Age of Information in SIC-based Non-Orthogonal Multiple Access

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***Abstract*—This paper uses the Age of Information (AoI) to investigate the information freshness of non-orthogonal multiple access (NOMA) with successive interference cancellation (SIC). We consider two sensors sending update packets to a common access point. The SIC decoder exploits the different powers of the signal received from the sensors to separate their signals, e.g., the signal from the strong sensor is decoded first, followed by the weak sensor. A key issue in analyzing the AoI of SIC-based NOMA is that the weak sensor needs to wait for the successful decoding of the strong sensor before decoding its own packet. In particular, the information rates of the two sensors in SIC-based NOMA may differ due to the different received signal powers, resulting in different packet durations. Therefore, one sensor may send more packets than the other sensor during the same period, and the SIC operation complicates the AoI analysis further. To this end, this paper puts forth algorithms based on different information rates of sensors to compute the average AoI of SIC-based NOMA. Numerical results show that when the received signal powers are significantly different, SIC-based NOMA outperforms orthogonal multiple access (OMA) schemes, such as time division multiple access (TDMA) and frequency division multiple access (FDMA), in terms of average AoI.**

***Index Terms*—Age of Information, information freshness, non-orthogonal multiple access, successive interference cancellation**

I. Introduction

In recent years, the Internet of Things (IoT) has become a significant growth area in many application fields, such as industrial IoT, vehicular networks, etc. In these fields, the timeliness of information update is of great importance, as correct decisions and precise controls rely on real-time data [1], [2]. A recently proposed metric, Age of Information (AoI), has been receiving increasing attention due to its advantages in characterizing the information freshness. Specifically, the instantaneous AoI is defined as the time elapsed since the generation time of the latest information update received by the destination [3]. As AoI captures both generation time and transmission delay, it is fundamentally different from conventional metrics such as throughput and latency. Previous works analyzed the average AoI, i.e., the time average of the instantaneous AoI, in various communication networks, such as point-to-point networks [4], multiple access networks [5], [6], broadcast networks [7], [8], etc. They showed that the requirement for low average AoI leads to fundamental changes in the design of communication systems.

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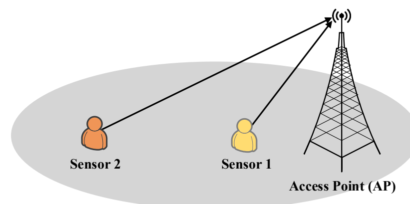

Fig. 1: An information update system where two sensors send update packets to a common access point (AP).

Non-orthogonal multiple access (NOMA) is a promising technique for 5G networks. Unlike conventional orthogonal multiple access (OMA) schemes, such as time division multiple access (TDMA) and frequency division multiple access (FDMA), uplink NOMA allows multiple users to transmit simultaneously to a common access point (AP) using the same frequency band, thus improving spectral efficiency and throughput [9]. Successive interference cancellation (SIC) has been extensively studied in many NOMA systems to separate the signals of different users [10]. To use SIC, let us consider an uplink NOMA system with a strong sensor and a weak sensor (i.e., the signal received from the strong sensor has higher power than that of the weak sensor), as shown in Fig. 1. Without loss of generality, we assume that sensor 1 is the strong sensor and sensor 2 is the weak sensor in this paper. In SIC, the AP first decodes the signal from sensor 1 by treating the signal from sensor 2 as noise. After canceling the signal of sensor 1, the AP tries to decode the signal of sensor 2 [11].

A potential benefit of applying NOMA to information update systems is that information from multiple sensors could be updated at the same time, i.e., the instantaneous AoI of the two sensors in Fig. 1 can drop simultaneously. Reference [12] first applied NOMA to a two-user network and showed that OMA and NOMA outperform each other under different packet arrival rates. Hence, [13] proposed a hybrid OMA/NOMA scheme to minimize the average AoI in a broadcast network.

Reference [14] also showed that NOMA significantly reduces the average AoI compared to TDMA under the generate-at-will model, where the source can sample the latest information of the observed phenomena at any given time.

All previous works on AoI for NOMA assumed that different transmitters have the same packet duration so that the receiver can try to decode update packets from different transmitters at the same time. Nevertheless, due to different powers of received signals in SIC-based NOMA, the theoretical information rates of sensors may differ, resulting in different packet durations between sensors. This is the main issue considered in this paper. Considering that the effective signal-to-noise ratio (SNR) of sensor 1 is higher than that of sensor 2, sensor 1 has a higher information rate, and thus its packets have a shorter duration. A packet from sensor 2 can only be decoded after the packets from sensor 1 have been successfully decoded. This delay causes a deterioration of the AoI performance of sensor 2 (and thus the whole network). We will illustrate this situation in detail in Section III.

To the best of our knowledge, there is no AoI study concerning different packet durations between sensors in SIC-based NOMA. Our paper attempts to fill this research gap. As benchmarks, we first derive the average AoI of TDMA and FDMA systems. In particular, unlike previous studies on the AoI of OMA schemes, in which the powers of the received signals from all sensors were assumed to be the same [15], this paper assumes that the received powers are different. Afterward, we design two algorithms to compute the average AoI of SIC-based NOMA based on the diverse information rates of the two sensors, i.e., whether sensor 1 or sensor 2 has a higher information rate (shorter packet duration). In both scenarios, the weak sensor has to wait for the successful decoding of the strong sensor in the SIC. However, the relative numbers of update packets sent by the two sensors during the same period are different. Our algorithm takes this difference into account when computing the corresponding average AoI.

Numerical results show that when the received powers of the signals from the two sensors are almost the same, both TDMA and FDMA have lower average AoI than NOMA does, due to substantial interference between the sensors in NOMA. On the contrary, when the received powers are significantly different, NOMA outperforms OMA in terms of average AoI. Our findings provide insights into the design of information update systems with SIC-based NOMA.

II. Preliminaries

A. Age of Information (AoI)

We consider a multiple access system in which two sensors 1 and 2 send update packets to a common AP, as shown in Fig. 1. The extension to multiple sensors is straightforward. The two sensors sample the status of physical characteristics (e.g., temperature, humidity, etc.) and generate update packets to be sent to the AP.

For information update systems, the sensors need to send their update packets to the AP as timely as possible. Let C_i^j denote the j-th status update packet sent by sensor i, $i \in \{1, 2\}$, which is generated at the time t_i^j and successfully received by the AP at $t_i^{j'}$. At time instant t, the instantaneous AoI of sensor i is defined as

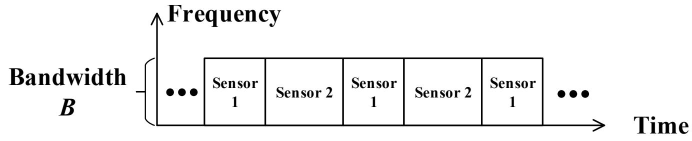

Fig. 2: System model of TDMA.

$$\Delta_i(t) = t - U_i(t), \tag{1}$$

where $U_i(t)$ is the generation time of the most recently received packet from sensor i. The smaller the instantaneous AoI $\Delta_i(t)$, the more recent the information from sensor i.

The average AoI of sensor i, defined by the time average of instantaneous AoI, is

$$\overline{\Delta_i} = \lim_{T \to \infty} \frac{1}{T} \int_0^T \Delta_i(t) dt. \tag{2}$$

The average AoI of the system is simply the average of $\overline{\Delta}_1$ and $\overline{\Delta}_2$, i.e., $\overline{\Delta} = (\overline{\Delta}_1 + \overline{\Delta}_2)/2$.

B. Average AoI of TDMA and FDMA Systems

We extend the previous AoI analysis on TDMA and FDMA to different powers in Section II-B, followed by the new investigation of NOMA in Section III.

1) TDMA: In TDMA, time is divided into time slots in which each sensor is assigned an independent time slot for transmission. As shown in Fig. 2, sensors 1 and 2 take turns to send update packets in the alternative time slots. Each transmission occupies the entire bandwidth B. If the current time slot is assigned to sensor i, sensor i generates and sends an update packet at the beginning of the time slot. We assume that the packet transmission ends at the end of the time slot, and the AP receives the update packet.

We define a round as the total transmission time of the two sensors, and each round has two time slots with durations T_1^{TD} and T_2^{TD} assigned to sensors 1 and 2, respectively. Therefore, the duration of a round T_r^{TD} is $T_r^{TD} = T_1^{TD} + T_2{}^{TD}$. Let P_1 and P_2 be the received power of the two sensors, respectively. Note that P_1 may not be equal to P_2 in this paper, which is different from the previous work with $P_1 = P_2$ [15]. Let L be the number of information bits of an update packet. With different received powers, the two sensors have different information rates. Specifically, the rates R_1^{TD} for sensor 1 and R_2^{TD} for sensor 2 are computed by the Shannon capacity

$$R_1^{TD} = B \log(1 + \frac{P_1}{BN_0}), \; R_2^{TD} = B \log(1 + \frac{P_2}{BN_0}). \tag{3}$$

With packet length L, the transmission time of sensor i is $T_i^{TD} = \frac{L}{R_i^{TD}}$. Thus, T_1^{TD} is generally different from T_2^{TD}.

As shown in Fig. 3, sensor 1 generates an update packet C_1^j at t_1^j in round j and completes the transmission at $t_1^{j'} = t_2^j$, where $t_1^{j'} = t_1^j + T_1^{TD}$. Sensor 2 generates the update packet C_2^j at t_2^j and finishes the transmission at $t_2^{j'} = t_1^{j+1} =$

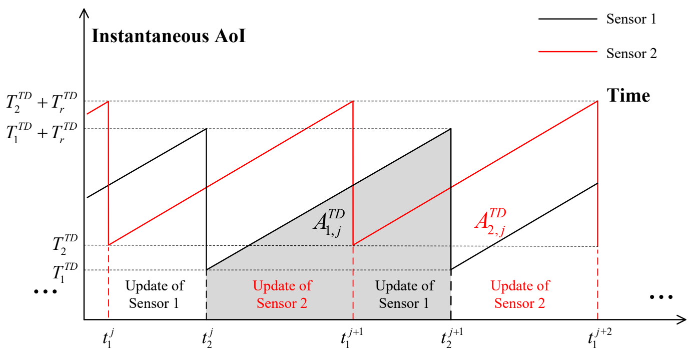

Fig. 3: The instantaneous AoI of the sensors in TDMA.

$t_2^j + T_2^{TD}$. In Fig. 3, as the update packet of sensor 1, C_1^j, is successfully decoded at $t_1^{j'}$ (i.e., t_2^j), the instantaneous AoI of sensor 1, $\Delta_1(t)$, is reset to T_1^{TD} (i.e., the black curve). $\Delta_1(t)$ continues to increase linearly until the next successful update at $t_1^{j+1'}$. The instantaneous AoI of sensor 2, $\Delta_2(t)$, evolves in the same way (i.e., the red curve).

We now calculate the average AoI of sensor 1. Let us consider the shaded area $A_{1,j}^{TD}$ between the j-th and the $j+1$-th successful updates of sensor 1, as shown in Fig. 3. These two successful updates occur at $t_1^{j'}$ and $t_1^{j+1'}$. Since $\Delta_1(t)$ is reset to T_1^{TD} after an update, $A_{1,j}^{TD}$ is calculated as

$$A_{1,j}^{TD} = \int_{t_1^{j'}}^{t_1^{j+1'}} \Delta_i(t)dt = T_1^{TD}T_r^{TD} + \frac{(T_r^{TD})^2}{2}. \quad (4)$$

The average AoI of sensor 1, $\overline{\Delta}_1^{TD}$, can be computed by

$$\overline{\Delta}_1^{TD} = \lim_{W\to\infty} \frac{\sum_{w=1}^{W} A_{1,w}^{TD}}{\sum_{w=1}^{W} T_r^{TD}} = \lim_{W\to\infty} \frac{\sum_{w=1}^{W} T_1^{TD}T_r^{TD} + \frac{(T_r^{TD})^2}{2}}{\sum_{w=1}^{W} T_r^{TD}}$$
$$= \frac{1}{2} \times (\frac{3L}{R_1^{TD}} + \frac{L}{R_2^{TD}}). \quad (5)$$

Similarly, the average AoI of sensor 2, $\overline{\Delta}_2^{TD}$, is

$$\overline{\Delta}_2^{TD} = T_2^{TD} + \frac{T_r^{TD}}{2} = \frac{1}{2} \times (\frac{L}{R_1^{TD}} + \frac{3L}{R_2^{TD}}). \quad (6)$$

2) FDMA: In FDMA, the total bandwidth B is divided into two subchannels, and each sensor uses one of the two subchannels for channel access. Since the two sensors do not affect each other, they can continuously send update packets to the AP simultaneously, and the instantaneous AoI of the two sensors evolves independently. Suppose that bandwidth $(1-\alpha)B$ is allocated to sensor 1 and αB is allocated to sensor 2, where $\alpha \in [0,1]$ is the allocation factor. Let T_1^{FD} and T_2^{FD} denote the packet transmission time of sensors 1 and 2, respectively.

Suppose that sensor i generates update packet C_i^j at time t_i^j and completes transmission at $t_i^{j+1} = t_i^j + T_i^{FD}$. If the update packet is successfully decoded at t_i^{j+1}, the instantaneous AoI $\Delta_i^{FD}(t)$ will be reset to T_i^{FD}. Therefore, the average AoI of sensor i is computed by

$$\overline{\Delta}_i^{FD} = \lim_{W\to\infty} \frac{\sum_{w=1}^{W} T_i^{FD}T_i^{FD} + \frac{(T_i^{FD})^2}{2}}{\sum_{w=1}^{W} T_i^{FD}} = \frac{3L}{2R_i^{FD}}, \quad (7)$$

where the corresponding achievable information rates R_1^{FD} and R_2^{FD} of sensors 1 and 2 are

$$R_1^{FD} = (1-\alpha)B\log(1+\frac{P_1}{(1-\alpha)BN_0}), \quad (8)$$
$$R_2^{FD} = \alpha B\log(1+\frac{P_2}{\alpha BN_0}).$$

III. Average AoI of SIC-Based NOMA Systems

Unlike TDMA and FDMA, sensors 1 and 2 in NOMA are allowed to use the same time and frequency resources to transmit signals to the AP, and the AP receives the superimposed signals. Without loss of generality, assume that the received power of the signal from sensor 1 is greater than or equal to that from sensor 2, i.e., $P_1 \geq P_2$. The SIC decoder first decodes the signal from sensor 1 by treating the signal from sensor 2 as noise. After successfully decoding the signal from sensor 1, it is subtracted from the overlapping signals, and then the AP tries to decode the signal from sensor 2.

Let R_1^{NO} and R_2^{NO} denote the information rates of sensors 1 and 2, respectively, in SIC-based NOMA. R_1^{NO} and R_2^{NO} are calculated by

$$R_1^{NO} = B\log(1+\frac{P_1}{P_2+BN_0}), R_2^{NO} = B\log(1+\frac{P_2}{BN_0}). \quad (9)$$

Based on the different received powers of the signals from the two sensors, R_1^{NO} may be greater or smaller than R_2^{NO}. This leads to a different AoI evolution in the SIC-based NOMA, as described in the following two subsections.

A. Case 1: $R_1^{NO} \geq R_2^{NO}$

In SIC-based NOMA, the transmission time of an update packet with packet length L is $T_i^{NO} = \frac{L}{R_i^{NO}}$ for sensor i. Note that if $R_1^{NO} \geq R_2^{NO}$, then $T_1^{NO} \leq T_2^{NO}$. Therefore, sensor 1 may send more update packets than sensor 2 during the same time, as shown in Fig. 4. We consider that $R_1^{NO}/R_2^{NO} = p/q$ where p and q are positive integers. We define a NOMA cycle in which sensor 1 sends p update packets and sensor 2 sends q update packets during the same time period, e.g., $p=3$ and $q=2$ in Fig. 4. Using SIC, the strong sensor (i.e., the signal received from this sensor has a higher power) is decoded first. In other words, the packets of sensor 1 are decoded without being affected by sensor 2. As a result, to evaluate the average AoI of sensor 1, the AoI analysis is the same as that in FDMA, except that the information rate R_i^{FD} is replaced by R_1^{NO}. That is, the average AoI of sensor 1 is $\overline{\Delta}_1^{NO} = \frac{3L}{2R_1^{NO}}$ in the SIC-based NOMA.

Note that sensor 1 could send more update packets before sensor 2 finishes sending one update packet, as shown in

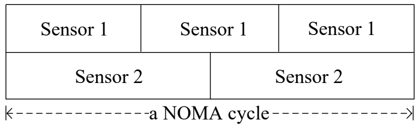

Fig. 4: A NOMA cycle when $R_1^{NO} \geq R_2^{NO}$.

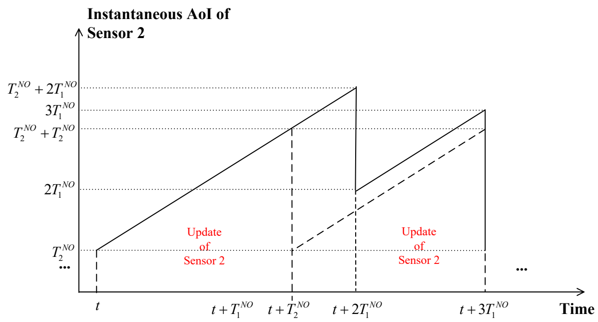

Fig. 5: Instantaneous AoI of sensor 2 in SIC-based NOMA when $R_1^{NO}/R_2^{NO} = 3/2$.

Fig. 4. Therefore, decoding the first update packet of sensor 2 in Fig. 4 needs to wait after decoding the second update packet of sensor 1. Thus, the calculation of the average AoI for sensor 2, $\overline{\Delta}_2^{NO}$, is more complicated than that for sensor 1, as detailed below.

We consider the instantaneous AoI of sensor 2 where $p = 3$ and $q = 2$, as shown in Fig. 5. In a NOMA cycle, suppose that both sensors generate the first update packet at time t. Sensor 1 completes the first packet transmission at $t + T_1^{NO}$. By the time of the first successful update of sensor 1, the first packet transmission of sensor 2 has not yet been completed. Although sensor 2 completes its first transmission at $t+T_2^{NO}$, the first packet of sensor 2 cannot be decoded immediately because sensor 1 has started its second packet transmission. In SIC, the first packet decoding of sensor 2 must wait until the second packet decoding of sensor 1 at $t + 2T_1^{NO}$. Hence, the instantaneous AoI of sensor 2 can only drop to $2T_1^{NO}$ at $t + 2T_1^{NO}$. At the end of the NOMA cycle, the third update packet from sensor 1 and the second update packet from sensor 2 are received simultaneously. Thus, the second update packet of sensor 2 can be decoded immediately at $t + 2T_2^{NO}$, and its instantaneous AoI is reset to T_2^{NO}.

We propose an algorithm to compute the average AoI of sensor 2, $\overline{\Delta}_2^{NO}$, in the general case as summarized in Algorithm 1. In a NOMA cycle, we calculate the area under the curve of the instantaneous AoI of sensor 2, divided by the total time of the NOMA cycle. Algorithm 1 takes the rates R_1^{NO} and R_2^{NO} and the packet length L as inputs and returns the average AoI $\overline{\Delta}_2^{NO}$.

We use Δ_{last} to denote the instantaneous AoI of sensor 2 after its last successful update. Δ_{last} is initialized to $T_2^{NO} = L/R_2^{NO}$ at the beginning of the NOMA cycle. The m_{last}-th update of sensor 1 is decoded when the last update packet of sensor 2 is successfully decoded (initially, $m_{last} = 0$). The accumulated area under the instantaneous AoI curve of sensor 2 is denoted by A_{sum}. In line 2, the algorithm compares R_1^{NO} and R_2^{NO} to determine the two positive integers p and q which are the number of updates from sensors 1 and 2, respectively, in the NOMA cycle.

Lines 3 to 11 of Algorithm 1 focus on computing A_{sum} in a total of q updates from sensor 2. For the i-th update of sensor 2, we determine the smallest number m, where the transmission time of m updates from sensor 1 is just longer than i updates of sensor 2, i.e., $mT_1^{NO} \geq iT_2^{NO}$. Note that the i-th update packet of sensor 2 can be decoded only after the m-th update of sensor 1 is decoded by the SIC. The difference between mT_1^{NO} and $m_{last}T_1^{NO}$ is the time elapsed between the two consecutive updates of sensor 2. We calculate the area between two consecutive updates and accumulate it as A_{sum} (line 7). In line 9, we update the instantaneous AoI Δ_{last} after the i-th update of sensor 2.

After q updates, we calculate the average AoI $\overline{\Delta}_2^{NO}$ through dividing the cumulative area A_{sum} by the total duration of a NOMA cycle at the end of the algorithm.

Algorithm 1 The average AoI of sensor 2 when $R_1^{NO} \geq R_2^{NO}$

Input: information rates R_1^{NO}, R_2^{NO}, packet length L

Output: the average AoI of sensor 2 $\overline{\Delta}_2^{NO}$

1: $\Delta_{last} \leftarrow T_2^{NO} = L/R_2^{NO}, m_{last} \leftarrow 0, A_{sum} \leftarrow 0$
2: Compute positive integers p and q such that $R_1^{NO}/R_2^{NO} = p/q, (p \geq q)$
3: **for** each integer i in 1 to q **do**
4: // The m-th update from sensor 1 should be decoded before the i-th update from sensor 2:
5: $m \leftarrow$ the smallest number in [1, p] such that $m * L/R_1^{NO} \geq i * L/R_2^{NO}$
6: // Compute the area in the current update and add it to the total area:
7: $A_{sum} \leftarrow A_{sum} + [\Delta_{last} + \Delta_{last} + (m - m_{last}) * L/R_1^{NO}] * (m - m_{last}) * L/(2 * R_1^{NO})$
8: // Update parameter:
9: $\Delta_{last} \leftarrow (m * L/R_1^{NO}) - (i-1) * L/R_2^{NO}$
10: $m_{last} \leftarrow m$
11: **end for**
12: $\overline{\Delta}_2^{NO} \leftarrow A_{sum}/(p * L/R_1^{NO})$
13: **return** $\overline{\Delta}_2^{NO}$

B. Case 2: $R_1^{NO} < R_2^{NO}$

In case 2, we consider $R_1^{NO} < R_2^{NO}$ and $T_1^{NO} > T_2^{NO}$. As shown in Fig. 6, sensor 2 sends more update packets than sensor 1, where sensor 1 sends $p = 2$ update packets and sensor 2 sends $q = 3$ update packets in a NOMA cycle. As in case 1, the decoding for sensor 1 is not affected by sensor 2, so the average AoI of sensor 1 is also $\overline{\Delta}_1^{NO} = \frac{3L}{2R_1^{NO}}$.

We consider the instantaneous AoI of sensor 2 in Fig. 7, where $p = 2$ and $q = 3$. In the SIC, the packet from sensor 2 is decoded after decoding the overlapping packet from sensor 1. Although sensor 2 completes its first transmission at $t + T_2^{NO}$, the decoding of its packet needs to wait until the first packet decoding for sensor 1 at $t + T_1^{NO}$. As a result, the instantaneous AoI of sensor 2 drops to T_1^{NO} at $t + T_1^{NO}$. Again, the second packet from sensor 2 cannot be

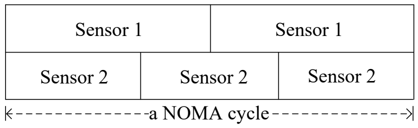

Fig. 6: A NOMA cycle when $R_1^{NO} < R_2^{NO}$.

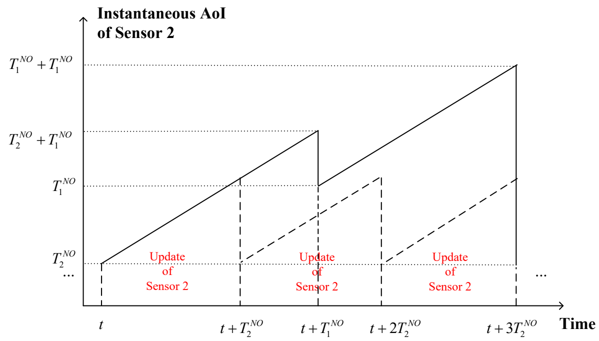

Fig. 7: Instantaneous AoI of sensor 2 in SIC-based NOMA when $R_1^{NO}/R_2^{NO} = 2/3$.

decoded until the second packet from sensor 1 is decoded. By the time sensor 1 completes its second packet transmission, the third packet transmission of sensor 2 also completes at $t + 3T_2^{NO}$. Therefore, the second and third packets of sensor 2 are decoded at the same time. Notice that in this example, the second update packet of sensor 2 can simply be discarded because the third update packet has already been decoded. Then, due to the successful decoding of the third update packet, the instantaneous AoI is reset to T_2^{NO} at $t + 3T_2^{NO}$.

We also propose an algorithm to calculate the average AoI of sensor 2 $\overline{\Delta}_2^{NO}$ for case 2. The initial parameters in Algorithm 2 are the same as those in Algorithm 1. Algorithm 2 first calculates the number of updates p and q for sensors 1 and 2, respectively, in the NOMA cycle. Lines 3 to 11 of Algorithm 2 calculates A_{sum} in q updates for sensor 2. For each update of sensor 1, say update i, Algorithm 2 determines the largest number m such that the transmission time of i updates of sensor 1 is longer than m updates of sensor 2, i.e., $iT_1^{NO} \geq mT_2^{NO}$. In other words, by the time the i-th update of sensor 1 is decoded, the m-th update of sensor 2 is decoded. This is the main difference between Algorithm 1 and Algorithm 2.

After each update, we calculate the area between two consecutive updates of sensor 2 and update the cumulative area A_{sum} (line 7). We can see that the duration between two consecutive updates of sensor 2 is always T_1^{NO}. In line 9, we update the instantaneous AoI Δ_{last} after the i-th update. As in Algorithm 1, we calculate $\overline{\Delta}_2^{NO}$ after q updates through dividing A_{sum} by the total duration of a NOMA cycle at the end of the algorithm.

To sum up, we obtain the average AoI of SIC-based NOMA:

$$\begin{aligned}\overline{\Delta}^{NO} &= \frac{\overline{\Delta}_1^{NO} + \overline{\Delta}_2^{NO}}{2} \\ &= \begin{cases} \frac{3L/2R_1^{NO} + \text{Algorithm1}(R_1^{NO}, R_2^{NO})}{2}, & R_1^{NO} \geq R_2^{NO} \\ \frac{3L/2R_1^{NO} + \text{Algorithm2}(R_1^{NO}, R_2^{NO})}{2}, & R_1^{NO} < R_2^{NO}. \end{cases}\end{aligned} \tag{10}$$

Algorithm 2 The average AoI of sensor 2 when $R_1^{NO} < R_2^{NO}$

Input: information rates R_1^{NO}, R_2^{NO}, packet length L
Output: the average AoI $\overline{\Delta}_2^{NO}$ of sensor 2
1: $\Delta_{last} \leftarrow L/R_2^{NO}, A_{sum} \leftarrow 0$
2: Compute positive integers p and q such that $R_1^{NO}/R_2^{NO} = p/q, (p < q)$
3: **for** each integer i in 1 to p **do**
4: // The transmission of the m-th update from sensor 2 ends before the i-th update from sensor 1:
5: $m \leftarrow$the largest number in [1, q] such that $i * L/R_1^{NO} \geq m * L/R_2^{NO}$
6: // Compute the area in the current update and add it to the total area:
7: $A_{sum} \leftarrow A_{sum} + (\Delta_{last} + \Delta_{last} + L/R_1^{NO}) * L/(2 * R_1^{NO})$
8: // Update parameter:
9: $\Delta_{last} \leftarrow (i * L/R_1^{NO}) - (m-1) * L/R_2^{NO}$
10: **end for**
11: $\overline{\Delta}_2^{NO} \leftarrow A_{sum}/(p * L/R_1^{NO})$
12: **return** $\overline{\Delta}_2^{NO}$

IV. Simulation Results

In this section, we perform numerical simulations to investigate which multiple access scheme minimizes the average AoI when the received power of the signals from the two sensors are different. The size of the source packet is normalized to $L = 1$. We also set the bandwidth B and the noise variance N_0 to 1 so that the unit of the received power is dB. We fix the received power of the signal from sensor 2, P_2, to be $0dB$, $5dB$, and $10dB$. For each P_2, we vary the received power of the signal from sensor 1, P_1, from P_2 to $P_2 + 50dB$. Since $P_1 \geq P_2$, in the SIC-based NOMA, sensor 1 is decoded first, followed by sensor 2.

Fig. 8(a-c) plot the average AoI when P_2 equals $0dB$, $5dB$, and $10dB$. For FDMA, we optimized α to minimize the average AoI for each pair (P_1, P_2). Note that in FDMA, its effective SNRs are higher than in TDMA and NOMA (i.e., the noise power in FDMA is lower) because the bandwidth of each sensor is less than B. For NOMA, to obtain the minimum average AoI for sensor 2, we compare R_1^{NO} and R_2^{NO} and decide to use either Algorithm 1 or Algorithm 2.

From Fig. 8, we can see that when the received powers of the two sensors are almost the same, the average AoI of both FDMA and TDMA is lower than that of SIC-based NOMA, i.e., FDMA and TDMA achieve better AoI performances than NOMA. When P_1 is close to P_2, the effective SNR of sensor 1 is almost zero dB, resulting in a low information rate R_1^{NO}. Therefore, the information rates of the two sensors in NOMA are largely different (i.e., $R_1^{NO} \ll R_2^{NO}$), and the transmission time of sensor 1 is much longer than that of sensor 2. The average AoI of the two sensors is high because decoding the update packet of sensor 2 has to wait for a long time until the overlapping update packet of sensor 1 is decoded by the SIC.

As the difference in received powers P_1 and P_2 increases, the AoI performance of NOMA gradually outperforms that

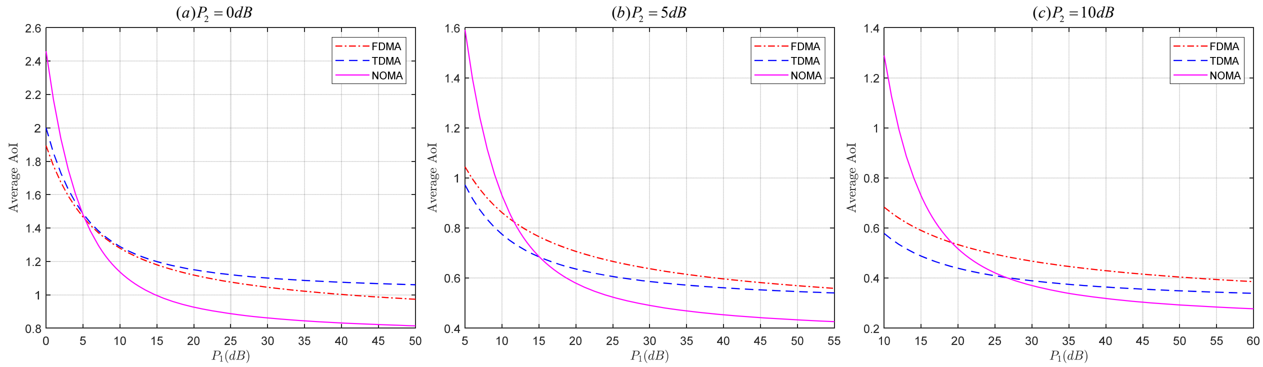

Fig. 8: Average AoI of different multiple access schemes.

of both TDMA and FDMA. As the increase in P_1 leads to an increase in R_1^{NO}, the difference between R_1^{NO} and R_2^{NO} gradually decreases, and R_1^{NO} eventually becomes greater than R_2^{NO}. As R_1^{NO} increases, the average AoI of sensor 1 decreases. More importantly, a higher R_1^{NO} significantly reduces the waiting time for decoding the update packets of sensors 2 by the SIC, thereby leading to a decrease in the average AoI of sensor 2. Overall, when SIC-based NOMA is adopted and the received powers are largely different, the average AoI of the whole system is minimized.

Interestingly, the above observation is different from previous studies concerning information rates. Let us compare the theoretical rates between TDMA and NOMA. For TDMA, since only one sensor is transmitting at a time, the maximum rate is $R_{TD} = \max\{B\log(1+\frac{P_1}{BN_0}), B\log(1+\frac{P_2}{BN_0})\}$. For NOMA, the best possible sum rate is $R_{NO} = B\log(1+\frac{P_1+P_2}{BN_0})$ since the two sensors can transmit at the same time. If we define the information rate gain of NOMA over TDMA by $\eta = \frac{R_{NO}}{R_{TD}}$, previous studies showed that η is large when P_1 and P_2 are almost the same [16]. However, when we use the average AoI as a performance metric, our results show that SIC-based NOMA significantly outperforms TDMA when P_1 and P_2 are significantly different, which is a key difference between information freshness and information rate.

V. Conclusion

In this paper, we analyze the average AoI of three multiple access schemes, namely TDMA, FDMA, and SIC-based NOMA. In contrast to previous works that assumed the same received power of signals from all sensors, this paper considers different received powers at the AP. A key issue in analyzing the average AoI of SIC-based NOMA is the different information rates of the two sensors. Specifically, due to the different packet durations between the sensors, the sensors may send different numbers of update packets in the same period (a NOMA cycle). The decoding for the weak sensor needs to wait for the successful decoding for the strong sensor in the SIC. To the end, we propose two algorithms based on different information rates of the two sensors to calculate the average AoI of SIC-based NOMA. Numerical results show that when the received powers are almost the same, the average AoI of TDMA and FDMA is lower than that of NOMA. However, when the received power differs significantly, NOMA is a better solution because it significantly outperforms TDMA and FDMA in terms of average AoI.

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