for different system complexities. For IAW, we show that there exists a maximal sensor number under which all the sensor nodes can constantly work. If the sensor number is larger than the critical value, we prove that it is always better to increase the reader speed. For JAW, we also show that the existence of the maximal sensor number by which all sensor nodes can constantly work. For the cases when the sensor number is larger than the critical value, we prove that for any given reader staying time it is always better to increase the reader speed. Moreover, with any given reader speed, we show how to design the optimal reader staying time. Specifically, we show the conditions under which it is always better to prolong the reader staying time. For JPW, which mainly focuses on scheduling the sensor nodes, we prove that if the expected event staying time is larger than a critical value, it is better not to schedule the sensor. Otherwise, it is always better to schedule the sensor as frequently as possible.

When multiple readers are employed, one direct solution is to treat all the readers as one big reader and optimize the reader patrolling speed, the reader staying time, and the WISP tag scheduling scheme. After that, each individual reader can work independently based on the optimization results. Note that it would also be interesting to investigate how to divide the WISP tags into sub-regions so that different individual subset of readers will take charge of each sub-region, however, the problem is beyond the scope of this paper and will be left as our future work.

V. Evaluation

In this section, extensive simulations are conducted to evaluate the analytical results of QoM for different application scenarios. According to the hardware settings, we can get the following system parameters: \( P_{\text{act}} = 1.42 \times 10^{-3} \text{W}, P_{\text{slp}} = 4.5 \times 10^{-6} \text{W}, P_{\text{wak}} = 1.17 \times 10^{-3} \text{W}, E_{\text{wak}} = 2.22 \times 10^{-5} \text{J}, T_{\text{wak}} = 1.9 \times 10^{-2} \text{s}, \beta = 0.2516, \tau = 4.23 \times 10^{-4} \). Meanwhile, if there is no otherwise statement, it will be assumed that: \( L = 100 \text{m}, N = 10, r = 2 \text{m}, \alpha = 0.5, \mu = 0.5 \). The distance between PoI \( i \) and \( i+1 \) is randomly selected as long as the distance is larger than \( 2r \). WISP tags are placed at each PoI to collect information of interesting events. As defined, we measure the QoM as the ratio of the number of captured events to that of total occurring events. We present both the Matlab numerical results (solid lines with discrete markers) and simulation results (dotted lines with discrete markers) to validate our analysis of QoM. For the ease of clarity, we report the simulation results for average QoM over 2000 different runs.

A. QoM of IAW

We vary the expected event staying time \( 1/\alpha \) to be 0.2, 1, 2 and 10s, and plot the QoM for different reader speeds \( v \), which is given in Fig. 4. It can be observed that the QoM increases with the reader speed \( v \), which is consistent with Theorem 1. Moreover, when the expected event staying time gets longer, the QoM also increases quickly. The reason is that a faster reader speed will increase the switching frequency between activate state and inactivate state so that the stayed events will be more likely to be captured. Meanwhile, longer event staying time will also enhance the probability that the stayed event will be captured.

In order to show the effects of \( L \), we depict the QoM against the reader speed \( v \) for different values of \( L \) in Fig. 5. It can be observed that the QoM will increase along with the reader speed \( v \) for each \( L \) which is consistent with the result of Theorem 1. On the other hand, for given \( v \), the QoM will be degraded by larger \( L \). The main reason is that the charged energy keeps the same while the cycling time \( T_{\text{act}} \) increases which reduces the switching frequency of activation state and inactive state.

B. QoM of JAW

For JAW scenario, assume \( d = 6 \text{m} \) during the stationary recharging in this JAW simulation, i.e., the reader stops at each PoI to charge WISP tag. Under the default parameters, we first show how the QoM changes with the reader speed \( v \) under different given staying time \( t \). Specifically, we let the staying time \( t \) equals 0, 1, 10, 60, and plot the corresponding QoM for varying reader speed \( v \), which is provided in Fig 6. Note that \( t = 0 \) represents the IAW policy. It can be observed that for...
different staying time \( t \), the QoM would increase along with the reader speed, which indicates the results of Theorem 3. Meanwhile, when we compare the QoM of different staying time \( t \), it can be seen that under the default settings, larger staying time \( t \) do help to improve the QoM which is also proved by Theorem 4. Moreover, the QoM approaches to a limitation (a capture probability around 0.55) when \( t \) gets large. Such a value also meets our analytical performance limitation of JAW given by (16).

However, as shown in Theorem 4, it is not always beneficial to prolong the stationary time \( t \) as large as possible. Instead, the optimal staying time \( t \) will depend on different parameters, e.g., expected event staying time, reader speed, and etc. Specifically, consider the case when the expected event staying time \( \frac{1}{\alpha} = 5 \). We let the staying time \( t \) equals 0, 0.5, 10, 60, and plot the corresponding QoM for varying reader speed \( v \), which is depicted in Fig. 7. It can be observed that for different staying time \( t \), QoM increases along with the reader speed, which validates the results of Theorem 3. However, when the reader speed becomes larger, it may not be always better to enlarge the staying time \( t \). For example, when the reader speed \( v = 20 \), it can be observed that \( t = 0.5s \) achieves better QoM than the other settings. In order to facilitate the understanding, for two different reader speeds, i.e., \( v = 7 \) and \( v = 20 \), we depict the QoM for varying stationary time \( t \), which is given in Fig. 8. It can be seen that when the moving speed is comparatively small, i.e., \( v = 7 \), it would be better to enlarge the stationary staying time for better QoM, and the QoM would monotonically increase to the performance limitation of JAW. However, when the moving speed is large, i.e., \( v = 20 \), the QoM will first increase, then decrease monotonically to the performance limitation of JAW, which means the optimal staying time is around \( t = 0.5s \) as proved by Theorem 4.

C. QoM of JPW

For JPW, the WISP tags will duty cycle its activation for improving the QoM of either IAW or JAW, rationally to maximize the QoM performance. Note that in the default
setting, the critical value of expected event staying time in Theorem 5, i.e., \( \frac{\Delta F}{T_{\text{act}}^{\text{iaw}}} \) is around 0.015. Thus for the default \( \alpha = 2 \), it is always better to increase the switching number \( n \) for better QoM. Let the staying time \( t = 5s \), we compare the QoM for different reader speeds under varying switching times \( n \) in Fig. 9. It can be seen that for each given \( v \), as predicted by Theorem 5, the increase of \( n \) improves the QoM dramatically. For example, when \( v \) is larger than 5\( m/s \), QoM becomes quite close to 1 when \( n \) is larger than 50.

Meanwhile, we can also observe that for given \( n \), the QoM still keeps increasing along with the reader speed which supports the analysis in Section IV-C. In order to show the effectiveness of rationally scheduling the available energy, we also compare JPW with JAW and IAW under the same settings. Specifically, we let the reader staying time \( t \) equal to 5\( s \) for both JAW and JPW, and choose the switching times \( n = 100 \) for JPW. Then we depict the QoM for three scenarios under varying reader speed \( v \) in Fig. 10. It can be observed that the gain of QoM for JPW is around averagely 100\% over that of JAW under the same reader staying time. For example, when the reader speed \( v = 1 \), the QoM of JAW is around 0.2 while the QoM of JPW is close to 0.8, which demonstrates the effectiveness of periodic scheduling at tag side. Meanwhile, it can also be seen that both JPW and JAW provides superior performance over IAW.

VI. CONCLUSION

In this paper, we for the first time studied the QoM problem in wireless rechargeable sensor networks. We divided the problem into three application scenarios: i) Independent Aggressive Wake-up, ii) Joint Aggressive Wake-up, and iii) Joint Periodic Wake-up, and derived the corresponding explicit performance expressions. We also analyzed extensively the impacts of varying parameters on the QoM. Our results provide fundamental insights into the scheduling problem in the wireless rechargeable sensor networks. Numerical results are offered to demonstrate the effectiveness and advantages of our solutions.

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APPENDIX

Proof of Theorem 1

Proof: From the expression of QoM in Eq. (10), we have

\[
QoM = \frac{\tau_{\text{aw}}^{\text{iaw}}}{\tau_{\text{iaw}}} + 1 + \frac{1}{2!} \alpha^2 \left( \tau_{\text{iaw}} - \tau_{\text{act}} \right)^2 + \frac{1}{3!} \alpha^3 \left( \tau_{\text{iaw}} - \tau_{\text{act}} \right)^3 + \cdots
\]

\[
= 1 + \frac{\alpha L}{\tau_{\text{iaw}}} \left( \frac{1}{2!} \alpha^2 \left( \frac{L}{v} - \tau_{\text{act}} \right)^2 + \frac{1}{3!} \alpha^3 \left( \frac{L}{v} - \tau_{\text{act}} \right)^3 + \cdots \right)
\]

\[
\text{with } f(v) = -\frac{\alpha L}{\tau_{\text{iaw}}} \left( \frac{1}{2!} \alpha^2 \left( \frac{L}{v} - \tau_{\text{act}} \right)^2 + \frac{1}{3!} \alpha^3 \left( \frac{L}{v} - \tau_{\text{act}} \right)^3 + \cdots \right)
\]

\[
\text{and } f(v) < 0. \text{ Denote } \frac{df(v)}{dv} \text{ as the derivative of } f(v) \text{ on } v.
\]

We have

\[
\frac{df(v)}{dv} = -\alpha^2 \left[ \frac{L}{v} - \tau_{\text{iaw}} \right] \left[ \frac{L}{v} - \tau_{\text{iaw}} \right]' \times \left[ 1 - \frac{\alpha L}{\tau_{\text{iaw}}} \left( \frac{L}{v} - \tau_{\text{act}} \right)^2 + \frac{1}{3!} \alpha^3 \left( \frac{L}{v} - \tau_{\text{act}} \right)^2 + \cdots \right]
\]

\[
= \alpha^2 \left[ \frac{L}{v} - \tau_{\text{iaw}} \right] \frac{LP_{\text{act}} - A}{(P_{\text{act}} - P_{\text{slp}})v^2}
\]
always positive for $\bar{v}$, and $\alpha L + \alpha N v > 0$, we get $\frac{df(v)}{dv} > 0$, indicating $f(v)$ is an increasing function of $v$. Denote $\frac{dQoM}{dv}$ as the derivative of QoM on $v$, we have

$$\frac{dQoM}{dv} = \frac{1}{\alpha L} \left[ f(v) + v \frac{df(v)}{dv} \right]$$

Now we will show that $\frac{dQoM}{dv}$ is always positive within the feasible set of $v$. Clearly, we have

$$\frac{L}{v} T_{act} = \frac{L}{v} - \frac{\alpha L + \alpha N v}{P_{act} - P_{slp}}$$

which can be denoted as $M + B$ with $M = \frac{P_{act} L - A}{P_{act} - P_{slp}}$ and $B = \frac{E_{wak} - P_{slp} T_{wak}}{P_{act} - P_{slp}}$. Then we have

$$f(v) + v \frac{df(v)}{dv} = 1 - \frac{M}{v} - \alpha B - e^{-\frac{M}{v} - \alpha B}$$

$$\frac{M}{v} \left[ 1 - e^{-\frac{M}{v} - \alpha B} \right]$$

$$= 1 - \alpha B - \frac{M}{v} e^{-\frac{M}{v} - \alpha B}$$

Denote $\hat{f}(v) = f(v) + v \frac{df(v)}{dv}$. We have $e^{-1 \alpha B} \hat{f}(v) = (1 - \alpha B) e^{-1 \alpha B} - (1 + \frac{M}{v} e^{-\frac{M}{v} - \alpha B})$ which is a decreasing function along with $v \geq 0$. On the other hand, $\frac{d\hat{f}(v)}{dv}$ is positive when $v$ approaches infinity which proves that $f(v)$ is positive when $v$ approaches $\infty$. Therefore, $\hat{f}(v)$ would be always positive for $v \geq 0$, which proves that the maximum value of QoM can only be achieved at $\hat{v}_{max}$.

**Proof of Theorem 3**

**Proof:** Following similar algebraic manipulations as the proof of Theorem 1, we have

$$QoM = 1 + \frac{v}{\alpha L + \alpha N v} \hat{f}(v),$$

where $\hat{f}(v) = -\frac{\alpha L}{v} + \alpha N v + T_{act}^2 \frac{\alpha N v}{v} + T_{jmax}^2 + \cdots$. Note that $T_{jmax}^2$ can be calculated by (14), and $\hat{f}(v) < 0$. On the other hand, we have

$$\frac{d\hat{f}(v)}{dv} = \alpha \frac{L P_{act} - A}{(P_{act} - P_{slp}) v^2} \left( 1 - e^{-\frac{M}{v} + \alpha N v + T_{act}^2} \right),$$

where $A = \frac{2 \pi}{\beta + \gamma}$, and $\frac{d\hat{f}(v)}{dv} > 0$. Then, for the quality of monitoring, we have

$$\frac{dQoM}{dv} = \frac{L}{\alpha L + \alpha N v} \frac{\hat{f}(v)}{\alpha L + \alpha N v} \frac{d\hat{f}(v)}{dv}$$

$$= \frac{1}{\alpha L + \alpha N v} \left[ \hat{f}(v) + v \frac{df(v)}{dv} \right]$$

$$> \frac{1}{\alpha L + \alpha N v} \left[ \hat{f}(v) + v \frac{df(v)}{dv} \right]$$

With a similar technique as in the proof of Theorem 1, we can prove that $\frac{dQoM}{dv}$ is always positive along with feasible $v$. Thus the maximum QoM can only be achieved at $\hat{v}_{max}$.

**Proof of Theorem 4**

**Proof:** Since $QoM = 1 + \frac{v}{\alpha L + \alpha N v} \hat{f}(v)$, where $\hat{f}(v) = -\frac{\alpha L}{v} + \alpha N v + T_{act}^2 + \frac{\alpha N v}{v} + T_{jmax}^2 + \cdots$, and $T_{jmax}$ is calculated from (14). For simplicity of expression, we denote $N v + T_{act} - T_{jmax} = St + U \geq U$. Hence we need to determine the sign of

$$\frac{dQoM}{dt} = \frac{v}{L + N v t} \left[ \sigma \frac{N v}{\alpha L + \alpha N v t} + S \right] \left( e^{-\alpha (St + U)} - 1 \right) + \frac{\alpha N v}{\alpha L + \alpha N v t} (St + U)$$

which is equivalent to investigate the sign of the following function

$$G(t) = e^{-\alpha (St + U)} + \alpha N v t - \alpha L - \alpha N v t + \alpha N v t + \alpha L + \alpha N v t$$

Let $G_1(v) = \alpha N v t - \alpha L - \alpha N v t + \alpha N v t + \alpha L + \alpha N v t$, which can be expressed as

$$G_1(v) = (P_{slp} + \alpha \Delta E - P_{act}) N v + \alpha \left( \frac{L T}{\beta^2} - \frac{2 N \tau}{\beta + \gamma} \right),$$

where $\Delta E = E_{wak} - P_{slp} T_{wak}$. Note that $\alpha \left( \frac{L T}{\beta^2} - \frac{2 N \tau}{\beta + \gamma} \right) > 0$. It is straightforward to see that if $G_1(v) > 0$, it can be guaranteed that $G(t) > 0$. Thus it would be always better to enlarge the staying time, i.e., the maximum QoM is achieved when $t \rightarrow \infty$, if either of the following conditions is satisfied

1. $\frac{1}{\alpha} \leq \frac{T_{jmax}}{P_{act} - P_{slp}}$;
2. $\frac{2 N \tau}{\beta + \gamma} < \frac{P_{act} - P_{slp} - \alpha \Delta E}{P_{act} - P_{slp}}$ and $v \leq \frac{1}{(P_{act} - P_{slp} - \alpha \Delta E) N v t + \alpha N v t}.$

Otherwise, the maximum QoM can only be achieved at the points where $G(t) = 0$ or $t = 0$. It should be noticed that, from the expression of $G(t)$, there are at most two points which satisfy $G(t) = 0$. Thus we just need to check the values of at most three points2 to find the $t^*$ which maximizes the QoM.

**Proof of Theorem 5**

**Proof:** For simplicity, we denote the QoM of JPW with $n$ slots as $QoM_n$. We first investigate the difference of $n$-slot and 1-slot schedule. Define $\Delta QoM = QoM_n - QoM_1$, which can be calculated as

$$\Delta QoM = \frac{(n - 1) \Delta E}{(P_{act} - P_{slp}) T_{jmax}} + \frac{1}{\alpha T_{jmax}} \left[ (n - 1) \right]$$

$$+ e^{-\alpha (T_{jmax}^2 - T_{act}^2)} - n e^{-\alpha (T_{jmax}^2 - T_{act}^2) + E_P}$$

Denote $\Delta E_P = T_{act} - P_{slp}$ and $T_{jmax} = \frac{1}{n} (T_{jmax} - T_{act} - E_P)$. By taking derivative of $\Delta QoM$, we have

$$\frac{d\Delta QoM}{dt} = \frac{\Delta E_P}{T_{jmax}^2} + \frac{1}{\alpha T_{jmax}^2} \left[ (1 + \alpha T_{jmax}) e^{-\alpha (T_{jmax} + \Delta E_P)} \right]$$

$$= \frac{e^{\alpha (E_P)} - (1 - \alpha E_P)}{\alpha T_{jmax}^2} \left[ (1 - \alpha E_P) e^{-\alpha (T_{jmax} + \Delta E_P)} \right]$$

2If some points are not feasible, we just need to check the boundary points and the remaining points satisfying $G(t) = 0$. 

By utilizing the property of function $xe^{-x}$ similar as in the proof of Theorem 1, it can be proved that:

If $\frac{1}{\alpha} \leq E_P$, then $\frac{dQoM}{dn} < 0$, which indicates that $QoM$ is a decreasing function of $n$, thus it would be better not to divide the $T_{jaw}$ into different slots and schedule the activation. Otherwise, if $\frac{1}{\alpha} > E_P$, then in order to enhance $QoM$, $n$ should be no greater than $n^*$ satisfying

$$(1 + \alpha T_{jaw})e^{−\alpha T_{jaw}} = (1 − \alpha E_P)e^{−(1−\alpha E_P)}.$$ 

Note that the left side is a decreasing function of $T_{jaw}$ and the right side can only be achieved when $T_{jaw} = \Delta E_P$ with $n$ approaches $\infty$. Recall that $T_{jaw}$ should be positive, thus the maximum $QoM$ will be achieved at the maximum value satisfying (18) and (20).

References


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