Age of Information and Energy Harvesting Tradeoff for Joint Packet Coding in Downlink IoT Networks

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Abstract—The paper investigates the information freshness and energy harvesting (EH) in downlink Internet of Things (IoT) networks. Information freshness is measured by Age of Information (AoI). We consider a scenario where an access point periodically sends short packets to \( N \) independent IoT devices. All the devices are equipped with capacitors to store energy through wireless power transfer (WPT) when the devices receive signals conveying unwanted packets. Conventionally, short packets for multiple devices are jointly coded into one larger packet to improve reliability. However, whether short packets should be jointly coded to reduce average AoI and improve EH performance has not been well investigated. On the one hand, a larger number of packets jointly coded decreases the packet error rate (PER), which may reduce the average AoI because the time to successfully receive the next update may be shorter. On the other hand, more packets jointly coded cause less time for WPT, as the devices spend most of their time receiving update packets, resulting in poor EH performance. Therefore, we investigate the tradeoff between AoI and EH by examining the number of packets to be jointly coded. Closed-form AoI and EH formulas are derived. Numerical results show that there exist optimal numbers of jointly coded packets that can achieve both high information freshness and high EH at the same time.

Index Terms—Age of information (AoI), energy harvesting (EH), information freshness, short packets, wireless power transfer (WPT).

I. INTRODUCTION

Internet of Things (IoT) is envisioned to support many aspects of our daily lives in the future [1]. Many IoT systems require real-time monitoring and tracking, in which Age of Information (AoI) quantifies the information freshness [2]. AoI was introduced in the seminal works [3], [4]. Specifically, AoI is defined as the time elapsed since the generation of the last successfully received update packet. Conventional performance metrics, such as throughput and delay, cannot properly describe the information freshness. In contrast, AoI captures both the latency and generation time of each status update. Motivated by the fact that monitoring and automation systems usually have short status update packets, the AoI metric under short packet communications has been studied in many works such as [5]–[7].

Limited battery storage in small IoT devices has become a key limitation in operations [8]. To get rid of the energy constraint in IoT networks, energy harvesting (EH) has been studied to extend the lifetime of devices [9], i.e., receiving nodes harvest energy from the radio-frequency (RF) signals in communication networks.

EH has attracted considerable attention from the research community. In particular, numerous works on simultaneous wireless information and power transfer (SWIPT) in downlink channels can be found in the literature. Reference [10] first studied SWIPT in a multiple-input multiple-output (MIMO) broadcast channel where a transmitter delivers information to one receiver and energy to another receiver. In [11], the authors focused on the MIMO broadcast channel with one transmitter, one information receiver, and multiple energy receivers. Subsequently, many works considered the case with multiple information and energy receivers, such as [12], [13]. Furthermore, [14] considered SWIPT in multiple-input single-output (MISO) multicasting systems where each receiver is equipped with a power splitting device for performing SWIPT. For more details about recent advances in SWIPT, please refer to the survey papers [8], [15].

In this paper, we consider a downlink IoT information update system which consists of one access point (AP) and \( N \) independent IoT devices. Downlink transmissions of short status update packets from the AP to the IoT devices are organized in a round-robin manner. We assume that all wireless links between the AP and the devices experience different
channel gains. Furthermore, the IoT devices are mounted with capacitors to store the energy from EH. The IoT devices perform EH only when wireless information transfer (WIT) is not required. In other words, an IoT device harvests energy when it receives wireless signals that do not contain an update packet aimed for itself. There are two main requirements in this setting: high information freshness (low AoI) and high EH.

There have been some studies on AoI with EH in the literature. For example, [16] investigated the age-energy tradeoff of two-hop status update systems with short packets where the truncated automatic repeat request (ARQ) scheme was considered. Reference [17] evaluated AoI and packet loss reduction by estimating the channel state before transmitting in single-hop communications with EH. In [18], the authors considered the average AoI minimization in cognitive radio communications where the secondary user is an EH sensor.

For short-packet communications in IoT information update systems, packet errors are inevitable. The packet error rate (PER) depends mainly on the blocklength of the packet, i.e., the number of coded bits [19]. To improve the reliability of short packets, small packets for multiple devices can be jointly encoded into one larger packet [20]. Although joint coding requires more power and time for the receivers to decode, it can reduce PER and more frequent successful updates may reduce the average AoI of the system. In addition, less power is wasted due to transmission failures. However, there has been no AoI with EH analysis regarding the joint coding for downlink short packet communications.

Our previous work [21] considered the joint packet coding design in an uplink two-hop model without EH to achieve high AoI performance. However, for the EH scenario considered in this paper, if more packets are jointly coded, fewer idle devices will be able to harvest energy from the background RF signals. Hence, there is a tradeoff between AoI and EH performances in downlink joint coding.

In this paper, we investigate how to jointly encode multiple update packets at the AP to simultaneously achieve favorable AoI and EH performances. To this end, we formulate the problem by deriving closed-form AoI and EH performances when different numbers of update packets are jointly coded. With the closed-form expressions derived, our simulation results show that a small number of update packets is usually sufficient to achieve high information freshness and high EH at the same time.

II. SYSTEM MODEL

As shown in Fig. 1, an AP sends updates to \( N \) IoT devices. The updates for each device are \( D \) bits, and the updates are independent of each other. The devices are equipped with capacitors to store energy from WPT. Note that the devices perform WPT only when WIT is not required.

Considering the path loss and Rayleigh fading, the received signal \( y_i \) at device \( i, i \in \{1, 2, \cdots, N\} \), can be expressed as

\[
y_i = h_i \sqrt{P_s} + n_i.
\]  

![Fig. 2. The AP sends jointly-coded packets to \( \frac{N}{M} \) groups in a round-robin manner. Here \( s \) is the transmitted packets to the AP, and \( E[\|s\|^2] = 1 \). \( P \) is the transmit power of the AP, \( \eta_i \) is the complex additive white Gaussian noise (AWGN) with variance \( \sigma_i^2 \). For simplicity, we assume that the variances of \( \eta_i \) are identical for all the devices, i.e., \( \sigma_i^2 = \sigma^2, \forall i \). \( h_i \) is the channel coefficient from the AP to device \( i \) where

\[
h_i = \sqrt{d_i^{-\gamma} g_i}, \quad (2)
\]

\( d_i \) is the line-of-sight (LoS) distance from the AP to device \( i \), and \( \tau \) denotes the path loss exponent. \( g_i \sim CN(0, 1) \) denotes the independent and identically distributed (i.i.d.) complex normal distribution with unit variance for device \( i \). Since \( \|g_i\|^2 \) is an exponentially distributed random variable with unit power gain, \( E[\|g_i\|^2] = 1 \). Therefore, the average received SNR of device \( i \) can be expressed as

\[
\gamma_i = \frac{E[\|h_i\|^2] P}{\sigma^2} = d_i^{-\gamma} \rho \quad (3)
\]

where \( \rho = \frac{P}{\sigma^2} \) is the transmitted SNR.

To improve reliability, small packets for multiple devices can be jointly coded into a larger packet. We assume that the AP sends jointly coded packets to the IoT devices group by group. Without loss of generality, the IoT devices are indexed in ascending order of the LoS distance from the AP to the IoT device, i.e., \( d_1 \leq d_2 \leq \cdots \leq d_{N-1} \leq d_N \), which means that the received SNRs are in decreasing order. \( N \) devices are divided into \( \frac{N}{M} \) groups by distance. Adjacent devices form a group, and each group has \( M \) devices, i.e., IoT devices with distances \( \{d_{qM+1}, d_{qM+2}, \cdots, d_{qM}\} \) from the AP belong to group \( q, q \in \{1, 2, \cdots, \frac{N}{M}\} \).

As shown in Fig. 2, the AP takes turns to send jointly coded packets to different groups of IoT devices. The transmission time from the AP to the devices in group \( q \) is denoted by \( T_q \). Then the total time for all the groups is defined as a round. More specifically, in round \( j \), the AP generates and transmits the jointly coded packet for group \( q \) at time \( t_{j,q} \), and completes the transmission at time \( t_{j,q+1} = t_{j,q} + T_q \). The total time duration of a transmission round \( T_{\text{round}} \) is given by

\[
T_{\text{round}} = \frac{N}{M} \sum_{q=1}^{\frac{N}{M}} T_q = \frac{1}{B} \sum_{q=1}^{\frac{N}{M}} L_q \quad (4)
\]

where \( T_q = \frac{L_q}{B} \). \( L_q \) is the blocklength of the jointly coded packet for the group \( q \). \( B \) is the bandwidth of the system.
We assumed that the channel is constant over a transmission round and varies independently with time.

III. ANALYSIS OF AGE OF INFORMATION AND ENERGY HARVESTING PERFORMANCES

A. Packet Error Rate (PER) of Short Packet

In this section, we will analyze both AoI and EH performances and derive the closed-form expressions. First, we give an introduction about the packet error rate. According to [19], the PER of short packets in AWGN channels can be approximated as

$$ P = Q(\frac{1}{2} \log_2 (1 + \gamma) - \frac{\xi}{L}). $$

(5)

Note that $\gamma$ is the signal-to-noise ratio and $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-\frac{u^2}{2}} du$ is the Q-function.

If an error occurs while decoding the transmitted information, the transmission is considered a failure for device $i$, and the device simply discards the packet without any feedback signal. Therefore, the error probability of each device $i$ in group $q$ is the number of source bits and $q_i$, respectively. We define $X_i$ as the number of packets delivered to device $i$ between two successful packet decoding and $e_i$ as the PER of IoT device $i$.

B. AoI Analysis

**Instantaneous AoI:** At time instant $t$, the instantaneous AoI of the AP, measured at device $i$ in group $q$, $\Delta_{i,q}(t)$, is defined by

$$ \Delta_{i,q}(t) = t - U_{i,q}(t) $$

(6)

where $U_{i,q}(t)$ is the generation time of the latest update received by device $i$ of group $q$.

**Average AoI:** The average AoI of device $i$ in group $q$, $\Delta_{q,i}$, is the time average of its instantaneous AoI, i.e.,

$$ \Delta_{q,i} = \lim_{T \to \infty} \frac{1}{T} \int_0^T \Delta_{i,q}(t) dt. $$

(7)

Therefore, the average AoI of the system $\Delta$ is $\Delta = \frac{1}{N} \sum_{q=1}^{q_M} \sum_{i=(q-1)M+1}^{qM} \Delta_{q,i}$. The lower average AoI of the system $\Delta$ indicates that the update packets in the devices are fresher in the general.

As shown in Fig. 3, if the update packet is successfully decoded in the device $i$ of group $q$, the instantaneous AoI $\Delta_{q,i}(t)$ will be $T_q$, which is the transmission time from the AP to the IoT devices in group $q$. Otherwise, $\Delta_{q,i}(t)$ increases linearly with time. Without loss of generality, we assume the $(k-1)$-th and the $k$-th successful updates of device $i$ in group $q$ occur at $t_{i,q,k-1}$ and $t_{i,q,k}$, respectively. We define $A_{i,q,k}$ for the $k$-th successful update as

$$ A_{i,q,k} = \int_{t_{i,q,k-1}}^{t_{i,q,k}} \Delta_{i,q}(t) dt = \int_0^{t_{i,q,k}} (t_{i,q,k} - t) dt $$

$$ = t_{i,q,k}^2 + \frac{(t_{i,q,k})^2}{2}. $$

(8)

**Fig. 3.** An example of $\Delta_{q,i}(t)$. The updates are successfully decoded at $t_{i,q,k}$. An example of $A_{i,q,k}$ is illustrated in the shaded area of Fig. 3. Therefore, the average AoI of device $i$ in group $q$ can be found by

$$ \Delta_{i,q} = \lim_{K \to \infty} \frac{1}{K} \sum_{k=1}^{K} A_{i,q,k} = T_q + \frac{E[X_i^0] T_{round}}{2E[X_i^0]}. $$

(9)

Then the average AoI of the system can be expressed as

$$ \Delta = \frac{1}{N} \sum_{q=1}^{q_M} \sum_{i=(q-1)M+1}^{qM} \Delta_{i,q} $$

$$ = \frac{1}{N} \sum_{q=1}^{q_M} \sum_{i=(q-1)M+1}^{qM} T_q + \frac{E[X_i^0] T_{round}}{2E[X_i^0]} \sum_{i=1}^{N} \frac{1 + \epsilon_i}{(1 - \epsilon_i)^2}. $$

(10)

We first consider the path loss channel model without Rayleigh fading. In this way, $X_i$ follows a geometric distribution with parameter $1 - \epsilon_i$ and we have

$$ E[X_i] = \frac{1}{1 - \epsilon_i}, $$

$$ E[X_i^2] = \frac{1 + \epsilon_i}{(1 - \epsilon_i)^2}. $$

(11)

(12)

where $\epsilon_i$ can be calculated by equation (5). As a result, the average AoI of the system can be expressed as

$$ \Delta = \frac{1}{N} \sum_{q=1}^{q_M} \sum_{i=(q-1)M+1}^{qM} \left( T_q + \frac{1 + \epsilon_i}{2(1 - \epsilon_i)} T_{round} \right) $$

$$ = \frac{1}{N} \sum_{q=1}^{q_M} \sum_{i=(q-1)M+1}^{qM} T_q + \frac{T_{round}}{2N} \sum_{q=1}^{q_M} \sum_{i=(q-1)M+1}^{qM} \frac{1 + \epsilon_i}{1 - \epsilon_i} $$

$$ = \frac{M}{N} T_{round} + \frac{T_{round}}{2N} \sum_{i=1}^{N} \frac{1 + \epsilon_i}{1 - \epsilon_i} T_{round}. $$

(13)

Regarding the system with Rayleigh fading, the simulation results can be found in the next section.

Finally, we need to decide the blocklength of the jointly coded packets in each group, $L_q$. Given the PER constraint of the system $\epsilon_{cons}$ and the average received SNR of the weakest link in each group, the blocklength is computed according to
(5). We will also investigate the impact of the PER constraint on the AoI and EH performances in the next section.

C. EH analysis

In this paper, when the IoT devices receive signals conveying unwanted packets, i.e., WIT is not required, the devices will harvest energy from the received RF signals. The time proportion of harvesting energy in a round for IoT devices in group \( q \) is \( \eta_q = \frac{\sum_{m=q+1}^{q+M} T_{\text{round}}}{T_{\text{round}}} \). Therefore, the average total power harvested by IoT devices can be formulated as

\[
EH = \sum_{q=1}^{N} \sum_{i=(q-1)M+1}^{qM} \theta_i \eta_q E[|y_i|^2]
\]

\[
\approx \sum_{q=1}^{N} \sum_{i=(q-1)M+1}^{qM} \frac{\theta_i \sum_{m=1, m \neq q}^{M} T_{m} d_{i}^{-\tau} P}{T_{\text{round}}}
\]

(14)

where \( \theta_i \) (\( 0 < \theta_i < 1 \)) is the conversion efficiency of EH at device \( i \). For simplicity, we assume all IoT devices have the same \( \theta \), i.e., \( \theta_i = \theta, \forall i \). Note that the noise power in EH is negligible comparing with the received signal.

IV. AOI AND EH PERFORMANCE EVALUATION

This section presents the simulation results of the average AoI and EH performances when different numbers of packets are jointly coded. In particular, we show that the optimal number of jointly coded packets can be found to achieve both high information freshness and high EH performance.

The simulation setup follows the system described in Section II with the following parameters. Each IoT device requires an information update with a data size of \( D = 100 \) bits. The bandwidth of the system \( B \) and noise variance \( \sigma^2 \) are normalized to 1. The path loss exponent \( \tau \) is 2. We assume that the energy conversion efficiency \( \theta \) is 0.5. Note that the SNR in this section refers to the transmitted SNR \( \rho \).

In Fig. 4, we consider a system with a total of \( N = 60 \) IoT devices. The packets for \( M = (1, 2, 3, 4, 5, 10, 30) \) devices are jointly encoded. The distances from the AP to the devices follow a uniform distribution within \( 10 - 20 \)m. In Fig. 4, the transmitted SNR \( \rho \) is \( (23 \text{dB}, 25 \text{dB}, 27 \text{dB}) \) and the PER constraint \( \varepsilon_{\text{cons}} \) is \( 10^{-5} \). We consider two channel models in this section: the path loss channel model with and without Rayleigh fading. The result shows that as \( \rho \) increases, the average AoI of the system decreases, while the average total power harvested by the IoT devices increases. It is worth noting that the average AoI without Rayleigh fading will be smaller (i.e., the information updates are fresher) than with Rayleigh fading. This is because the blocklength of the jointly coded packets is determined based on the expected channel states. However, in the channel model with Rayleigh fading, the received SNR is always changing, resulting in worse AoI performance than in the case without Rayleigh fading. Meanwhile, Fig. 4 shows that the fading does not affect the EH performance under the joint packet coding.

Furthermore, Fig. 4 indicates that the difference in AoI performance between the two channel models decreases as the transmitted SNR \( \rho \) increases. This is because the effect of the randomness in channel states will be reduced in the high SNR regime. More importantly, we can observe that there exist optimal numbers of jointly coded packets that achieve high EH and low AoI performances simultaneously. It is worthwhile to note the case of \( M = 1 \) in Fig. 4, which implies that there is no joint coding in the AP. We can observe that joint coding (e.g., \( M = 2 \) or 3) can significantly reduce the average AoI compared to the conventional strategy (i.e., no joint coding, \( M = 1 \)) while achieving comparable EH performance.

We also study the case of a total of \( N = 30 \) IoT devices, as shown in Fig. 5. The packets for \( M = (1, 2, 3, 5, 6, 10, 15) \) devices are jointly coded. As in the \( N = 60 \) case, Fig. 5 shows that a small number of update packets (\( M = 2 \) or 3 in this case) is usually sufficient to achieve low AoI and high EH. In addition, Fig. 5 shows the impact of the distance from the AP to the devices and plots the AoI and EH performances for the two channel models when the distances are uniformly distributed within \( 10 - 20 \)m, \( 20 - 30 \)m, and \( 30 - 40 \)m. The PER constraint \( \varepsilon_{\text{cons}} \) is \( 10^{-5} \), and the transmitted SNR \( \rho \) is
25dB. It is clear that as the distance increases, the average total power harvested by the IoT devices decreases while the average AoI of the system increases.

Finally, we investigate the cases when $\epsilon_{cons}$ varies. In Fig. 6, $\rho$ is 25dB and $\epsilon_{cons}$ is $(10^{-3}, 10^{-4}, 10^{-3})$. The distances from the AP to the devices follow uniform distribution within $10-20m$. We consider path loss channels without Rayleigh fading with a total of 30 IoT devices. The packets for $M = (1, 2, 3, 5, 6, 10, 15)$ devices are jointly encoded. Fig. 6 indicates that the average AoI of the system reduces as the PER constraint is relaxed. The performance improvement mainly comes from the shorter blocklength of the jointly coded packet, which may decrease the average AoI of the system. The result gives a hint about future work on optimizing the blocklength, i.e., to minimize the average AoI of the system without the PER constraint.

V. CONCLUSION

In this paper, we consider a downlink IoT network in which an AP sends jointly coded packets in a round-robin manner to $M$ groups of IoT devices, each group consisting of $M$ devices. All devices are equipped with capacitors that store energy from wireless power transfer (WPT) when the devices receive signals targeted at others. There are two main requirements in this scenario: high information freshness and high energy harvesting (EH) performance. On the one hand, more packets jointly coded reduce the packet error rate (PER). Thus the time between two successful updates may be reduced, which may contribute to higher information freshness (lower AoI). On the other hand, more packets jointly coded lead to less idle time for the devices to harvest energy from the radio-frequency (RF) signals, which leads to lower EH performance. Hence, we investigate the performances of AoI versus EH by examining the number of packets jointly encoded. From the derived closed-form AoI and EH formulas and numerical results, we find that a small number of packets jointly coded is usually sufficient to achieve high information freshness and EH performance.

References