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# Energy-Age Tradeoff in Status Update Communication Systems Based on HARQ

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***Abstract*—The development of the Internet of Things (IoT) has given birth to many real-time applications, which have strict requirements for fresh data. Therefore, a new indicator, age-of-information (AoI), is defined to measure data freshness. On the other hand, the IoT devices such as remote sensors are usually energy-constrained. In this paper, we study the energy-age tradeoff in a state update system. In this system, a source node senses the status data and transmits to a receiver through an error-prone channel. When the transmission fails, the source may either retransmits the existing data to save energy, or sense and transmits new data to reduce the age-of-information. Hybrid Automatic Repeat request (HARQ) and threshold-based retransmission strategy are adopted. Then, we derive the expressions of the average information age and average energy consumption of the system. Finally, the theoretical results are verified via simulations, and the energy-age tradeoff relationship is analyzed. In addition, it is shown that HARQ strategy is more efficient than Automatic Repeat request (ARQ) when the channel condition is very poor.**

***Index Terms*—IoT, HARQ, AoI, energy consumption.**

## I. INTRODUCTION

With the development of the Internet of Things(IoT), there are many real-time IoT applications, which have strict requirements on the timeliness of the system status to ensure fast and accurate response. It is foreseeable that in the future wireless communications, fresh information will become more and more important. Therefore, there is a new indicator for the freshness of information called *age-of-information(AoI)*, which is defined as the time elapsed since the generation of the latest received update [1].On the other hand, for status sensing applications, the sensor nodes are usually energy-constrained. Thus, it is also significant to reduce the energy consumption of end nodes. However, intuitively, the two goals, keeping data fresh and reducing energy consumption, can not be achieved at the same time. In order to minimize AoI, the sensor should sense and transmit in time, which consumes lots of energy. In order to reduce energy consumption, the sensor should sense at a lower frequency. Therefore, there is a tradeoff between energy consumption and AoI.

In the literature, the concept of AoI has been extensively studied. The average AoI in the first-come, first-served (FCFS) queuing model was analyzed in [1], where information updates are generated randomly. The research on energy consumption and AoI can be originated from [2], which analyzes AoI in an energy harvesting system. The average AoI performance under the condition of random data and energy arrival was considered in [3] and [4]. A reinforcement learning method to minimize the average AoI under energy harvesting constraints was proposed in [5]. The above works only optimizes AoI under certain energy constraints. However, in many cases such as the status changes slowly, AoI performance can be sacrificed to save energy.

The state update system based on error-prone channels has been extensively studied in many literature. Timely updating on the erasure channel to achieve infinite incremental redundancy and fixed redundancy was studied in [6] considering. The optimal state update strategy without feedback was studied in [7]. Hybrid Automatic Repeat request (HARQ) protocol and ACK/NACK feedback are adopted in [8]–[10] to keep the data fresh. However, none of the above articles considers the energy consumption of sensing. In many applications, the energy consumption of sensing is not negligible. It may be even higher than the transmission energy [11]. Moreover, there is a huge difference in the design of strategies after considering the energy consumption of sensing. Specifically, without sensing energy consumption, it is always preferred to re-sensing a new data before each transmission, because it does not increase energy consumption but can reduce AoI. On the contrary, when sensing energy consumption is considered, there is a tradeoff between reducing AoI through sensing new data and saving energy through retransmission.

In this paper, we try to analyze the age-energy tradeoff relationship in a state update system based on the HARQ protocol. Our system includes a source that can sense the state of the environment, and transmit status updates to the receiving end through an error-prone channel. The receiving end will feed back ACK/NACK to the source based on whether the reception is successful. If the source receives a NACK, it decides whether re-sensing the new data and transmitting or retransmitting the current data. Since both the sensing and transmission processes require energy, different strategies make the system energy consumption and AoI different. The

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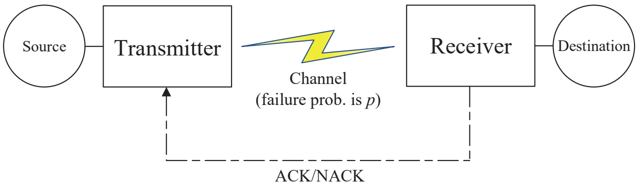

Fig. 1. Status update system model.

main work of this paper is to analyze the average AoI and average energy consumption under the threshold-based retransmission strategy.

## II. System Model

Consider a status update system as shown in Fig. 1. The system consists of two nodes, a source and a destination. The source node first senses the state information from the environment into a packet and delivers it to the transmitter. The energy consumed by status sensing is represented by $E_s$. Then, the transmitter transmits this packet to the receiver through an identically and independently distributed (i.i.d.) channel with a transmission failure probability $p \in (0, 1)$, and the energy consumed in the transmission process is represented by $E_t$. If the packet is successfully received, the receiver will send an ACK signal back to the transmitter through an error-free feedback channel. Otherwise, a NACK means failed. When the transmitter receives the ACK signal, it will inform the source node to update the status information. On the other hand, when the NACK signal is received, the transmitter will also inform the source node that the data packet has not been successfully received. At this time, the source node has two choices: one is to sense and generate a new packet to pursue the freshness of the information, the other is to keep the current packet to save energy. We adopt the HARQ strategy, which means that each failed packet is stored for the next joint decoding, so the failure probability of the next transmission is smaller than the previous one. In this case, generally, we assume that for each packet, the failure probability of the first transmission is $p_1$, the second transmission is $p_2$, and so on. In addition, we adopt $M$-threshold strategy that each packet is allowed to be sent no more than $M$ times, so $p_1 > p_2 > p_3 > \cdots > p_M$. In our system, a time slot is defined as the duration from sending a packet to receiving an acknowledgement feedback signal. The length of the time slot is denoted by $T$. Without loss of generality, we will set $T = 1$ in the rest of this paper.

## III. Average Age-of-Information and Energy Consumption

### A. Calculation of Average Age-of-Information

Age-of-information characterizes the freshness of data. Assuming that the current time is $t$, the generation time of the latest successfully accepted data packet is $U(t)$. Then the age from source to destination is defined as

$$\Delta(t) = t - U(t). \tag{1}$$

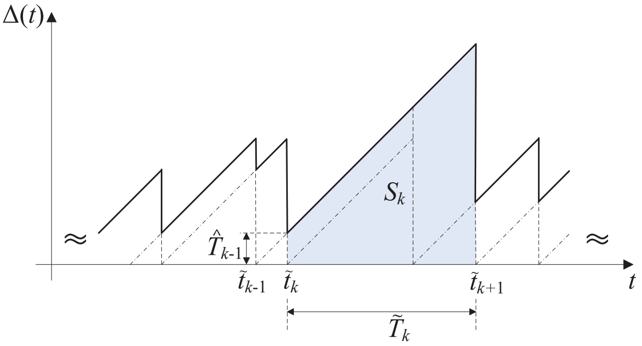

Fig. 2. Evolution of age-of-information.

Fig. 2 describes the evolution of AoI. $\tilde{t}_k$ represents the time instance when the $k$-th data packet is successful received. $\tilde{T}_k = \tilde{t}_{k+1} - \tilde{t}_k$ represents the time duration between two consecutive successful receptions. And $\hat{T}_k$ is the transmission time duration for the $k$-th successfully received packet. If the current transmission fails, the AoI will increase linearly with time. If the current transmission succeeds, the instantaneous age will decrease, and a new update will be generated. If a packet fails $M$ times, a new packet is generated and transmitted and the age-of-information will continuously increase until a successful reception. The average age-of-information is usually defined as

$$\bar{\Delta} = \lim_{\tau \to \infty} \frac{1}{\tau} \int_0^{\tau} \Delta(t) \mathrm{d}t. \tag{2}$$

Calculating the average information age, we can express it as the average area of the gray trapezoid $S_k$, i.e.

$$\bar{\Delta} = \lim_{k \to \infty} \frac{\sum_{i=1}^{k} S_i}{\sum_{i=1}^{k} \tilde{T}_i} = \frac{\mathbb{E}[S_k]}{\mathbb{E}[\tilde{T}_k]}. \tag{3}$$

First, the expectation of $S_k$ can be obtained by defining the area of the trapezoid

$$\begin{aligned} \mathbb{E}[S_k] &= \mathbb{E}\left[\frac{1}{2}(\hat{T}_{k-1} + \tilde{T}_k + \hat{T}_{k-1})\tilde{T}_k\right] \\ &= \mathbb{E}\left[\hat{T}_{k-1}\tilde{T}_k\right] + \frac{1}{2}\mathbb{E}[\tilde{T}_k^2] \\ &= \mathbb{E}[\hat{T}_k]\mathbb{E}[\tilde{T}_k] + \frac{1}{2}\mathbb{E}[\tilde{T}_k^2], \end{aligned} \tag{4}$$

the third equality holds because of the independance of each packet. Combining (3) and (4), we have

$$\bar{\Delta} = \mathbb{E}[\hat{T}_k] + \frac{\mathbb{E}[\tilde{T}_k^2]}{2\mathbb{E}[\tilde{T}_k]}. \tag{5}$$

Therefore, to calculate $\bar{\Delta}$, we distributions of $\tilde{T}_k$ and $\hat{T}_k$ are needed.

By definition, the random variable $\tilde{T}_k$ is equal to the number of transmissions between two consecutive successful receptions. So we have

$$\Pr(\tilde{T}_k{=}m){=}{p_1}^{a+1}{p_2}^{a+1}\dots{p_{m'}}^{a}{p_{m'+1}}^{a}\dots{p_M}^{a}(1{-}p_{m'}), \tag{6}$$

where $m = aM + m', (a = 0, 1, 2, \cdots, m' = 0, 1, 2, \cdots M)$. To simplify the expression, we let $p_1 p_2 \ldots p_M = P$, $p_1 p_2 \ldots p_{m'-1}\left(1 - p_{m'}\right) = P_{m'}$. Thus, (6) can be simplified as

$$\Pr(\tilde{T}_k = m) = P^a \cdot P_{m'}. \tag{7}$$

Then, we have

$$\begin{aligned} \mathbb{E}[\tilde{T}_k] &= \sum_{m=1}^{\infty} m \cdot P^a \cdot P_{m'}, \\ &= \sum_{m'=1}^{M} \frac{\left(M - m'\right)P + m'}{\left(1 - P\right)^2} P_{m'}, \end{aligned} \tag{8}$$

$$\begin{aligned} \mathbb{E}[\tilde{T}_k^2] &= \sum_{m=1}^{\infty} m^2 \cdot P^a \cdot P_{m'} \\ &= \sum_{m'=1}^{M} \frac{M^2\left(1{+}P\right)P{+}2MP\left(1{-}P\right)m'{+}\left(1{-}P\right)^2 m'^2}{\left(1 - P\right)^3} P_{m'}. \end{aligned} \tag{9}$$

Recall that the random variable $\hat{T}_k$ represents he number of transmissions of the $k'$-th successfully transmitted data packet, so its maximum is M, i.e., $\hat{T}_k \in \{1, 2, \cdots, M\}$. In particular, $\hat{T}_k = m$ corresponds to the events $\tilde{T}_k = lM{+}m, \forall l$, which means consecutive $l$ packets that were discarded due to failure plus a latest packet with $m$ retransmission before success. Therefore, its distribution can be calculated based on the distribution of $\tilde{T}_k$

$$\begin{aligned} \Pr(\hat{T}_k = m) &= \sum_{l \geq 0} \Pr(\tilde{T}_k = lM + m) \\ &= \sum_{l \geq 0} P^l \cdot P_m \\ &= \frac{1}{1 - P} P_m, \end{aligned} \tag{10}$$

where $m = 1, 2, \cdots, M$. Then we have

$$\mathbb{E}[\hat{T}_k] = \sum_{m=1}^{M} \frac{m P_m}{1 - P}. \tag{11}$$

Combining (5), (8), (9), and (11), the average age-of-information (19) can be obtained

$$\begin{aligned} \bar{\Delta} &= E[\hat{T}_k] + \frac{E[\tilde{T}_k^2]}{2E[\tilde{T}_k]} \\ &= \sum_{m=1}^{M} \frac{m P_m}{1{-}P} \\ &+ \frac{\sum\limits_{m=1}^{M} \left[M^2\left(1{+}P\right)P{+}2MP\left(1{-}P\right)m{+}\left(1{-}P\right)^2 m^2\right] P_m}{2\sum\limits_{m=1}^{M}\left(1 - P\right)\left[\left(M - m\right)P + m\right] P_m}. \end{aligned} \tag{12}$$

### B. Calculation of Average Energy Consumption

Recalling that the energy consumption of sense is $E_s$, and we assume it is a constant.

The energy consumption of transmit module can be modeled as a function of the transmit power $P_t$, i.e.,

$$E_t = P_c + \eta P_t, \tag{13}$$

where $P_c$ is the circuit energy consumption, $P_t$ is the transmit power, and $\eta$ is the inverse of the drain efficiency of power amplifier. $P_t$ affects the channel failure probability. Assuming that the channel follows Rayleigh fading, so the channel failure probability can be expressed by [12, Eq. 5.55]

$$p = 1 - \exp\left(-\frac{(2^R - 1)\sigma^2}{P_t}\right), \tag{14}$$

where $R$ is data rate, $\sigma^2$ is the noise power.

According to Fig. 2, the average energy consumption can be expressed as

$$\begin{aligned} \bar{E} &= \lim_{k \to \infty} \frac{\sum_{i=1}^{k} g(\tilde{T}_i) E_s + \sum_{i=1}^{k} \tilde{T}_i E_t}{\sum_{i=1}^{k} \tilde{T}_i} \\ &= \lim_{k \to \infty} \frac{\sum_{i=1}^{k} g(\tilde{T}_i)}{\sum_{i=1}^{k} \tilde{T}_i} E_s + E_t \\ &= \frac{\mathbb{E}[g(\tilde{T}_k)]}{\mathbb{E}[\tilde{T}_k]} E_s + E_t, \end{aligned} \tag{15}$$

where $g(\tilde{T}_k)$ is defined as the number of status sensing during the interval $\tilde{T}_k$ (including the first one at the beginning of the interval). So $g(\tilde{T}_k) = l$ represents that $l{-}1$ consecutive packets are transmitted failure and the $l$-th packet is successfully received. It corresponds to $\tilde{T}_k = (l{-}1)M{+}m, \forall m = 1, \cdots, M$. Therefore, the distribution of $g(\tilde{T}_k)$ can be calculated by

$$\begin{aligned} \Pr(g(\tilde{T}_k) = l) &= \sum_{m=1}^{M} \Pr(\tilde{T}_k = (l - 1)M + m) \\ &= \sum_{m=1}^{M} P^{l-1} P_m, \end{aligned} \tag{16}$$

where $l = 1, 2, \cdots$. Thus, the expectation can be expressed as

$$\begin{aligned} \mathbb{E}[g(\tilde{T}_k)] &= \sum_{l \geq 1} l \sum_{m=1}^{M} P^{l-1} \cdot P_m \\ &= \sum_{m=1}^{M} \frac{P_m}{\left(1 - P\right)^2}. \end{aligned} \tag{17}$$

Combining (8), (15), and (17), the average energy consumption (20) can be obtained

$$\begin{aligned} \bar{E} &= \frac{\mathbb{E}[g(\tilde{T}_k)]}{\mathbb{E}[\tilde{T}_k]} E_s + E_t \\ &= \frac{\sum\limits_{m=1}^{M} P_m}{\sum\limits_{m=1}^{M} \left[\left(M - m\right)P + m\right] P_m} E_s + E_t. \end{aligned} \tag{18}$$

### *C. Summary of Main Results*

The main results are summarized in the following theorem.

**Theorem 1.** *The average AoI and average energy consumption can be expressed as*

$$\bar{\Delta}=\sum_{m=1}^{M}\frac{mP_m}{1-P}+\frac{\sum\limits_{m=1}^{M}\left[M^2\left(1+P\right)P+2MP\left(1-P\right)m+\left(1-P\right)^2m^2\right]P_m}{2\sum\limits_{m=1}^{M}\left(1-P\right)\left[\left(M-m\right)P+m\right]P_m}. \quad (19)$$

$$\bar{E}=\frac{\sum\limits_{m=1}^{M}P_m}{\sum\limits_{m=1}^{M}\left[\left(M-m\right)P+m\right]P_m}E_s+E_t. \quad (20)$$

**Remark 1.** *It is worth noting that ARQ strategy is a special case of HARQ, where $p_1=p_2=\cdots=p_M=p$. We substitute this condition into* (19) *and* (20)*, $\bar{\Delta}$ and $\bar{E}$ can be expressed as*

$$\bar{\Delta}=\frac{3+p}{2\left(1-p\right)}-\frac{Mp^M}{1-p^M}, \quad (21)$$

$$\bar{E}=\frac{1-p}{1-p^M}E_s+E_t. \quad (22)$$

*which are equal to the results in [13, Eqs. (6),(7)].*

## IV. NUMERICAL RESULTS

In this section, a specific HARQ strategy is adopted to numerically simulate the performance of the energy-age tradeoff and compare it with the one in [13]. In this simulation, the HARQ strategy we adopted makes $p_i=p^i, i=1,2,...,M$. $p$ represents the channel quality. In addition, the power consumption model for home applications from EARTH project [14] is adopted, in which $P_c=2.1$ Watt, $\eta=19.2308$, and $P_t\leq P_{\max}=20$ dBm.

### *A. Fixed transmission power*

First, we consider the case where the transmission energy consumption $E_t=P_c+\eta P_{\max}$ is a constant, and let $E_s=E_t$.

As shown in Fig. 3, we can see that the ARQ curve group and the HARQ curve group have similarities. For a given transmission failure probability $p$, as the retransmission threshold $M$ increases, the average age-of-information increases while the average energy consumption decreases. It is because intuitively, the larger the $M$, the smaller the frequency of sensing new data packets, so the information is relatively less fresh and the energy consumption is relatively low. Therefore, changing the value of $M$ can make a tradeoff between the average AoI and the average energy consumption. However, when $M$ is smaller, the increase in $M$ has less influence on the tradeoff relationship. For example, when $p=0.1$ in the ARQ curve group, the average age and average energy consumption of $M=3,4,5,6$ are almost the same. That is because a small $p$ means that the channel conditions are good, and each data packet can be successfully received without having to retransmit many times, so it is meaningless to achieve a large maximum number of retransmissions. Above property can be seen in each curve in the HARQ curve group. The reason is that under the HARQ strategy, each transmission failure probability will be lower than the previous one, especially with an exponential decrease. So there is almost no difference in $M\geq3$. In addition, when $M=1$, the average energy consumption of both ARQ and HARQ curve group is always 8.05, because the strategy at this time is to sense a new packet and transmit it in each time slot, so the average energy consumption is $\bar{E}=E_s+E_t$ is a fixed value.

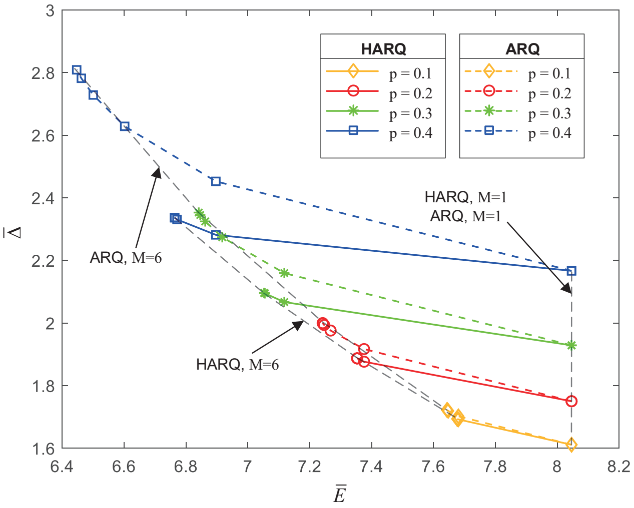

Fig. 3. Energy-Age tradeoff with constant transmit power. $E_s=E_t$.

On the other hand, when we focus on the differences between the two groups, we can clearly see that the average AoI of HARQ curves is smaller than that of the ARQ ones, and the average energy consumption is larger. Because adopting HARQ strategy increases the probability of successful transmission, and make the frequency of sensing larger. So the average information age will be smaller, and leads a higher average energy consumption.

### *B. Variable transmission power*

Next, we consider the case where the transmission power is variable, and study the influence of the transmission power on the energy-age tradeoff curve. The channel failure probability is determined by (14), where $\sigma^2=1dBm$, $R=2$bps/Hz, and the fixed $Es=P_c+\eta P_{max}$ is a constant. We set the transmit power to 2dBm to 20dBm, and the sampling interval is 3dB.

As shown in Fig. 4, we can see that for a fixed $M$, as the transmission power increases, the average information age decreases, and the average energy consumption increases. This is an intuitive performance, because the larger the transmission power, the smaller the channel error probability according to (14), so the conclusion is similar to Fig. 3. However, different

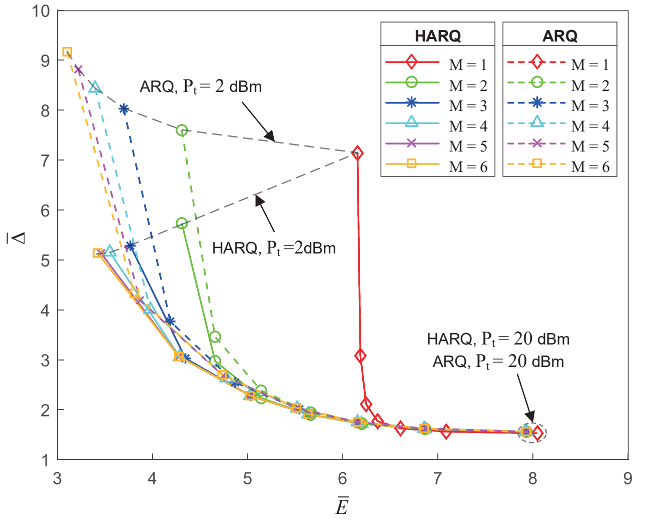

Fig. 4. Energy-Age tradeoff with transmit power control. $E_s = P_c + \eta P_{\max}$.

from Fig. 3, when $M = 1$, there is still an age-energy tradeoff under variable transmission power, even if the curve is steep.

In addition, there is a unique set of data, that is, the $P_t = 2dBm$ curve in the HARQ curve group. The relationship between the average AoI and the average energy consumption is not a tradeoff relationship, but a positive relationship, that is, with $M$ increasing, both the average AoI and the average energy consumption decrease.

The reason for this phenomenon can be analyzed from Fig. 2. As shown in Fig. 2, the AoI will drop if and only if the data packet is successfully transmitted, and the height of the drop depends on the time instance for the generation of the latest data packet. Therefore, the value of the AoI is determined by two factors, one is the frequency of successful transmission, the other is the frequency of sensing new data packets. When the ARQ strategy is adopted, increasing the value of $M$ will increase the AoI, because increasing the maximum number of retransmissions simply reduces the frequency of sensing new data packets, but does not change the frequency of successful transmission. While in the case of HARQ, it can make the next transmission failure probability smaller than the previous one, it means that the frequency of data packets being successfully transmitted increases. And because the channel quality is very poor, the channel failure probability corresponding to $P_t = 2dBm$ reaches 0.85. The current HARQ strategy makes it exponentially attenuated. Therefore, from the perspective of AoI, the benefit of increasing the frequency of successful transmission is greater than impact of reducing the frequency of sensing new data packets. So we can conclude that increasing $M$ when the channel failure probability is large will make the average AoI decreases.

sensing and transmission energy can be balanced by adjusting

## V. CONCLUSION AND FUTURE WORK

In this paper, the tradeoff relationship between age-of-information and energy consumption based on HARQ has been studied. The main conclusions are as follows: (1) The the retransmission threshold $M$ to make a tradeoff between energy consumption and AoI. In addition, the transmission power control provides a new degree of freedom for the tradeoff. (2) Compared with ARQ strategy, the HARQ strategy can effectively reduce the average AoI with lower energy consumption, which further shows that the use of HARQ provides another degree of freedom to improve energy-age tradeoff. (3) When the channel conditions are poor, both the average AoI and the average energy consumption can be reduced by increasing the retransmission threshold $M$.

It is remarkable that introducing HARQ leads to a narrower tradeoff range compared with ARQ. In future work, we may consider sleep mode at the transmitter, so that the source no longer transmits data packet in each time slot. When the AoI is small, it can choose to reduce the frequency of sending data or even sleep to save energy.

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