Age of Information in Two-way Updating Systems Using Wireless Power Transfer

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Abstract—We consider a two-way updating system with a master node and a slave node. In each block, the master node transfers energy and updates to the slave node alternatively. The slave node performs transmission to the master node if it has sufficient energy for current block, i.e., using best-effort policy. Moreover, the slave node generates a new update immediately after the completion of previous update. We examine the freshness of the updates received by the master node in terms of age of information (AoI), which is defined as the time elapsed after the generation of the latest received update. We derive average uplink AoI and uplink update rate as functions of downlink update rate in closed form. The obtained results illustrate the performance limit of the unilaterally powered two-way updating system in terms of timeliness and efficiency. The results also specify the achievable tradeoff between the update rates of the two-way updating system.

Index Terms—Age of information, two-way updating, wireless power transfer.

I. INTRODUCTION

The recent prevalence of Internet-of-Things has spawned a plethora of real-time services that require timely information/status updates [1]. In vehicular networks [2], [3], for example, accurate status information (e.g., position, speed, acceleration) needs to be timely shared among vehicles to ensure safety. In these scenarios, neither traditional delay nor throughput can be adequate [4]. To be specific, if update delay is small, the received updates may not be fresh due to too infrequent transmissions. On the other hand, if throughput is high, the received updates may not be fresh either due to large queuing delays [5]–[7]. To convey the freshness of information at the receiver, therefore, a new metric was proposed in [8], i.e., age of information (AoI).

AoI is defined as the elapsed time since the generation of the latest received update [8], i.e., the age of the newest update of the system. Since AoI is closely related with queueing theory, it has been studied for various queueing systems, e.g., M/M/1, M/D/1 and D/M/1 [8], and under several serving disciplines, e.g., first-come-first-served (FCFS) [8], [9] and last-generate-first-served (LGFS) [10]. The zero-wait policy where a new update are served immediately after the completion of previous update was also investigated in [11]. Moreover, the authors of [12] studied the average AoI of transmitting k-symbol updates over an erasure channel with either infinite incremental redundancy (IIR) or fixed redundancy (FR). Although these serving disciplines may find their own suitable applications, neither of them can be generally optimal. This has motivated many update scheduling schemes to minimize AoI. For example, the authors of [13] discussed protocols where any new updates seeing a busy server or more than one waiting updates would be discarded. The method of replacing the updates waiting in the buffer with newer updates was studied in [13]–[14]. The AoI of energy harvesting powered systems has also attracted many attentions. Due to the randomness of the energy harvesting process, energy buffers are needed to store the harvested energy. To this end, the authors of [15], [16] investigated how buffer size affects AoI and the optimal threshold of remaining energy to trigger a new update has been found in [17]. Moreover, AoI was also investigated in multi-source [18], multi-class [19], multi-hop [20] scenarios.

In this paper, we consider the uplink updating from the slave node to the master node, as shown in Fig. 1. We assume that only the master node has a constant energy supply. When the master node is not transmitting updates, it transfers energy to the slave node using wireless power transfer [21], which may find many applications in implantable biomedical devices. Since these applications are very time-sensitive, the transmission time to deliver an update over the downlink or the uplink channel cannot be ignored. In this paper, therefore, we model the transmission time of updates as the service time of the updating system. Constrained the limited energy supply at the master node, we investigate the fundamental updating capability of the slave node in terms of average uplink AoI and uplink update rate. We prove that average uplink AoI approaches some constant as p goes to zero and goes to infinity gradually when p is increased. We also present uplink rate q as a function of downlink update rate p in closed form. We show that as p goes to zero, uplink update rate q is a constant; when p is increased, uplink update rate goes to zero gradually. Since downlink update rate and uplink update rate cannot be optimized at the same time, the obtained results are also showing the best achievable tradeoff between them.

This paper is organized as follows. Section III presents the system model and the AoI model. In Section IV, we derive average uplink AoI and average uplink update rate as functions of downlink update rate p, as well as their asymptotic behaviors. Finally, numerical results are provided in Section V and our work is concluded in Section VI.
II. SYSTEM MODEL

We consider a two-node status updating system as shown in Fig. 1 where a master node and a slave node exchange their status updates through block fading channels. We assume that time is discrete.

A. Channel Model

We assume that the distance between the master node and the slave node is \( d = 1 \) meter. We also assume that the channels in both directions suffer from block Rayleigh-fading and additive white Gaussian noise (AWGN), i.e., the power gain \( \gamma_n \) follows exponential distribution

\[
f_\gamma(x) = \lambda e^{-\lambda x}.
\]

For both downlink and uplink transmissions, let \( P_t \) be the transmit power, \( T_b \) be the block length, \( \lambda \) be the limited system bandwidth, and \( N_0 \) be the noise spectrum density. We further assume that \( P_t \) is small and the received signal-to-noise-ratio (SNR) is much smaller than unity. Hence, the amount of information that can be transmitted in a block would be

\[
b_n = T_b \lambda \log \left( 1 + \frac{2\lambda P_t}{N_0} \right) \approx \frac{2\lambda P_t T_b}{N_0}.
\]

It is clear that \( b_n \) also follows exponential distribution. In addition, we assume that downlink and uplink transmissions use different frequency bands.

B. Status Update Model

In each block, the master node generates an update of \( \ell \) nats with probability \( p \), which is referred to as downlink update rate. The updates will be transmitted according to FCFS policy. We denote the number of blocks used to deliver update \( k \) as service time \( S_k \). According to [6], \( S_k \) follows Poisson distribution\(^1\)

\[
p_j^k = \Pr\left\{ \sum_{i=1}^{j-1} b_i < \ell, \sum_{i=1}^{j} b_i \geq \ell \right\} = \frac{\theta^{j-1}}{(j-1)!} e^{-\theta},
\]

where \( j = 1, 2, \ldots \), and

\[
\theta = \frac{N_0 \ell}{P_t T_b}.
\]

\(^1\)With some minor changes, our analysis can also be used for scenarios with general SNR and general fading models. The obtained results, however, might be more complex in expression.

\(^2\)Note that we have \( j \geq 1 \) in our case, which is slightly different from Poisson distribution. In addition, we say the service time is \( S_k = 1 \) even if its completion time is less than \( T_b \).

The probability generating function (PGF) and the first two order moments of \( S_k \) are given by

\[
G_S(z) = E\left( z^S \right) = ze^{\theta(z-1)},
\]

\[
E(S) = \lim_{z \to 1^{-}} G'_S(z) = 1 + \theta,
\]

\[
E(S^2) = \lim_{z \to 1^{-}} G''_S(z) + G'_S(z) = \theta^2 + 3\theta + 1.
\]

A period when the master node is busy in transmitting updates is referred to as a downlink busy period and a period when the status queue of the master node is empty and no new update arrives is referred to as a downlink idle period. In downlink idle periods, the master node transfers energy to the slave node. Let \( \eta \) be the efficiency of downlink energy transfer, the energy received by the slave node would be

\[
E_n = \eta \gamma_n P_t T_b.
\]

For the slave node, it generates an update immediately after the completion of previous update, namely, according to the best-effort policy. Moreover, the slave node transmits a certain amount of information to the master node as long as its remaining energy is no less than \( P_t T_b \).

C. Age of Information

Definition 1: In block \( n \), uplink age of information is the difference between \( n \) and the generation time \( U(n) \) of the latest received update at the master node:

\[
\Delta(n) = n - U(n).
\]

Fig. 2 presents a sample variation of uplink AoI with initial age \( \Delta_0 \). The updates are generated at arrival epochs \( n_k \) and are completely transmitted at departure epochs \( n'_k \). We denote the time that an uplink update \( k \) stays in the system as uplink system time \( T_k \). Note that if downlink power transfer is weak, an uplink update would take a long period to complete, which may covers several downlink idle periods and busy periods. Thus, \( T_k \) includes the service time of the update, the time for harvesting energy, and the time waiting for downlink power transfer (if any).

It is observed that AoI increases linearly in time and is reset to a smaller value at the end of departure blocks. Over a period of \( N \) blocks where \( K \) uplink updates are transmitted, the average uplink AoI is defined as

\[
\Delta_N = \frac{1}{N} \sum_{n=1}^{N} \Delta(n).
\]
Starting from the first block, the area under $\Delta(n)$ can be seen as the concatenation of areas $Q_0, Q_1, \cdots$, and the triangular-like area of width $T_K$. Thus, the average uplink AoI can be written as

$$\bar{\Delta} = \lim_{N \to \infty} \frac{1}{N} \left( Q_0 + \sum_{k=1}^{K-1} Q_k + \frac{1}{2} T_K (T_K + 1) \right).$$ (7)

Given a downlink update rate $p$, we denote the achievable uplink update rate as $q(p)$, which is given by

$$q(p) = \lim_{N \to \infty} \frac{K}{N}.$$ (8)

### III. Uplink Age of Information

In this section, we first investigate the statistic property of the energy harvesting process and the uplink service time, and then derive the average uplink AoI in closed form.

#### A. Energy Harvesting Process

Note that energy transfer efficiency is always smaller than unity. In each block, therefore, the harvested energy at the slave node can support one block of transmission at most. Thus, the transmissions of the slave node always occur during downlink idle periods. In a period of $j$ blocks during downlink idle period, we denote $e_j$ as the harvested energy, i.e.,

$$e_j = \sum_{i=1}^{j} E_{m_i} = \eta P_T B \sum_{i=1}^{j} \gamma_{m_i},$$

where $m_i$ is the index of the $i$-th block of this period and $\gamma_i$ is the exponentially distributed power gain. It can be seen that $e_j$ follows Erlang$(j, \frac{\lambda}{\eta P_T B})$ distribution and the corresponding probability density function is given by

$$f_{e_j}(x) = \frac{\mu^j e^{-\mu x}}{j!(j-1)!},$$ (9)

where $\mu = \frac{\lambda}{\eta P_T B}$.

Let $\tau_H$ be the number of downlink idle blocks for the slave node to accumulate sufficient energy to perform a block of transmission and $e_r$ be the remaining energy after the previous transmission. We have $\Pr\{\tau_H = 0\} = \Pr\{e_r > P_T B\}$ and

$$\Pr\{\tau_H = j\} = \Pr\{e_r + e_{j-1} < P_T B, e_r + e_j \geq P_T B\},$$

for $j = 1, 2, \cdots$. Thus, the actual time to perform a block of uplink transmission is $s = \max\{1, \tau_H\}$.

Since both energy transfer efficiency $\eta$ and average channel power gain $\mathbb{E}[\gamma] = \frac{\lambda}{\eta}$ are quite small in general, the harvested energy in each block is not enough to perform a block of transmission. Thus, $\tau_H$ would be larger than 1 almost surely. In this case, $e_r$ would be the the remaining part of energy $E_m$ harvested in a block. According to (6), $E_m$ follows exponential distribution. Due to the memoryless property of exponential distribution, $e_r$ follows the same distribution as $E_m$. We have,

$$\Pr\{\tau_H = j\} = \Pr\{e_r < P_T B, e_{j+1} \geq P_T B\} = \int_0^{P_T B} f_{e_r}(x) \int_{x}^{\infty} f_{e_1}(y) dy = \frac{1}{(j-1)!} e^{-\mu x}. \tag{10}$$

Since uplink transmission suffers the same fading and uses the same transmit power as downlink channel, the required number $S$ of blocks to deliver an uplink update also follows distribution law (10). We denote the uplink service time as $S_{UL}$, which includes the actual service time for transmitting the update (i.e., $S$), and the time required for harvesting and accumulating energy. Thus, we have

$$S_{UL} = \sum_{i=1}^{S} s_i. \tag{11}$$

In particular, the moments of $S_{UL}$ are given by the following proposition.

**Proposition 1:** The first-two order moments of the uplink service time $S_U$ are, respectively, given by

$$\mathbb{E}(S_{UL}) = \left( \frac{\lambda}{\eta} + e^{-\frac{\lambda}{\eta}} \right) (1 + \theta),$$ (12)

$$\mathbb{E}(S_{UL}^2) = \left( \frac{\lambda}{\eta} + e^{-\frac{\lambda}{\eta}} \right)^2 (\theta^2 + 2\theta) + \left( \frac{\lambda^2}{\eta^2} + \frac{\lambda}{\eta} - e^{-\frac{\lambda}{\eta}} \right) (1 + \theta).$$

**Proof:** See Appendix A.

#### B. Uplink System Time

Note that all the transmissions of uplink updates are started and completed during downlink idle periods. If the previous uplink update is completed exactly at the end of a downlink idle period, however, the starting time of current uplink update would coincide with the beginning of a downlink busy period, as shown in the example in Fig. 3. Moreover, if a new update is generated immediately after a busy period, two busy periods would appear unintoshertially. In this case, we say that the length of the idle period between the two consecutive busy periods is $I_{DI} = 0$. In particular, the distribution of downlink idle period is given by $\Pr\{I_{DI} = j\} = (1 - p)^j p, j = 0, 1, \cdots$. We denote the number of downlink busy periods coming unintoshertially as $F$, then the distribution and the first two order moments of $F$ can be given by

$$p_j^f = \Pr\{F = j\} = p^j (1 - p), \quad j = 0, 1, 2, \cdots, \tag{13}$$

$$\mathbb{E}(F) = \frac{p}{1 - p}, \tag{14}$$

$$\mathbb{E}(F^2) = \frac{p(1 + p)}{(1 - p)^2}. \tag{15}$$

Since there might exist one or more downlink busy periods before each of the blocks of uplink service time $S_{UL}$, the uplink system time can be expressed as

$$T_k = S_{ULk} + \sum_{i=1}^{F_k} \sum_{j=1}^{S_i} B_{Dj}. \tag{16}$$

In particular, the first two order moments of downlink busy period $B_{Dj}$ are given by the following proposition.
the achievable uplink update rate is given by

\[ q = \frac{(1-p)(1-p+\theta p^2)}{\frac{\theta}{1+\theta} + (1+\theta)(1-p+\theta p^2)}. \]  

To obtain more insights, we further investigate the following two special cases.

Corollary 1: In the case \((\theta + 1)p \approx 0\), average uplink AoI and uplink update rate are, respectively, given by

\[ \bar{\Delta} = \frac{1}{2} \left( \frac{2^2 + \frac{\theta}{\theta} + \exp \left(-\frac{\theta}{\theta}\right)}{\frac{\theta}{1+\theta} + (1+\theta)(3\theta^2+6\theta+2)} \right) + \frac{1}{2}, \]

\[ q(p) = \frac{p(1-p)}{p+\theta}. \]

Proof: The corollary readily follows the approximations \(p \approx 0\) and equations (20) and (21).

The condition \((\theta + 1)p \approx 0\) indicates that downlink channel (19) is lightly occupied by information transmission and thus much energy can be transferred to the slave node. Under the best-effort policy, therefore, both uplink AoI and uplink update rate would be finite, as shown in Corollary 1. Note that the key parameters in this case include the expected service time \(E(S) = 1 + \theta\), the expected channel power gain \(\frac{1}{\theta}\), and the energy transfer efficiency \(\eta\).

Corollary 2: In the case \((\theta + 1)p \approx 1 - o\) where \(o\) is an infinitesimal, average uplink AoI and uplink update rate are, respectively, given by

\[ \bar{\Delta} = \left( \frac{2^2 + \frac{\theta}{\theta} + \exp \left(-\frac{\theta}{\theta}\right)}{\frac{\theta}{1+\theta} + (1+\theta)(3\theta^2+6\theta+2)} \right) \frac{1+\theta}{\theta^2} \cdot \frac{1}{2}, \]

\[ q(p) = \frac{p(1-p)}{p+\theta} \cdot o. \]

Proof: This corollary can be readily proved by using the approximation in equations (20) and (21).

When \((\theta + 1)p\) approaches unity, the downlink channel is very busy and little energy can be harvested at the slave node. Thus, the uplink service time would be very large. As a result, uplink AoI goes to infinity and uplink update rate goes to zero, as observed in Corollary 2.
IV. NUMERICAL RESULTS

In this section, we investigate the AoI of the two-way updating via numerical results. We set the transmit power of both the master node and the slave node, for both transmitting information and transferring energy, as $P_1 = 0.01$ W. The system bandwidth is $\omega = 1$ MHz, the noise spectrum density (including noise figure, etc.) is $N_0 = 4 \times 10^{-7}$. The Rayleigh channel parameter is $\lambda = 3$, the block length is $T_B = 10^{-3}$ s, and the energy transfer efficiency is $\eta = 0.5$. For simplicity, we set the distance between the master node and the slave node to $d = 1$ m. For update length, we consider the following three cases: $\ell = 10$ bits, $\ell = 30$ bits, and $\ell = 90$ bits. By using (2), the corresponding parameter $\theta$ can be obtained as $\theta = 1.2$, $\theta = 3.6$, and $\theta = 10.8$, respectively. Note that for any given $\theta$, the maximal downlink update rate enabling a stable queue at the master node is $p_{\text{max}} = \frac{1}{1+\theta}$.

We present average uplink AoI in Fig. 4(a). In general, average uplink AoI is large, especially when downlink update rate $p$ is large. On one hand, if $p$ is very small, the master node would transfer energy to the slave node for most of the time. In this case, the slave node seldom needs to wait for harvesting energy so that uplink system time is determined only by energy transfer efficiency $\eta$ and actual service time $S$. As $p$ approaches zero, therefore, average uplink AoI would converge to a constant, as shown in Fig. 4(a) and Corollary 1. On the other hand, as $p$ approaches the maximal downlink update rate $p_{\text{max}}$, average uplink AoI goes to infinity, which is consistent with Corollary 2.

We plot how uplink update rate $q$ (see (21)) varies when downlink update $p$ is changed in Fig. 4(b). We observe that $q$ decreases rapidly when $p$ is increased. In particular, $q$ reduces to zero as $p$ approaches $p_{\text{max}}$. Moreover, for each given $\theta$, the area under the curve can be regarded as the achievable region of update rate pair $(p, q)$. That is, each point under the curve is achievable while the points above the curve are not. Since the power supply at the master node is the only energy source of the system, downlink update rate and uplink update rate cannot be optimized at the same time. Thus, the curves in Fig. 4(b) can also be regarded as best-achievable tradeoff between downlink update rate and uplink update rate. To see this clearly, one may use a weighted-sum characterization of the system update rate. That is, an update rate pair $(p, q)$ is said to be optimal if it maximizes the weighted sum update rate $wp + (1-w)q$, where $0 \leq w \leq 1$ is a constant showing the priority of downlink transmission and uplink transmission. Intuitively, the solution to this optimization can be obtained by searching the tangent point between line $wp + (1-w)q = c$ and the curves in Fig. 4(b).

V. CONCLUSION

In this paper, we have studied the AoI of a two-way updating system with a unique power supply at the master node. We obtained average uplink AoI in closed form and presented the corresponding asymptotic behavior. Based on these results, we can also determine the achievable region of downlink update rate and uplink update rate. It is clear that downlink performance is constrained by the limited transmit power of the master node. The uplink performance, however, is also affected by downlink update rate $p$. To be specific, average uplink AoI would be smaller and average uplink update rate would be larger if $p$ is decreased. Since the performance of downlink and uplink cannot be optimized at the same time, one needs to find the tradeoff between them under some criteria, e.g., weighted-min/max, as discussed in Subsection V and Fig. 4(b). Thus, the obtained results have presented a full characterization of the updating capability of the two-way system. This work has focused on the FCFS serving discipline. Considering the performance of the system under other serving disciplines and update management is also very interesting and will be explored in our future work.

APPENDIX

A. Proof of Proposition 1

Proof: Since the actual time to perform a block of uplink transmission is $s = \max\{1, \tau_H\}$, we have $\Pr\{s = 1\} = \Pr\{\tau_H = 0\} + \Pr\{\tau_H = 1\} = (1 + \frac{\lambda}{\eta})e^{-\lambda T_B}$.

Based on (10) and (11), we have

$$E(S_U) = E(1)E(s) = \left(\frac{1}{\eta} + e^{-\frac{1}{\eta}}\right)(1 + \theta),$$

$$E(S^2_U) = \sum_{i=1}^{S} S^2_i + \sum_{i=1}^{S} \sum_{j \neq i} S_i S_j$$

$$= E(S)E(s^2) + E(S^2 - S)E^2(s)$$

$$= \left(\frac{1}{\eta} + e^{-\frac{1}{\eta}}\right)^2 \left(\theta^2 + 2\theta + \left(\frac{\lambda}{\eta} + \frac{1}{\eta} - e^{-\frac{1}{\eta}}\right)(1 + \theta).$$

This completes the proof of the proposition. □

B. Proof of Proposition 2

Proof: According to the definition of uplink system time and the independency among downlink busy periods,

$$E(T) = E\left(S_{UL} + \sum_{i=1}^{F_i} \sum_{j=1}^{F_i} B_{Dj}\right) = E(S_{UL}) + E(S_{UL})E(F)E(B_D),$$

where $E(S_{UL}), E(F),$ and $E(B_D)$ are given by (12), (14), and (17), respectively.

Denote $y_i = \sum_{j=1}^{F_i} B_{Dj},$ we then have

$$E(T^2) = E\left(S_{UL} + \sum_{i=1}^{S_{UL}} y_i^2\right)$$

$$= E(S^2_{UL}) + 2E(S^2_{UL})E(F)E(B_D) + E\left(\sum_{i=1}^{S_{UL}} y_i^2\right).$$

where the last term is given by

$$E\left(\sum_{i=1}^{S_{UL}} y_i^2\right) = E\left(\sum_{i=1}^{S_{UL}} y_i^2 + \sum_{i=1}^{S_{UL}} \sum_{i \neq i_1} S_{UL} y_{i_1} y_{i_2}\right)$$

$$= E(S_{UL})E(F)E(B_D^2) + E(S_{UL})E(F^2 - F)E^2(B_D) + E(S^2_{UL} - S_{UL})E^2(F)E^2(B_D).$$

The proof of Proposition 3 is readily completed by combing results (A.22)–(A.24). □
Thus, the queue length at the master node would be infinitely large if $p(\theta + 1) \geq 1$. That is, the master node will be always in the busy period and no energy can be transferred to the slave node. In this case, the average uplink AoI would be infinitely large and the uplink update rate would be zero. Next, we consider the case of $p(\theta + 1) < 1$.

According to the definition of uplink update rate \( \bar{\Delta} \), we have

$$
q(p) = \lim_{N \to \infty} \frac{K}{N} = \frac{1}{(1-p)(1-p-\theta p)} \left( \frac{1}{\theta + e^{-\theta}} \right) \left( 1 + p(1+p^2+\theta p) \right),
$$

(A.25)

where \( E(T) \) is given by (19).

In the definition of \( \bar{\Delta} \) (cf. (7)), we note that \( Q_0 \) is finite and \( T_k \) is finite in probability. Thus, the average uplink AoI can be rewritten as

$$
\bar{\Delta} = \lim_{N \to \infty} \frac{1}{N} \sum_{k=1}^{K-1} Q_k
= \lim_{N \to \infty} \frac{K - 1}{N} \sum_{k=1}^{K-1} Q_k
= qE(Q_k).
$$

(A.26)

Note that the average of area \( Q_k \) is given by

$$
E(Q_k) = E(T_k T_{k+1} + \frac{1}{2} T_k (T_k + 1))
= E^2(T) + \frac{1}{2} E(T^2) + \frac{1}{2} E(T).
$$

(A.27)

Using the results in Proposition [3] and (A.25–A.27), the average uplink AoI can be rewritten as

$$
\bar{\Delta} = E(T) + \frac{1}{2} + \frac{1}{2} E(T^2)
= \frac{1-p+p^2+\theta p^2}{2(1-p)(1-p-\theta p)} \left( \frac{s^2 + \frac{1}{\eta} - e^{-\frac{1}{\eta}}}{\frac{1}{\theta} + e^{-\theta}} \right) \left( \frac{\theta^2 + 2\theta + 1}{1+\theta} \right)
+ \frac{p(1+p-p^2)(1+\theta)^2+\theta(1-p)}{2(1-p)(1-p-\theta p)(1-p+p^2+\theta p^2)} + \frac{1}{2}.
$$

Thus, the proof of Theorem [1] is completed. \( \Box \)

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