immediate

March 8, 2021

1 System Model

We consider an multi sensor IOT network, as depicted in Figure 1, where sensors desire to transmit their data to the Access point (AP). Since a sensor is lack of energy, it has to harvest energy from a Wireless Power Source (WPS) that deployed in the system and used to charge the wireless devices via wireless power transfer. All of the IOT sensors are deployed to observe one physical process (such as temperature, humidity, etc.) in different places and to transmit update packets to the destination so that the information status of their observed process at the destination remains fresh. In this network, we consider a RF communication for uplink and a visible light communication for downlink. Thus, we should have a VLC/RF access point and photodetector in the receiver. To minimize the age of information, we need to analyze the AOI in either the downlink (VLC) or the uplink (RF). In the downlink, factors that can cause information to be lost are physical obstacles. Therefore, it is easy to ensure that updated information is received at the receiver by creating a suitable position for the sensors (receiver) and access point (transmitter) as well as strengthening the LOS component. If the distance between sensors and AP is small, the LED in the VLC transmitter can be used. By increasing the distance between the sensors and the AP, higher power LEDs can be used, and if the distance between them is too large, we should use LD instead of LED lamps. Since in IoT systems sending fresh and update data from the sensors to the control center is very important, it is necessary to analyze the age of the information in the uplink. Because multiple sensors are used in this network, by using Non-Orthogonal multiple access (NOMA) method, the network can be decomposed into multiple point-to-point networks which is shown in Figure 2.

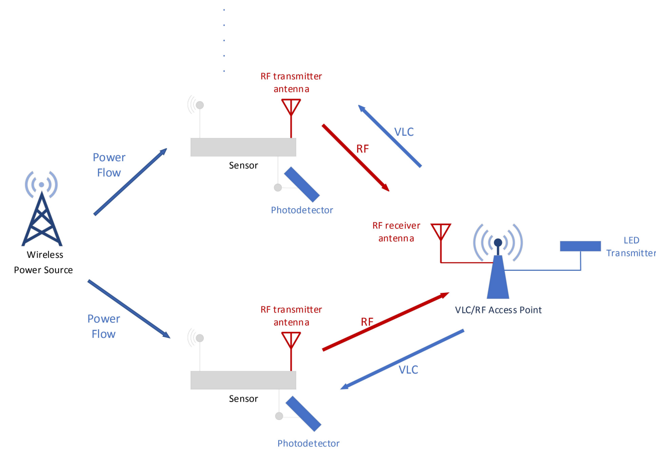

Figure 1: A VLC/RF based multi sensor IoT network

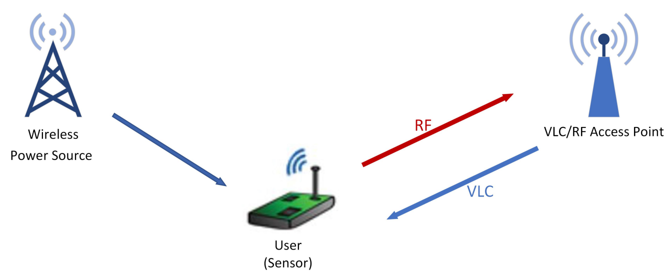

Figure 2: A point-to-point VLC/RF based IOT network

2 Sensors Energy Harvesting

Sensors harvest energy from radio frequency signals (transmitted by the wireless power source) to transmit real-time status updates. The average AoI performance of the considered greedy policy is derived in closed form and is a function of the capacitor's size. The optimal value of the capacitor that maximizes the freshness of the information, corresponds to a simple optimization problem requiring a one-dimensional search. The derived theoretical results provide useful performance bounds for practical WPS networks. Figure 3 shows how energy is received by sensors for a point-to-point network.

When receiving power, there may be interference between the power signal and the RF transmitter in the sensor, as well as between the power signal and the RF receiver in the AP. To avoid this interference, we assume that the sensors generate an update when their capacitor/battery becomes fully charged and transmit by using all the available energy without further energy management. Therefore, while receiving energy, no sending and receiving is done in the sensor and AP and there will be no interference.
This interference can also be prevented by energy management. Since in the sensor, a capacitor is installed as a battery, which only receives RF power from the power source and is charged if there is not enough power to send. While receiving this power, sending is not done in Uplink. Also, since the required power of the sensors is low, so it is possible to prevent the interference of the transmitted power signal with the AP by placing the power source and AP at the appropriate distance. In this paper, it is assumed that the energy

transmission and data transmission are over orthogonal frequency bands.

It is assumed that the system works in a discrete time manner. That is, the time is divided into blocks with equal interval T_b. The time period from the epoch n to the epoch $n+1$ is referred to as the time block n. By using one of the multiplexing methods, AOI analysis can be performed separately on each point-to-point network. For this purpose, let $h_1[n]$ and $h_2[n]$ be the channel coefficients of the links from the WPS to the sensor and from the sensor to the AP, respectively, associated with time block n. The corresponding power gains $|h_1|^2$ and $|h_2|^2$ follow the exponential distribution, which can be expressed by

$$\begin{aligned} f_{|h_1|^2}(x) = \lambda_1 e^{-\lambda_1 x} \\ f_{|h_2|^2}(x) = \lambda_2 e^{-\lambda_2 x} \end{aligned} \qquad (1)$$

where λ_1 and λ_2 are the exponential distribution parameters.

In each block, the sensor generates a data packet with size of δ bits randomly with a certain probability p and then the generated data packets are transmitted within RF channel. Denote the distance between the WPS and the sensor and between the sensor and the AP to be d_1 and d_2,respectively. Let the transmit power of the WPS be P_ω. If in time block n, the user performs energy harvesting, the energy received at the sensor from the WPS in time block n is given by

$$E[n] = \mu |h_1[n]|^2 P_\omega T_b \qquad (2)$$

where η is the energy transfer efficiency and $\mu = \frac{\eta}{d_1^\alpha}\alpha$ is the pass loss factor. For simplicity we can assume that $T_b = 1$.

Since the energy transfer efficiency η is less than one and the received power is also relatively small due to pass loss, the sensor may take several blocks to harvest and accumulate energy to complete a block of transmission. The energy accumulated at the sensor within j blocks is

$$e_j = \sum_{i=1}^{j} E[i] = \mu P_w T_b \sum_{i=1}^{j} |h_1[i]|^2 \qquad (3)$$

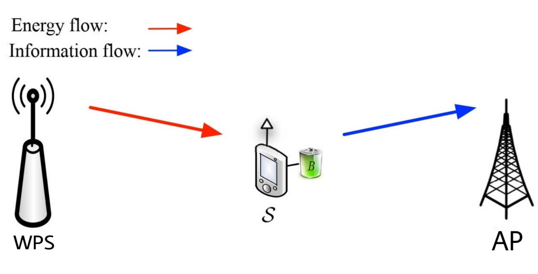

Figure 3: A three node sensor network topology

3 Non-Orthogonal Multiple Access Implementation

The fundamental difference between OMA and NOMA schemes is that NOMA has the ability to increase the spectral efficiency of a network by multiplexing multiple users in a single time or frequency unit. The key technologies used in NOMA are superposition coding (SC) and successive interference cancellation (SIC). In superposition coding, the sensors send multiple information messages to AP over the same bandwidth. The successive interference cancellation (SIC) is implemented at devices end to decode the received SC messages from the sensors. In SIC, access point obtains respective information messages from all sensor's messages in a received SC message by exploiting the channel qualities. The weak sensor performs no SIC to extracts their information while stronger sensors first need to subtract the weaker sensor's message from received

SC signal to get their message. There are generally two common techniques involved with NOMA scheme, power-domain NOMA (PD-NOMA) and code-domain NOMA (CD-NOMA). In PD-NOMA, multiple sensor devices are multiplexed through the difference in channel gains for each sensor, whereas, in CD-NOMA, they are multiplexed through concurrent use of spreading code sequences for a specific sensor.
In our work, we use PD-NOMA method for uplink. In this model, all sensors transmit data in the same spectrum resource unit (same frequency band) block through the use of duplexing in the power domain. In this network, sensors residing in the coverage zone of gateway have different channel gains. These channel gains are dependent upon the various factors, such as the distance of user or device from the gateway, multipath structure of the environment, fadings phenomenon, etc. The sensors can reap the channel gain differences by transmitting the information signal with different power levels. In uplink, the sensor with experiencing weaker channel gain communicates with a larger power, while the sensor experiencing high channel gain transmits with low power. At the receiver side, the gateway does decoding on a received superimposed signal by applying SIC technique. The stronger signal is extracted first from a superimposed signal and decoded. Afterward, the weaker sensor signal is decoded. Figure 5 shows the uplink NOMA scenario for two sensors.

Figure 4: NOMA scheme for uplink

By using NOMA scheme for this network, the AP receives the superimposed signal R_s and performs a NOMA decoding by employing SIC technique. The received superimposed signal, for N uplink transmission is given by,

$$R_s = \left(\sum_{k=1}^{N} \sqrt{P_{R_k} G_k} s_k \right) + z \qquad (4)$$

where z denotes the additive white Gaussian noise (AWGN) with variance σ^2 (noise power spectral density), G_k is uplink channel gain for $k-th$ sensor, s_k represents the transmitted signal from $k-th$ sensor and P_{R_k} is the transmitted power from $k-th$ sensor.
The SIC operation is performed on the superimposed signal received and retrieves the strongest sensor signal while considering the other merely low power signal from second sensor as interference. For example in the network shown in Figure 5 (2 sensors), the SINR for second multiplexing sensor during SIC operation is given as

$$(SINR)_{k=2} = \frac{P_{R_2} G_2}{\sigma^2 + P_{R_1} G_1} \qquad (5)$$

Once the stronger signal data is successfully recovered from R_s, the SIC process proceeds to retrieve the second sensor signal. The second signal is decoded from the residual signal and doesn't include interference,

Table 1: Table of Parameters

Parameters	**Definitions**
R_s	Received superimposed signal
N	Number of uplink transmissions
G_k	Uplink channel gain for kth sensor
P_{R_k}	Transmitted power from kth sensor
s_k	Transmitted signal from kth sensor
z	Additive white Gaussian noise
σ^2	Noise power spectral density
p'	Success probability for $S-AP$ link
r	Spectral efficiency
γ_k	Signal-to-noise ratio at the AP
B	Capacitor size
λ	Exponential parameter for channel coefficients
ε	Outage probability threshold

which results by subtracting a stronger sensor signal from R_s. SNR for the first sensor is given by,

$$(SNR)_{k=1} = \frac{P_{R_1} G_1}{\sigma^2} \qquad (6)$$

To calculate the probability of a successful decoding at the AP, we need to calculate the following two probabilities. We assume that all links have Rayleigh block fading (the channel is constant at one time slot and does not change, and the channel changes at each slot are independent of the other slots). Therefore the probability of successful decoding at the AP is

$$p' = prob\{\log_2(1+\gamma_k) > r\} = e^{(-\lambda \frac{2^r - 1}{B/\sigma^2})} \qquad (7)$$

where γ_k is received SNR and r represents the spectral efficiency.

On the other hand, we can calculate the outage probability for received signal at the AP. If SINR of received signal surpasses the set threshold ε, then the signal of sensor is assumed to be successfully decoded and vice versa. The outage probability of a sensor in a network can be expressed as,

$$\mathrm{P}(SINR_i < \varepsilon) = prob\left(\frac{P_{R_i} G_i}{\sigma^2 + \sum\limits_{k=1, k\neq i}^{N} P_{R_k} G_k} < \varepsilon\right) \qquad (8)$$

In the decoding process, if the SINR for a sensor is below the threshold, the sensor goes into outage. The decoding process stops and it does not continue for remaining weaker sensors.

4 AoI Analysis

In this paper, we present two types of optimization problems with different constraints. First, we calculate AoI according to update generation rate.

By using one of the multiplexing methods, AOI analysis can be performed separately on each point-to-point network. Therefore, let the transmit power of each sensor be P_u. Assume that the received signals are suffered from additive white Gaussian noise. If in time block n, the sensor performs data transmission, the capacity can be delivered in block n is

$$c[n] = T_b B \log\left(1 + \frac{|h_2[n]|^2 P_u}{B N_0}\right) \qquad (9)$$

Table 2: Table of Parameters

Parameters	**Definitions**
T_b	Time block interval
$h_1[n]$	Channel coefficients of the WPS-S link
$h_2[n]$	Channel coefficients of the S-AP link
$\lvert h_1\rvert^2$	Power gain for the WPS-S link
$\lvert h_2\rvert^2$	Power gain for the S-AP link
λ_1, λ_2	Exponential distribution parameter for channel power gains
δ	Data packet size
p	Update packets generation rate
d_1, d_2	Distance between WPS-S and between S-AP
P_w	Transmit power of the WPS
B	Channel bandwidth
P_u	Transmit power of the sensors
η	Energy transfer efficiency
μ	Path loss factor
N_0	Noise spectral density
$p_j^{n_i}$	Probability of successfully completing a packet transmission with j time blocks
n_k	Generation time of the kth data packet
n'_k	Time when the kth data packet is completely transmitted
$T_k^{(T)}$	System time
I_k	Interval time
$T_k^{(W)}$	Waiting time
$\bar{\Delta}$	Average Age of Information
$p_{\max}$	Maximum update generation rate

where B is the system bandwidth and N_0 denotes the noise spectral density. For such a system, our goal is to analyze its average AoI performance in fading channels.
In IoT and sensor networks, the transmit power of the devices is usually very low, so that the received energy from the transmitted signals of WPS at the sensor is relatively very small. Therefore, we analyze the system AoI performance in the low SNR regime, where $c[n]$ can be approximated by

$$c[n] \approx \frac{\lvert h_2[n]\rvert^2 P_u T_b}{N_0} \qquad (10)$$

Since $\lvert h_2\rvert^2$ follows exponential distribution, from approximated $c[n]$ equation, $c[n]$ has exponential distribution.

For analyzing AOI, we assume that the most recently received data packet at AP in block n was generated at the time $u[n]$. Therefore, the AoI in block n, can be expressed by

$$\Delta[n] = n - u[n] \qquad (11)$$

Figure 6 illustrates a sample evolution of AoI versus time blocks with initial age Δ_0 ($\Delta[0] = \Delta_0$). Since time is discrete, the AoI is constant within each block and varies from a block to next block. Let n_k denote the generation time of the kth data packet, and n'_k denote the time when the kth data packet is completely transmitted. The number of blocks from the generation of a data packet to the completion of the transmission is $T_k^{(T)}$

$$T_k^{(T)} = n'_k - n_k \qquad (12)$$

which is called the system time. The interval time between the generation of data packet $k-1$ and data packet k is set as I_k

$$I_k = n_k - n_{k-1} \qquad (13)$$

Let $T_k^{(W)}$ denote the waiting time of data packet k. The time of a data packet in system is also equal to the sum of waiting time $T_k^{(W)}$ and service time $T_k^{(S)}$

$$T_k^{(T)} = T_k^{(W)} + T_k^{(S)} \qquad (14)$$

It is observed that the AoI increases linearly in time and is reset to a smaller value when a data packet is received.That is, at n'_k, the AOI is reset to $\Delta[n] = n'_k - n_k$. Thus, over a period of N blocks where K data packets are delivered, the average AoI is defined as

$$\bar{\Delta} = \frac{1}{N}\sum_{n=1}^{N}\Delta[n] \qquad (14)$$

As illustrated in Figure 6, the average AoI of system can be calculated as the average area of the blue graphic Q_k

$$\bar{\Delta} = \lim_{N\to\infty}\frac{1}{N}\left(Q_0 + \sum_{k=1}^{K-1} Q_k + R_k\right) \qquad (15)$$

where $R_K = \frac{1}{2}T_K^{(T)}(T_K^{(T)}+1)$.

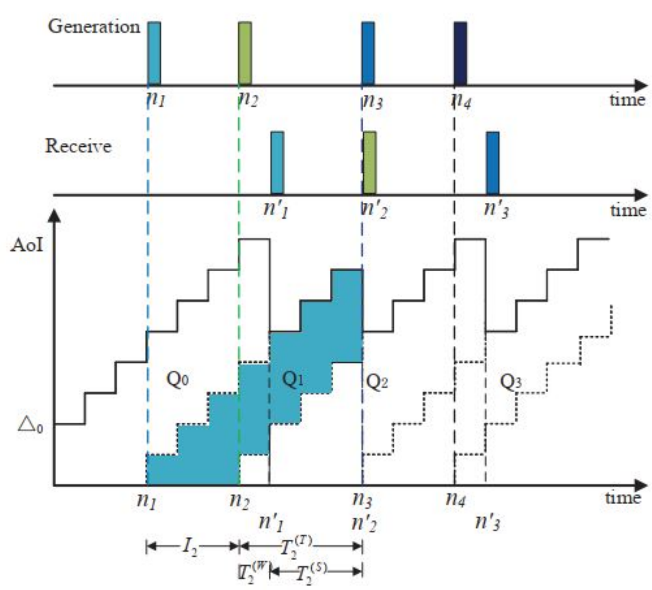

Figure 5: An illustration of a sample evolution of AoI versus time blocks

From Figure 6, one can see that the area of Q_0 and R_k are limited, with large enough N, $\frac{Q_0}{N}$ and $\frac{R_k}{N}$ are close to zero. Therefore, $\bar{\Delta}$ can be approximatively give by

$$\begin{aligned}\bar{\Delta} &= \lim_{N\to\infty} \tfrac{1}{N}\sum_{k=1}^{K-1} Q_k = \lim_{N\to\infty} \left(\tfrac{K-1}{N}\right)\left(\tfrac{1}{K-1}\right)\sum_{k=1}^{K-1} Q_k \\ &= p\mathrm{E}(Q_k) \qquad (16)\end{aligned}$$

Moreover, one can see that the area of Q_k is the difference of the area of the large red triangle minus the area of the small black triangle, as illustrated in Figure 7. That is,

$$\begin{aligned}\mathrm{E}(Q_k) &= \mathrm{E}\left(\tfrac{1}{2}\left(T_K^{(T)} + I_k + \tfrac{1}{2}\right)^2 - \tfrac{1}{2}\left(T_K^{(T)} + \tfrac{1}{2}\right)^2\right) \\ &= \tfrac{1}{2}\mathrm{E}(I_k) + \tfrac{1}{2}\mathrm{E}\left(I_k^2\right) + \mathrm{E}\left(I_k T_K^{(T)}\right) \qquad (17)\end{aligned}$$

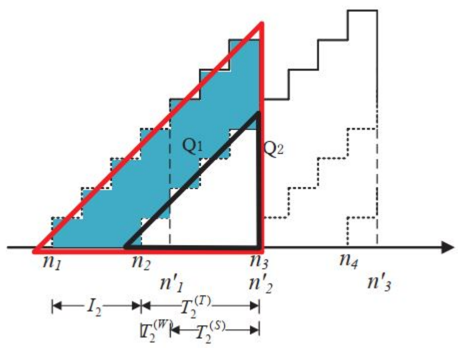

Figure 6: An illustration of an example of calculating AoI

Since p is the generation rate of the data packet at the sensor, i.e., data generating with probability p in each block. Therefore, the inter arrival time I_k follows geometric distribution. $I_k = j$ means that in the j-th block data packet is successfully generated, but was not generated in the previous $j-1$ consecutive blocks. Thus,

$$\Pr\{I_k = j\} = p(1-p)^{j-1} \qquad j = 1, 2, ...$$

and

$$\begin{aligned}\mathrm{E}(I_k) &= \tfrac{1}{p} \\ \mathrm{E}(I_k^2) &= \tfrac{2-p}{p^2} \qquad (18)\end{aligned}$$

For expressing $\mathrm{E}\left(I_k T_K^{(T)}\right)$, we use the equation of the system time of data packet k. As $T_k^{(W)}$ and I_k are not independent of each other, and $T_k^{(S)}$ is independent of I_k, one has

$$\begin{aligned}\mathrm{E}\left(I_k T_K^{(T)}\right) &= \mathrm{E}(I_k(T_k^{(W)} + T_k^{(S)})) \\ &= \mathrm{E}(I_k)\mathrm{E}(T_k^{(S)}) + \mathrm{E}(I_k T_k^{(W)}) \qquad (19)\end{aligned}$$

Our objective is to minimize the average AoI. The maximum data rate that can make the data packets queue stable is $p_{\max} = \frac{1}{1+\frac{(1+\theta)\lambda_1}{k\mu}}$ and $\theta = \frac{\lambda_2 N_0 \delta}{P_u T_b}$.

Hence, we can formulate the problem as follows:

$$\begin{aligned}\min_{p} \quad & \bar{\Delta} \\ s.t \quad & 0 < p < p_{\max} \qquad (20)\end{aligned}$$

It is also possible to use the average of all the $\bar{\Delta}$ (average AOI of each of each point-to-point network) to solve the optimization problem for the whole network. For M point-to-point network, the total average AOI is defined as follows

$$\bar{\Delta}_{Total} = \frac{1}{M}\sum_{n=1}^{M}\bar{\Delta}_n \qquad (21)$$

We also need to define a maximum data rate based on the maximum possible capacity in the network, which will be as follows:

$$p_{\max_{Total}} = \max\{p_{\max_1}, ..., p_{\max_M}\}$$

where $p_{\max_1}, ..., p_{\max_M}$ are maximum data rate of each point-to-point network.

Therefore, we can formulate the problem as follows:

$$\begin{aligned} &\min_{p} \qquad \bar{\Delta}_{Total} \\ &s.t \qquad 0 < p < p_{\max_{Total}} \qquad (22) \end{aligned}$$

It is clear that if the packet size in any point-to-point network is small, the $\bar{\Delta}_{Total}$ will be smaller and the information will be fresher. Therefore, data rate or transmission probability (p) needs to be low for each smaller network. Also, if the transmitted power of each sensor increases, it is obvious that $\bar{\Delta}_{Total}$ decreases. Because the update packets of each network are sent faster and in the AP, the amount of update information also increases. On the other hand, if the time block size is the same for all sensors, this parameter will not affect the total average AOI.

In order to calculate AoI according to battery capacity, we assume that the power source broadcasts an energy signal with power P_w. The harvested energy is stored in a capacitor of finite-size B. When the capacitor becomes fully charged, the sensors generate a status update and transmit it towards the AP by using all the stored energy. As mentioned before, time is considered to be slotted with a slot size equal to one time unit ($T_b = 1$). We assume that all links have Rayleigh block fading (the channel is constant at one time slot and does not change, and the channel changes at each slot are independent of the other slots). Let $h_1[k], h_2[k] \sim \exp(\lambda)$ be the channel coefficients of the links from the WPS to the sensor and from the sensor to the AP, respectively, associated with time block k.

$$f_{|h_1|^2}(x) = f_{|h_2|^2}(x) = \lambda e^{-\lambda x} \qquad (23)$$

In addition, all wireless links exhibit additive white Gaussian noise (AWGN) with variance σ^2. The amount of available energy in the battery at time slot k, denoted as E_k. If the available energy at slot $k-1$ is less than the battery capacity, then we have

$$E_k = \min\{E_{k-1} + \eta|h_1[k]|^2 P_w, B\} \qquad (24)$$

and if the capacitor becomes fully charged at time slot k, $E_k = B$, the sensors transmit a status update to the AP. Due to the spectral efficiency r bits per channel use (BPCU), the signal-to-noise ratio at the AP for the k-th time slot is

$$\gamma_k = \frac{B|h_2[k]|^2}{\sigma^2} \qquad (25)$$

Figure 8 presents more details of the age evolution for the sensor network.

An update is generated at the sensor node when the capacitor becomes fully charged and transmitted in the next slot (one time slot of delay); in case of a successful decoding ($\log_2(1+\gamma_k) \geq r$), the AoI at the AP is reset to one. Let n'_k and n'_{k+1} denote the time slots of two consecutive updates at the AP. Thus $I'_k = n'_{k+1} - n'_k$ denotes the k-th interarrival time. In addition, T_k denotes the time (in time slots) between two consecutive capacitor recharges and we have

$$I'_k = \sum_{i=1}^{M} T_i \qquad (25)$$

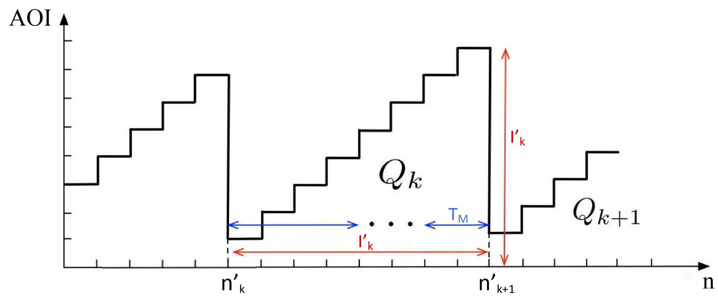

Figure 7: Example of the age evolution

where M is a discrete random variable that denotes the number of the update transmissions until successful decoding. For a time period of N time slots where K successful transmissions occur, the average AoI can be written as

$$\bar{\Delta} = \frac{1}{N}\sum_{n=1}^{N}\Delta[n] = \frac{1}{N}\sum_{k=1}^{K} Q_k \qquad (26)$$

where Q_k denotes the area under $\Delta[n]$ corresponding to the k-th status update. For $N \to \infty$, the average AOI tends to the ensemble average age

$$\bar{\Delta}_{\lim} = \lim_{N\to\infty} \bar{\Delta} = \frac{E(Q_k)}{E({I'}_k)} \qquad (27)$$

where $\lim\limits_{N\to\infty} \frac{K}{N} = \frac{1}{E(I'_k)} = p_{max}$ is the rate of updates generation.
The area under $\Delta[n]$ for the k-th update corresponds to the sum of ${I'}_k$ rectangles with one side equal to one and the other side equal to m, with $1 \leq m \leq {I'}_k$. Therefore, Q_k can be written as

$$Q_k = \sum_{m=1}^{{I'}_k} m = \frac{{I'}_k({I'}_k+1)}{2} \qquad (28)$$

By taking the expectation operator, the average area under $\Delta[n]$ can be expressed as

$$E(Q_k) = \frac{E({{I'}_k}^2) + E({I'}_k)}{2} \qquad (29)$$

To calculate the expectation of T_k and ${I'}_k$, we use the first-order and second-order moments of them. The first-order and the second-order moments for two consecutive capacitor recharges, are given by

$$\begin{cases} E(T_k) = 1 + \beta \\ E(T_k^2) = 1 + 3\beta + \beta^2 \end{cases} \qquad (30)$$

where $\beta = \frac{\lambda B}{\eta P_w}$.

Proof: See Appendix (A).

The first-order and the second-order moments for the interarrival time between two consecutive updates at the AP, are given by

$$\begin{cases} E(I'_k) = \frac{1+\beta}{p'} \\ E(I_k'^2) = \frac{1+3\beta+\beta^2}{p'} + \frac{2(1+\beta)^2(1-p')}{p'^2} \end{cases} \quad (31)$$

where $p' = prob\{\log_2(1+\gamma_k) > r\} = e^{(-\lambda \frac{2^r-1}{B/\sigma^2})}$ is the success probability for the link from sensor to AP (Rayleigh fading).

Proof: See Appendix (B).

By using equations (30) and (31) and by substituting (29) in (27), the average AoI for the considered sensor network is given by

$$\begin{aligned} \bar{\Delta} &= \frac{E({I'_k}^2)+E(I'_k)}{2E(I'_k)} \\ &= \frac{1+3\beta+\beta^2}{2(1+\beta)} + \frac{(1-p')(1+\beta)}{p'} + \frac{1}{2} \end{aligned} \quad (32)$$

By optimizing problem below, we can design the capacitor B such as the AP has as much as possible fresh information. we assume that the transmit power is given and we minimize the AoI with respect to the size of the capacitor B. The optimal capacitor size is given by

$$\begin{aligned} \min_{B} \quad & \bar{\Delta} \\ s.t \quad & B > 0 \end{aligned} \quad (33)$$

Also we can minimize the average AOI by solving optimization problem below. The new equation for maximum update generation rate is

$$p_{\max} = \frac{1}{E(I'_k)} = \frac{1}{\frac{1+\beta}{p'}} = \frac{p'}{1+\beta} \quad (34)$$

where $\beta = \frac{\lambda B}{\eta P_w}$ and $p' = prob\{\log_2(1+\gamma_k) > r\} = e^{(-\lambda \frac{2^r-1}{B/\sigma^2})}$.

Proof: See Appendix (C).

Therefore, the new optimization problems with update generation rate and battery capacity are given by

$$\begin{aligned} \min_{B,p} \quad & \bar{\Delta} \\ s.t \quad & 0 < p < p_{\max} \\ & p_{\max} = \frac{p' P_w \eta}{\lambda B} \end{aligned} \quad (35)$$

$$\begin{aligned} \min_{B,p} \quad & \bar{\Delta} \\ s.t \quad & 0 < p < p_{\max} \\ & B > 0 \end{aligned} \quad (36)$$

Table 3: Table of Parameters

Parameters	**Definitions**
P_w	Energy signal power
B	Capacitor size
h_1	Channel coefficient of the $WPS - S$ link
h_2	Channel coefficient of the $S - AP$ link
T_b	Time slot size
λ	Exponential parameter for channel coefficients
E_k	Available energy in the battery at time slot k
η	Transfer efficiency
r	Spectral efficiency
γ_k	Signal-to-noise ratio at the AP
${n'}_k, {n'}_{k+1}$	Time slots of two consecutive updates at the AP
${I'}_k$	k-th interarrival time
T_k	Time (in time slots) between two consecutive capacitor recharges
M	Number of the update transmissions until successful decoding
K	Number of the successful transmissions
$\Delta[n]$	Age of information in time slot n
Q_k	Area under $\Delta[n]$
$p_{\max}$	Maximum rate of updates generation
β	Energy efficiency
p'	Success probability for $S - AP$ link