

# AoI-Constrained Energy Efficiency Optimization in Random-Access Poisson Networks

Fangming Zhao, Xinghua Sun, Wen Zhan, Bingpeng Zhou, Xiaoxia Huang  
 School of Electronics and Communication Engineering, Sun Yat-sen University  
 zhaofm@mail2.sysu.edu.cn, {sunxinghua, zhanw6, zhoubp3, huangxiaoxia}@mail.sysu.edu.cn

**Abstract**—For battery-limited IoT networks, the energy efficiency and Age of Information (AoI) are two key performance metrics. Yet the tradeoff between energy efficiency and AoI remains unclear for large-scale networks since the analysis becomes challenging due to the couple queue problem. This paper aims to address this issue by studying the performance limit of energy efficiency under AoI constraint.

Specifically, we evaluate the energy efficiency via the expected number of successfully transmitted packets during each transmitter’s life time for which the explicit expression is derived based on the spatio-temporal analytical framework in [1]. By further taking the AoI constraint into consideration, explicit expressions of the Maximum Expected Number of Successfully Transmitted Packets (MENSTP) and the corresponding channel access probability are obtained. The analysis reveals that if the Power Ratio of the Transmission state and the Waiting state (PRTW) equals one, i.e., the energy consumption per time slot of the transmission state equals to that of the waiting state, then the expected number of successfully transmitted packets during each transmitter’s life time and the peak AoI can be optimized simultaneously; otherwise, the MENSTP declines with a stringent AoI constraint. Moreover, the performance gap enlarges when the PRTW or the node distribution density increases which reveals a crucial tradeoff between the energy efficiency and AoI. It is therefore of importance to properly tuning the channel access probability to strike an optimal energy-age tradeoff in battery-limited large-scale IoT networks.

**Index Terms**—Energy efficiency, age of information, random access.

## I. INTRODUCTION

Energy efficiency and the timeliness of information are two critical performance metrics for many Internet of Thing (IoT) applications, such as the forest fire warning system, in which battery-limited sensor nodes are places in remote areas for monitoring the forest fire. A high energy efficiency is required to support a long battery life time and the information reporting

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needs to be timely, especially in the state of emergency. To measure the freshness of the status information, Age of information (AoI), which is defined as the time elapsed since the latest packet has been delivered, was proposed in [2] and has drawn wide attention in existing literature.

Extensive studies have been conducted to optimize the AoI performance when there is an energy constraint. For instance, various works considered energy harvest sources with finite or infinite battery capacity [3]–[6]. By proposing various types of information updating policy, such as the lazy updating policy [7], the monotone threshold policy [8] and the optimal online status policy [9], the average AoI performance was optimized with constraints on energy harvest rate. It was clearly pointed out that there exists an age-energy tradeoff in energy-constrained networks, where the optimization of one metric is usually achieved at the cost of the other. Note that the above works focus on AoI performance optimization because the devices can be recharged via energy harvest. If the battery replenishment is infeasible, then the energy efficiency gains the overarching priority, for which it is of paramount importance to study how to optimize the energy efficiency with AoI constraint.

This issue is particularly challenging in the multiple access scenario as queueing status of neighboring nodes coupled with each other due to the interference. Optimizing the energy efficiency by constraining the AoI in cognitive sensor network has been considered in [10]. However, the channel error probability was assumed to be a constant value and is unrelated with the interference among nodes. The effect of interference was considered in [11] while the scenario is limited to two-node case. An energy cost minimization problem with average AoI constraints was studied in [12] by using Lyapunov optimization theory. In this work, the sensors share orthogonal sub-channel and only effect of the noise was taken into consideration. The sampling cost was minimized in [13] subject to average AoI constraints in a wireless channel, yet the formulation only captures channel fading and the noise. In short, above works ignored or idealized key physical attributes in wireless systems, i.e., the interference, and node distribution density, from which it remains largely unknown on how those factors affect the tradeoff between energy efficiency and AoI performance, and how to perform the AoI-constrained energy efficiency optimization when those factors are included.

This paper aims to address those open issues based on a

spatio-temporal analytical framework in [1], which was established by combining the stochastic geometry and queueing theory. The contributions of this paper are as follows:

- We derive an explicit expression of the expected number of successfully transmitted packets during each transmitter's life time for a Poisson bipolar network by taking the physical attributes, i.e., the interference, channel fading and the node distribution density, into consideration.
- To study the tradeoff between energy efficiency and AoI performances, we first examine whether the expected number of successfully transmitted packets during each transmitter's life time and the peak AoI can be optimized simultaneously. It is found that they can be optimized simultaneously only when the Power Ratio of the Transmission state and the Waiting state (PRTW) equals one. The tradeoff between the energy efficiency and the peak AoI becomes significant when the PRTW increases, which reveals that a proper tuning of the channel access probability is of necessity.
- We further optimize the expected number of successfully transmitted packets with a constraint of the peak AoI by tuning the channel access probability. Explicit expressions of both the MENSTP and the optimal channel access probability are obtained. It is found that when the PRTW is larger than one, the feasible region of the optimal channel access probability can be divided into two parts depending on the peak AoI constraint. When the AoI constraint is not stringent, the optimal channel access probability is determined by the PRTW instead of the peak AoI constraint; otherwise, the optimal channel access probability depends on the peak AoI constraint and is insensitive to the PRTW.

The rest of the paper is organized as follows. Section II presents the system model and the derivation of the expected number of successfully transmitted packets during each transmitter's life time. In Section III, the expected number of successfully transmitted packets during each transmitter's life time is optimized by tuning channel access probability. Simulation results are presented in Section IV. Finally, concluding remarks and future work are summarized in Section V.

## II. SYSTEM MODEL AND PRELIMINARY ANALYSIS

Let us consider a Poisson bipolar network where transmitters are scattered according to a homogeneous Poisson point process (PPP) of density  $\lambda$ . Each transmitter is paired with a receiver that is situated in distance  $R$  and oriented at a random direction. In this network, the time is slotted into equal-length intervals and the transmission of each packet lasts for one slot. The packets arrive at each transmitter following independent Bernoulli processes of mean rate  $\xi$ . We assume each transmitter is equipped with a unit-size buffer and hence a newly incoming packet will be dropped if the buffer is full. At the beginning of each time slot, transmitters with non-empty buffers will access the channel with a fixed channel access probability  $q$ .

Due to the broadcast nature of wireless medium, i.e., all the nodes utilize the same spectrum for packet delivery, each transmission would be affected by others' due to the interference. Consider a packet is successfully delivered if the received SINR exceeds a decoding threshold  $\theta$ . Therefore, the corresponding probability of successful transmission for node  $i$  can be written as

$$p_i(t) = P(\text{SINR}_i(t) > \theta). \quad (1)$$

Similar to [1], we assume a high mobility random walk model for the positions of transmitters. Therefore, the received  $\text{SINR}_i(t)$  of each transmitter  $i$ ,  $i \in \mathbb{N}$ , can be considered as i.i.d. across time  $t$ . By symmetry, the probability of successful transmission is also identical across all the transmitters. To that end, we drop the indices  $i$  and  $t$  in (1) and denote  $p$  as the probability of successful transmission. The probability of successful transmission of a generic transmitter has been obtained in [1] as

$$p = \exp \left\{ -\frac{\lambda \pi \theta^{\frac{2}{\alpha}} R^2}{\text{sinc}(\frac{2}{\alpha})} \frac{q\xi}{\xi + pq(1 - \xi)} - \theta R^\alpha \gamma^{-1} \right\}, \quad (2)$$

where  $\alpha$  is the path-loss exponent,  $\gamma$  is the SNR at the receiver. In the following, we let  $c = \pi \theta^{\frac{2}{\alpha}} / \text{sinc}(\frac{2}{\alpha})$  for simplicity. The dynamics of packet transmissions over each wireless link can be regarded as a Geo/Geo/1/1 queue with the service rate  $qp$ .

In this paper, we leverage the peak AoI  $A_p$  as a metric for the timeliness of information, which is defined as the time average of age values at time instants when there is a packet transmitted successfully. The peak AoI  $A_p$  in the considered scenario has been obtained in [1] as

$$A_p = \frac{1}{\xi} + \frac{2}{qp} - 1. \quad (3)$$

Different from [1], we assume that each transmitter has a finite amount of initial energy  $E$ , and thus the life of a transmitter comes to an end if its battery runs out. When the network size is large, the expected life time of each node is assumed to be identical, which is denoted as  $T$  in unit of time slots. During the life time, each node could be in the following four states: **1) idle state**, i.e., the queue is empty; **2) waiting state**, i.e. the queue is not empty and the nodes do not transmit; **3) successful transmission state**, i.e., the packet transmission is successful; **4) failure state**, i.e., the packet transmission fails. Note that no matter the transmission is successful or not, the amount of energy consumption is identical. Let  $T_I$ ,  $T_W$ ,  $T_S$ ,  $T_F$  denote the expected number of time slots for each node being in the idle, waiting, successful and failure transmission states during its life time, respectively. We have

$$T = T_S + T_F + T_W + T_I. \quad (4)$$

Let  $P_I$ ,  $P_W$  and  $P_T$  denote the energy consumption in the idle, waiting and transmission states per time slot, respectively. According to the total energy constraint of each node, we have

$$\begin{aligned} E &= P_W T_W + P_I T_I + P_T (T_S + T_F) \\ &= P_W (T_W + T_I) + P_T (T_S + T_F), \end{aligned} \quad (5)$$

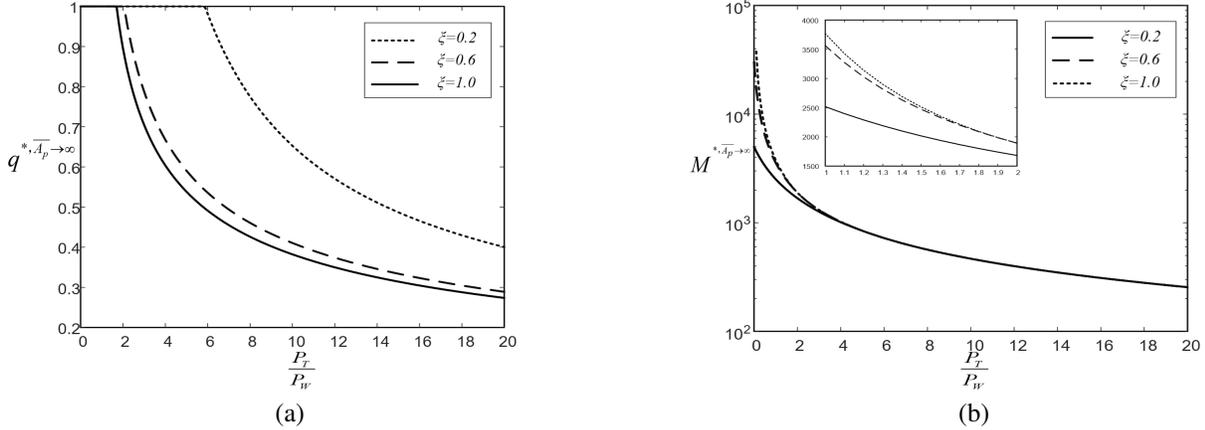


Fig. 1. Optimal channel access probability  $q^{*,\bar{A}_p \rightarrow \infty}$  and the corresponding MENSTP  $M^{*,\bar{A}_p \rightarrow \infty}$  versus the PRTW  $\frac{P_T}{P_W}$ .  $E = 2 * 10^4 J$ ,  $P_W = 1 W$ ,  $\lambda = 0.01$ ,  $\alpha = 3$ ,  $\gamma = 20$ ,  $R = 3$ ,  $\xi \in \{0.2, 0.6, 1\}$ . (a)  $q^{*,\bar{A}_p \rightarrow \infty}$  versus  $\frac{P_T}{P_W}$ . (b)  $M^{*,\bar{A}_p \rightarrow \infty}$  versus  $\frac{P_T}{P_W}$ .

where we assume that the energy consumption per time slot in the idle state equals that in the waiting state, i.e.,  $P_I = P_W$ , for simplicity. In each transmission attempt, with probability  $p$ , the transmitter spends one time slot in successful transmissions; otherwise, with probability  $1 - p$ , it spends one time slot in failure. Therefore, we have

$$\frac{T_S}{T_F} = \frac{p}{1-p}. \quad (6)$$

Recall that each transmitter accesses the channel with probability  $q$  in each time slot; otherwise, it stays in the waiting state. Thus,

$$\frac{T_W}{T_S + T_F} = \frac{1-q}{q}. \quad (7)$$

Since the mean service rate of each queue is given by  $qp$ , we have

$$\frac{T_S}{T_W + T_S + T_F} = qp. \quad (8)$$

Let  $\rho$  denote the non-empty probability of each transmitter's queue which has been derived in [1] as

$$\rho = \frac{\xi}{\xi + qp - \xi qp}, \quad (9)$$

and we also have

$$\frac{T_W + T_S + T_F}{T_I} = \frac{\rho}{1-\rho}. \quad (10)$$

In this paper, we are interested in the expected number of successfully transmitted packets  $M$  during each transmitter's life time, as it is an important performance metric that reflects the energy efficiency. Since one packet lasts for one time slot, the expected number of successfully transmitted packets equals that of time slots that transmitters spend in successful transmission state, we have

$$M = T_S = \frac{E\xi qp}{P_W(1-q)\xi + P_I qp(1-\xi) + P_T q\xi}, \quad (11)$$

by combining (4)-(9). It is clear from (11) that the expected number of successfully transmitted packets  $M$  depends on the channel access probability  $q$ .

### III. AOI-CONSTRAINED ENERGY EFFICIENCY OPTIMIZATION

In this section, we consider to maximize the expected number of successfully transmitted packets  $M$  under the constraint that the peak AoI  $A_p$  is expected to no larger than a certain threshold  $\bar{A}_p$ , by tuning the channel access probability  $q$ . We have the following optimization problem

$$\begin{aligned} M^* &= \max_{q \in (0,1]} M \\ \text{s.t. } & A_p \leq \bar{A}_p, \end{aligned} \quad (12)$$

The following theorem shows the solution to the optimization problem (12).

**Theorem 1.** *The Maximum Expected Number of Successfully Transmitted Packets (MENSTP) under constraint  $A_p \leq \bar{A}_p$ ,  $M^*$  is given by (13), otherwise (12) has no feasible solution. The corresponding optimal channel access probability  $q^*$  is given by (14), in which the lower bound of the feasible solution set  $q_{\min}$  given by*

$$q_{\min} = \frac{\mathbb{W}_0 \left( \frac{-2\lambda c R^2 \xi \exp\{\theta R^\alpha \gamma^{-1}\}}{2(1-\xi) + \xi(\bar{A}_p - \frac{1}{\xi} + 1)} \right)}{\frac{\lambda c R^2 \xi (\bar{A}_p - \frac{1}{\xi} + 1)}{2(1-\xi) + \xi(\bar{A}_p - \frac{1}{\xi} + 1)}}, \quad (15)$$

where  $\mathbb{W}_0(\cdot)$  is the principal branch of the Lambert  $W$  function, and  $p_*$  is the non-zero root of the following equation

$$p_* = \exp \left\{ -\lambda c R^2 \frac{\xi}{\xi + p_*(1-\xi)} - \theta R^\alpha \gamma^{-1} \right\}. \quad (16)$$

*Proof.* Due to lack of space, we sketch the outline here.

- Prove that  $A_p \leq \bar{A}_p$  is equivalent to  $q \geq q_{\min}$ .
- Solve  $q_{\min}$  by combining (2), (3) and  $A_p = \bar{A}_p$ .
- Solve the unconstrained optimization problem of  $M$  by combining  $\frac{\partial M}{\partial q}|_{q \rightarrow 0}$ ,  $\frac{\partial M}{\partial q}|_{q=1}$  and  $\frac{\partial M}{\partial q} = 0$ .
- Prove that  $q^{*,\bar{A}_p \rightarrow \infty} \leq q_{\text{AoI}}^*$ . The solution to (12) can then be obtained by comparing  $q_{\min}$  and  $q^{*,\bar{A}_p \rightarrow \infty}$ .

□

<sup>1</sup> $q_{\text{AoI}}^*$  is the optimal channel access probability to achieve the optimal peak AoI, which has been derived in [1].

$$M_{\xi}^* = \begin{cases} \frac{2E\xi}{P_W \left( \bar{A}_p + 1 - \frac{1}{\xi} - \left( \bar{A}_p - 1 + \frac{1}{\xi} \right) q_{\min} \right) + P_T q_{\min}}, & \text{if } \lambda cR^2 > \frac{[\xi + p_*(1-\xi)]^2}{\xi^2 \frac{P_T}{P_W} + p_*\xi(1-\xi)} \text{ and} \\ & 2\lambda cR^2 \exp\{\theta R^\alpha \gamma^{-1} + 1\} - \frac{1-\xi}{\xi} \leq \bar{A}_p \leq \frac{\lambda cR^2 \left( 1 + \sqrt{1 + \frac{4}{\lambda cR^2} \left( \frac{P_T}{P_W} - 1 \right)} \right)}{\exp\left\{ \frac{-2}{\sqrt{1 + \left( \frac{4}{\lambda cR^2} \left( \frac{P_T}{P_W} - 1 \right) \right)}} - \theta R^\alpha \gamma^{-1} \right\}}, \\ \frac{\frac{E}{P_W} \exp\left\{ -\frac{2}{1 + \sqrt{1 + \frac{4}{\lambda cR^2} \left( \frac{P_T}{P_W} - 1 \right)}} - \theta R^\alpha \gamma^{-1} \right\}}{\frac{\lambda cR^2}{2} \left( 1 + \sqrt{1 + \frac{4}{\lambda cR^2} \left( \frac{P_T}{P_W} - 1 \right)} \right) + \left( \frac{P_T}{P_W} - 1 \right)}, & \text{if } \lambda cR^2 > \frac{[\xi + p_*(1-\xi)]^2}{\xi^2 \frac{P_T}{P_W} + p_*\xi(1-\xi)} \text{ and } \bar{A}_p \geq \frac{\lambda cR^2 \left( 1 + \sqrt{1 + \frac{4}{\lambda cR^2} \left( \frac{P_T}{P_W} - 1 \right)} \right)}{\exp\left\{ \frac{-2}{\sqrt{1 + \left( \frac{4}{\lambda cR^2} \left( \frac{P_T}{P_W} - 1 \right) \right)}} - \theta R^\alpha \gamma^{-1} \right\}}, \\ \frac{Ep_*\xi}{P_W p_*(1-\xi) + P_T \xi}, & \text{if } \lambda cR^2 \leq \frac{[\xi + p_*(1-\xi)]^2}{\xi^2 \frac{P_T}{P_W} + p_*\xi(1-\xi)} \text{ and } \bar{A}_p \geq \frac{1}{\xi} + \frac{2}{p_*} - 1 \end{cases} \quad (13)$$

$$q_{\xi}^* = \begin{cases} W_0 \left( \frac{2\lambda cR^2 \xi \exp\{\theta R^\alpha \gamma^{-1}\}}{2(1-\xi) + \xi \left( \bar{A}_p - \frac{1}{\xi} + 1 \right)} \right) / \left( \frac{\lambda cR^2 \xi \left( \bar{A}_p - \frac{1}{\xi} + 1 \right)}{2(1-\xi) + \xi \left( \bar{A}_p - \frac{1}{\xi} + 1 \right)} \right), & \text{if } \lambda cR^2 > \frac{[\xi + p_*(1-\xi)]^2}{\xi^2 \frac{P_T}{P_W} + p_*\xi(1-\xi)} \text{ and } 2\lambda cR^2 \exp\{\theta R^\alpha \gamma^{-1} + 1\} - \frac{1-\xi}{\xi} \leq \bar{A}_p \leq \frac{\lambda cR^2 \left( 1 + \sqrt{1 + \frac{4}{\lambda cR^2} \left( \frac{P_T}{P_W} - 1 \right)} \right)}{\exp\left\{ \frac{-2}{\sqrt{1 + \left( \frac{4}{\lambda cR^2} \left( \frac{P_T}{P_W} - 1 \right) \right)}} - \theta R^\alpha \gamma^{-1} \right\}}, \\ \frac{1}{\left( \frac{\lambda cR^2}{2} \left( 1 + \sqrt{1 + \frac{4}{\lambda cR^2} \left( \frac{P_T}{P_W} - 1 \right)} \right) - \frac{1-\xi}{\xi} \exp\left\{ -\frac{2}{1 + \sqrt{1 + \frac{4}{\lambda cR^2} \left( \frac{P_T}{P_W} - 1 \right)}} - \theta R^\alpha \gamma^{-1} \right\} \right)}, & \text{if } \lambda cR^2 > \frac{[\xi + p_*(1-\xi)]^2}{\xi^2 \frac{P_T}{P_W} + p_*\xi(1-\xi)} \text{ and } \bar{A}_p \geq \frac{\lambda cR^2 \left( 1 + \sqrt{1 + \frac{4}{\lambda cR^2} \left( \frac{P_T}{P_W} - 1 \right)} \right)}{\exp\left\{ \frac{-2}{\sqrt{1 + \left( \frac{4}{\lambda cR^2} \left( \frac{P_T}{P_W} - 1 \right) \right)}} - \theta R^\alpha \gamma^{-1} \right\}}, \\ 1, & \text{if } \lambda cR^2 \leq \frac{[\xi + p_*(1-\xi)]^2}{\xi^2 \frac{P_T}{P_W} + p_*\xi(1-\xi)} \text{ and } \bar{A}_p \geq \frac{1}{\xi} + \frac{2}{p_*} - 1, \end{cases} \quad (14)$$

## A. Discussion

1)  $\bar{A}_p \rightarrow +\infty$ : Let us first examine the case when  $\bar{A}_p \rightarrow \infty$ , with which based on Theorem 1, the MENSTP  $M^*, \bar{A}_p \rightarrow \infty$  is give by

$$M^*, \bar{A}_p \rightarrow \infty = \begin{cases} \frac{\frac{E}{P_W} \exp\left\{ -\frac{2}{1 + \sqrt{1 + \frac{4}{\lambda cR^2} \left( \frac{P_T}{P_W} - 1 \right)}} - \theta R^\alpha \gamma^{-1} \right\}}{\frac{\lambda cR^2}{2} \left( 1 + \sqrt{1 + \frac{4}{\lambda cR^2} \left( \frac{P_T}{P_W} - 1 \right)} \right) + \left( \frac{P_T}{P_W} - 1 \right)}, & \text{if } \lambda cR^2 > \frac{[\xi + p_*(1-\xi)]^2}{\xi^2 \frac{P_T}{P_W} + p_*\xi(1-\xi)}, \\ \frac{Ep_*\xi}{P_W p_*(1-\xi) + P_T \xi}, & \text{otherwise,} \end{cases} \quad (17)$$

which is achieved when the optimal channel access probability  $q^*, \bar{A}_p \rightarrow \infty$  is set to be

$$q_{\xi}^*, \bar{A}_p \rightarrow \infty = \begin{cases} \frac{1}{\left( \frac{\lambda cR^2}{2} \left( 1 + \sqrt{1 + \frac{4}{\lambda cR^2} \left( \frac{P_T}{P_W} - 1 \right)} \right) - \frac{1-\xi}{\xi} \exp\left\{ -\frac{2}{1 + \sqrt{1 + \frac{4}{\lambda cR^2} \left( \frac{P_T}{P_W} - 1 \right)}} - \theta R^\alpha \gamma^{-1} \right\} \right)}, & \text{if } \lambda cR^2 > \frac{[\xi + p_*(1-\xi)]^2}{\xi^2 \frac{P_T}{P_W} + p_*\xi(1-\xi)}, \\ 1, & \text{otherwise.} \end{cases} \quad (18)$$

Fig. 1 demonstrates how the optimal channel access probability  $q^*, \bar{A}_p \rightarrow \infty$  and the corresponding MENSTP  $M^*, \bar{A}_p \rightarrow \infty$  vary with the PRTW  $\frac{P_T}{P_W}$  under different values of the packet arrival rate  $\xi$ . It is clear from Fig. 1a that  $q^*, \bar{A}_p \rightarrow \infty = 1$  when  $\frac{P_T}{P_W}$  is small, indicating that each transmitter should transmit at each time slot due to a low energy consumption in the transmission state. As  $\frac{P_T}{P_W}$  increases,  $q^*, \bar{A}_p \rightarrow \infty$  decreases. Intuitively, a high energy consumption in the transmission state makes the cost of transmission failures unaffordable, and thus each transmitter should reduce the channel access probability so as to enhance the probability of successful transmission. Due to similar reasons, the optimal channel access probability also decreases as the packet arrival rate  $\xi$  increases, as Fig. 1a illustrates. Moreover, from Fig. 1b, we observe that when  $\frac{P_T}{P_W}$  is small, a larger arrival rate always leads to a better  $M^*, \bar{A}_p \rightarrow \infty$ . When  $\frac{P_T}{P_W}$  increases, it is interesting to see that  $M^*, \bar{A}_p \rightarrow \infty$  is not sensitive to the packet arrival rate  $\xi$  and becomes solely dependent on  $\frac{P_T}{P_W}$ . This is because, the optimal channel access probability is low with a large  $\frac{P_T}{P_W}$ , with which a newly-incoming packet would often be discarded since it sees a full buffer. Thus the increment of the arrival rate is not helpful for improving the performance of MENSTP and is

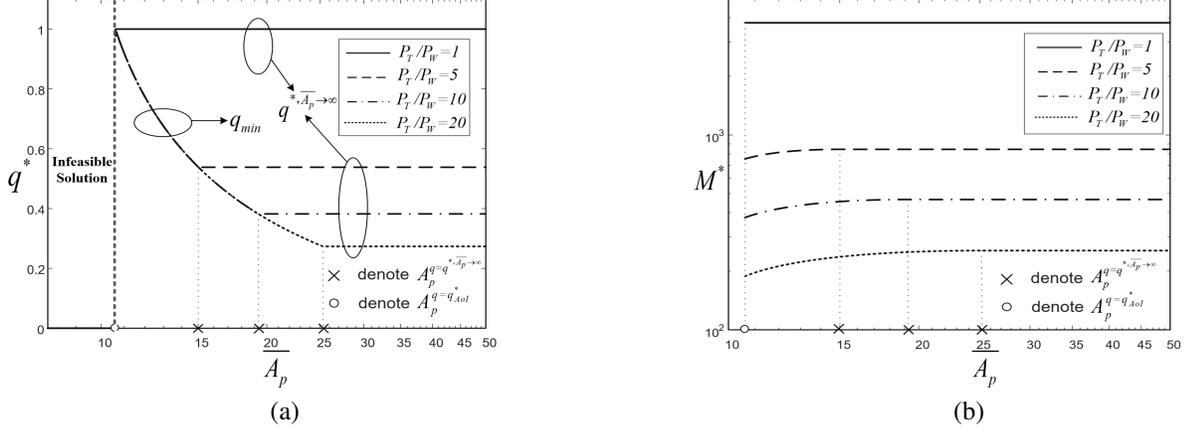


Fig. 2. Optimal channel access probability  $q^*$  and the corresponding MENSTP  $M^*$  versus the timeliness constraint  $\bar{A}_p$ .  $E = 2 * 10^4 J$ ,  $P_W = 1 W$ ,  $\lambda = 0.01$ ,  $\alpha = 3$ ,  $\gamma = 20$ ,  $R = 3$ ,  $\xi = 1$ ,  $\frac{P_T}{P_W} \in \{1, 5, 10, 20\}$ .

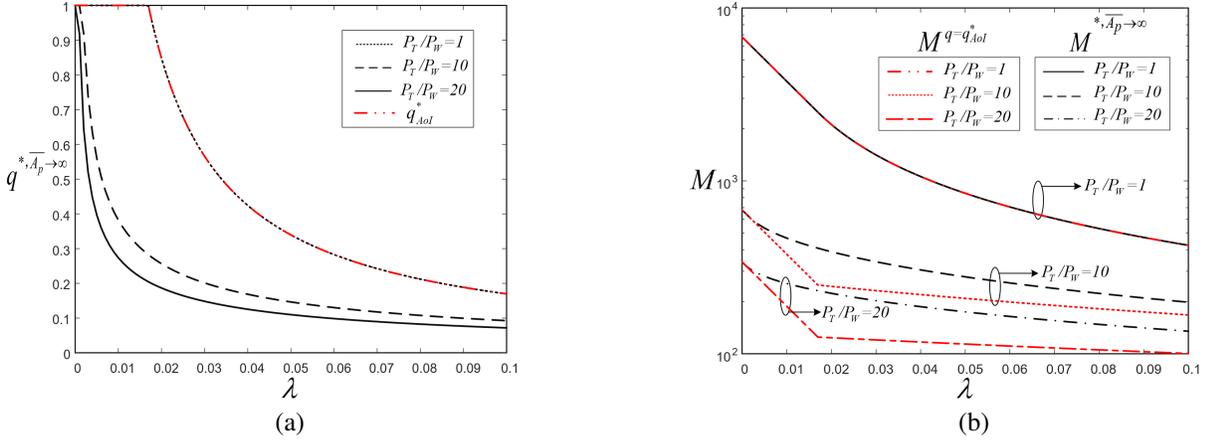


Fig. 3. Optimal channel access probability  $q^*, \bar{A}_p \rightarrow \infty$  and the corresponding MENSTP  $M^*, \bar{A}_p \rightarrow \infty$ ,  $M^{q=q_{AoI}^*}$  versus the node density  $\lambda$ .  $E = 2 * 10^4 J$ ,  $P_W = 1 W$ ,  $\lambda = 0.01$ ,  $\alpha = 3$ ,  $\gamma = 20$ ,  $R = 3$ ,  $\xi = 1$ ,  $\frac{P_T}{P_W} \in \{1, 10, 20\}$ . (a)  $q^*, \bar{A}_p \rightarrow \infty$  versus  $\lambda$ . (b)  $M^*, \bar{A}_p \rightarrow \infty$ ,  $M^{q=q_{AoI}^*}$  versus  $\lambda$ .

solely determined by  $\frac{P_T}{P_W}$ .

2)  $\bar{A}_p < +\infty$ : With a finite peak AoI constraint  $\bar{A}_p < \infty$ , Fig. 2 presents the optimal channel access probability and the corresponding MENSTP. With  $\frac{P_T}{P_W} = 1$ , there are two cases for the optimal channel access probability, i.e., (1) infeasible region; (2)  $q^* = 1$ . In case (1), as  $\bar{A}_p$  is too small such that no feasible solution exists. When the  $\bar{A}_p$  constraint is relaxed, i.e., in case (2), the optimal channel access probability  $q^* = 1$  regardless of  $\bar{A}_p$ .

When  $\frac{P_T}{P_W} > 1$ , as shown in Fig. 2, the feasible region of the optimal channel access probability is further partitioned into two parts, i.e., (1)  $q^* = q_{\min}$  when  $\bar{A}_p \leq A_p^{q=q^*, \bar{A}_p \rightarrow \infty}$ ; (2)  $q^* = q^*, \bar{A}_p \rightarrow \infty$  when  $\bar{A}_p > A_p^{q=q^*, \bar{A}_p \rightarrow \infty}$ . In case (1), the optimal channel access probability  $q^*$  decreases as  $\bar{A}_p$  increases. As we have shown in Fig. 1, a lower access probability is required to optimize  $M$ . When the AoI constraint further looses and  $\bar{A}_p$  exceeds  $A_p^{q=q^*, \bar{A}_p \rightarrow \infty}$ ,  $q^*$  is solely determined by  $\frac{P_T}{P_W}$ , which is consistent with the analysis in Fig. 1.

### B. Tradeoff between Energy Efficiency and AoI

So far, we have demonstrated the MENSTP  $M^*$  and corresponding optimal channel access probability  $q^*$ . Note that

instead of focusing on energy efficiency, lots of existing works focus on the AoI optimization, i.e.,  $q_{AoI}^* = \arg \min_q q$ . Due to the difference in optimization objective,  $q_{AoI}^*$  might be different from  $q^*$ , which leads to energy efficiency performance loss if the focus is on AoI.

To evaluate the tradeoff between energy efficiency optimization and AoI optimization, Fig. 3 further illustrates how the optimal channel access probability  $q^*, \bar{A}_p \rightarrow \infty$  and the corresponding MENSTP  $M^*, \bar{A}_p \rightarrow \infty$  vary with the node density  $\lambda$  under different values of the PRTW  $\frac{P_T}{P_W}$ . Note that the optimal channel access probability for AoI optimization, i.e.,  $q = q_{AoI}^*$ , and the corresponding energy efficiency  $M^{q=q_{AoI}^*}$  were presented, and have been highlighted in red in Fig. 3. We can see that when  $\frac{P_T}{P_W} = 1$ , we have  $q_{AoI}^* = q^*, \bar{A}_p \rightarrow \infty$ , and the corresponding  $M^{q=q_{AoI}^*} = M^*, \bar{A}_p \rightarrow \infty$ , indicating that  $M$  and  $A_p$  can be optimized simultaneously. As  $\frac{P_T}{P_W}$  increases, the gap between the curves of  $M^*, \bar{A}_p \rightarrow \infty$  and  $M^{q=q_{AoI}^*}$  increases, implying a noticeable tradeoff between the energy efficiency optimization and AoI optimization. In this case, each transmitter should access the channel less frequently to alleviate the channel contention so as to reduce energy consumption in the transmission state, which, nevertheless, leads to a large queuing delay in the buffer and poor AoI performance.

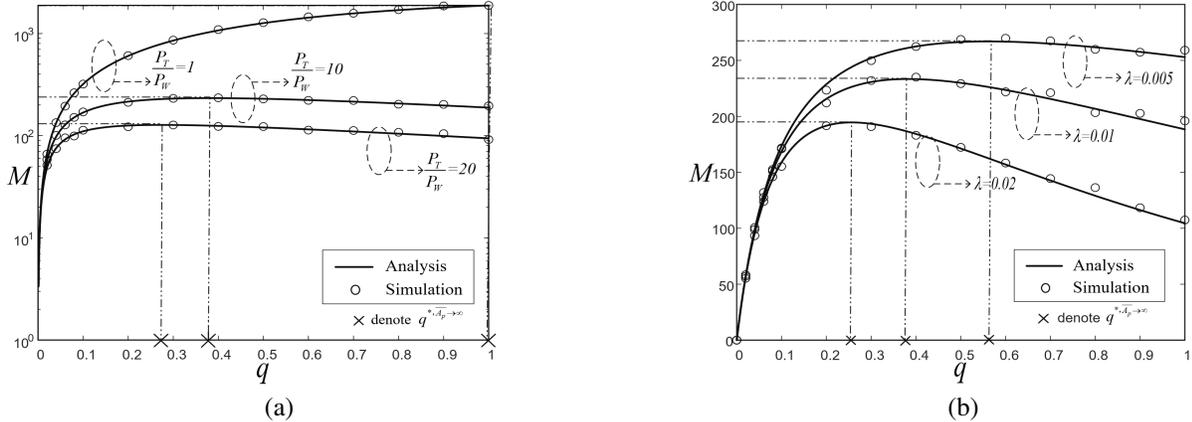


Fig. 4. The expected number of successfully transmitted packets  $M$  during each transmitter's life time versus the channel access probability  $q$ . (a)  $\lambda = 0.01$ ,  $\frac{P_T}{P_W} \in \{1, 10, 20\}$ . (b)  $\frac{P_T}{P_W} = 10$ ,  $\lambda \in \{0.005, 0.01, 0.02\}$ . Public parameters:  $E = 10^4 J$ ,  $P_W = 1W$ ,  $R = 3$  m,  $\xi = 1$ ,  $\theta = 0.8$ ,  $\alpha = 3$ , SIR  $\gamma = 20$ .

#### IV. SIMULATION RESULTS AND DISCUSSIONS

In this section, we provide simulation results to validate the analysis. Specifically, in the beginning of each simulation run, we realize the locations of transmitter-receiver pairs over a  $100 \times 100$   $m^2$  square area according to independent PPPs and place the typical link where the receiver is located at the center of the area. In each time slot, the location of each pair is regenerated except for the typical link, and each simulation lasts for  $10^4$  time slots. The simulation results are obtained by average over 20 realizations.

In Fig. 4, we depict the expected number of successfully transmitted packets  $M$  during each transmitter's life time as a function of the channel access probability  $q$ , under different values of the PRTW  $\frac{P_T}{P_W}$  and under different values of the node distribution density  $\lambda$ . It can be seen that the expected number of successfully transmitted packets  $M$  during each transmitter's life time varies with the channel access probability  $q$  and can be optimized when  $q$  is carefully tuned; otherwise, the energy efficiency will be severely degraded. It is therefore important to properly tune the channel access probability towards a high energy efficiency. A close match between the simulation and analytical results can be observed from Fig. 4, which verifies the analysis.

#### V. CONCLUSION AND FUTURE WORK

In this paper, we maximize the expected number of successfully transmitted packet during each transmitter's life time with the consideration of the peak AoI constraint for the mobile random access Poisson networks. Explicit expressions of MENSTP and the corresponding optimal channel access probability are obtained.

The analysis shows that the MENSTP and the corresponding optimal channel access probability decrease with the PRTW regardless of the AoI constraint. The AoI constraint would affect the optimal energy efficiency performance only if the constraint is stringent. Moreover, the tradeoff between energy efficiency and peak AoI is also studied. The analysis shows that they can be optimized simultaneously when PRTW equals to one, and the tradeoff between them becomes significant with

a large PRTW. These observations reveal crucial age-energy tradeoff in battery-limited IoT networks.

Note that this paper analyzed the age-energy tradeoff and studied the performance limit of energy efficiency by tuning the channel access probability. With the stochastic arrival model, the packet arrival rate is also a vital tunable parameter that affects the performance limits. How to jointly adjust the channel access probability and the packet arrival rate to optimize the MENSTP deserves further study.

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