Weighted AoI Minimization for RIS-Assisted Multi-User mmWave Communications

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***Abstract*—In this paper, we focus on a reconfigurable intelligent surface (RIS)-assisted millimeter-wave (mmWave) communications system, where a RIS is deployed to create reliable reflection links and alleviate multi-user interference. In the system, each user equipment (UE) is concerned with the freshness of the information received from the base station (BS) and has a certain transmission requirement. The age of information (AoI) is adopted as the metric for information freshness and on this basis, we define the weighted AoI to take into account the satisfaction of UE transmission requirements. Then, an average weighted AoI minimization problem is formulated by jointly optimizing the precoding, the discrete RIS phase shifts, and the scheduling strategy. The problem is decomposed into two subproblems. For the first precoding and RIS design subproblem, we aim to satisfy the transmission requirements of the scheduled UEs with minimum power consumption under a given scheduling strategy. We use the zero-force (ZF)-based precoder and adopt the local search method for the RIS design. For the second scheduling strategy design subproblem, we propose a heuristic scheduling algorithm to minimize the system's average weighted AoI. Simulation results verify the effectiveness of our proposed method over several baseline schemes.**

***Index Terms*—Reconfigurable intelligent surface (RIS), weighted age of information (AoI), millimeter-wave (mmWave) communication, scheduling strategy.**

I. INTRODUCTION

Future communication networks are required to support many new inspiring applications such as intelligent transportation systems (ITS), virtual reality (VR), and Industry 4.0. The effectiveness of decision-making in these applications depends on the freshness of received information, the outdated and aging information will severely impair system performance and even cause security risks. To characterize the information freshness, age of information (AoI) has been proposed, which is defined as the elapsed time since the generation of the most recently received status update [1]. This metric captures the freshness of information from the receiver's perspective, which is closer to the receiver's genuine perception. Therefore, considerable work has been carried out on AoI optimization problems in various wireless communication systems, such as edge computing-assisted networks [2], unmanned aerial vehicles (UAV) communications [3], vehicular networks [4], and joint radar communication (JRC) design [5], etc.

In practice, reliable and timely information delivery is quite challenging due to the random and uncontrollable wireless channel. This issue is particularly severe for millimeter-wave (mmWave) communications. Although the large available spectrum provided by mmWave can effectively increase communication capacity [6, 7], due to the high directivity, mmWave signals can be easily blocked by obstacles [8]. Fortunately, reconfigurable intelligent surface (RIS) has the ability to improve the quality of wireless links by flexibly configuring the propagation environment through software programming. Specifically, RIS is a planar array composed of numerous passive reflection elements. Each of them can independently control the amplitude and phase of the incident signal in a software-defined manner [9]. Through a proper design, the passive reflections of all the RIS reflection elements can be coherently superposed at the intended receiver, thus creating a more reliable reflection link to overcome the link blockage and enhance network coverage [10]. Also, such passive reflections can be destructively superposed at the undesired receivers for interference suppression [11].

Therefore, we can anticipate that RIS will bring great benefits to the improvement of information freshness. Recently, some research has integrated RIS in AoI-focused systems. However, on the one hand, most of the existing works focus on single-antenna systems or sub-6 GHz systems [12–15]. On the other hand, most of the research adopts the orthogonal time-frequency resources allocation strategy to avoid multi-user interference [12–16]. The advantages of multi-antenna systems have not been fully exploited, limiting the spectral efficiency of the systems. In addition, none of the prior works take into account the transmission requirement of user equipment (UE).

Motivated by these observations, we define the weighted AoI, which is related to both AoI and satisfaction of UE transmission requirements. We investigate the average weighted AoI performance in RIS-assisted mmWave systems. The main contributions of this paper are summarized as follows:

- We focus on a RIS-assisted mmWave communication system, where a multi-antenna base station (BS) simultaneously sends time-sensitive messages to multiple single-antenna UEs. Considering both AoI and satisfaction of UE transmission requirements, we define the weighted AoI and formulate the average weighted AoI minimization problem.

- To facilitate the solution, we decompose the problem into two subproblems. We first propose a precoding and RIS design method to satisfy scheduled UEs' requirements with minimum power consumption, and then present a heuristic scheduling algorithm to minimize the average weighted AoI.
- We compare the system performance of the proposed scheme with two baseline schemes. Simulation results show that the proposed scheme can satisfy the transmission requirements of more UEs while reducing average AoI, and achieves better average weighted AoI performance for different SINR thresholds and numbers of RIS elements.

II. SYSTEM OVERVIEW

A. System Description

As shown in Fig. 1, we consider a RIS-assisted single-cell mmWave communication system, where K single-antenna UEs need to obtain time-sensitive messages from a BS equipped with N_T antennas. A typical example of time-sensitive messages is real-time traffic information for trip planning. The freshness of the information is critical to the feasibility of the plan. The set of UEs is denoted by $\mathcal{K} = \{1, 2, \cdots, K\}$. The RIS consists of M passive reflection elements, each of which can independently adjust the phase of the incident signal. The set of RIS elements is denoted by $\mathcal{M} = \{1, 2, \cdots, M\}$. System time is divided into a series of non-overlapping superframes. Each superframe can be further slotted into T time slots. We focus on the system performance in one superframe. The set of time slots is denoted as $\mathcal{T} = \{1, 2, \cdots, T\}$. At each time slot, the BS can simultaneously serve up to $K_{max} < K$ UEs. We use $u_{k,t}$ to indicate whether UE k is scheduled at time slot t. If UE k is scheduled, $u_{k,t} = 1$, and then the BS sends information to UE k; otherwise, $u_{k,t} = 0$. Therefore, we have

$$\sum_{k=1}^{K} u_{k,t} = K_t \leq K_{max}, \ \forall t \in \mathcal{T}, \tag{1}$$

where the set of scheduled UEs at time slot t is represented by $\mathcal{K}_t$. We denote the transmit data symbol to UE k at time slot t by $s_{k,t}$ with $\mathbb{E}\{s_{k,t}\} = 0$ and $\mathbb{E}\{s_{k,t}s_{k,t}^H\} = 1$. Then, the signal transmitted by the BS at time slot t can be given by $\mathbf{x}_t = \sum_{k\in\mathcal{K}_t} \mathbf{w}_{k,t} s_{k,t}$, where $\mathbf{w}_{k,t} \in \mathbb{C}^{N_T \times 1}$ denotes the precoding vector at the BS. Assuming that the maximum transmit power is P, the precoding vector should satisfy the power constraint:

$$\sum_{k\in\mathcal{K}_t} ||\mathbf{w}_{k,t}||^2 \leq P, \ \forall t \in \mathcal{T}. \tag{2}$$

Let $\mathbf{h}_{\mathrm{d},k}^H \in \mathbb{C}^{1\times N_T}$, $\mathbf{G} \in \mathbb{C}^{M\times N_T}$, and $\mathbf{h}_{\mathrm{r},k}^H \in \mathbb{C}^{1\times M}$ denote the baseband equivalent channels from the BS to UE k, from the BS to the RIS, and from the RIS to UE k, respectively. Considering the severe path loss, we consider only the signal reflected by the RIS for the first time and ignore the signals reflected by it twice or more. Let $\mathbf{\Phi}_t = \mathrm{diag}(e^{j\varphi_{1,t}}, \ e^{j\varphi_{2,t}}, \ \cdots, \ e^{j\varphi_{M,t}}) \in \mathbb{C}^{M\times M}$ denote the reflection-coefficient matrix of the RIS, where $\varphi_{m,t}$ represents the phase shift of RIS element m at time slot t. For the sake of hardware implementation, we assume that each RIS element can realize 2^b different discrete phase shift values by b-bit quantization, and the set of discrete phase shifts is represented as $\mathcal{F} = \left\{0, \frac{2\pi}{2^b}, \cdots, \left(2^b - 1\right)\frac{2\pi}{2^b}\right\}$. Therefore, the channel matrix between the BS and UE k is given by $\mathbf{h}_{k,t}^H = \mathbf{h}_{\mathrm{d},k}^H + \mathbf{h}_{\mathrm{r},k}^H \mathbf{\Phi}_t \mathbf{G}$, and the received signal at the scheduled UE k at time slot t is expressed as

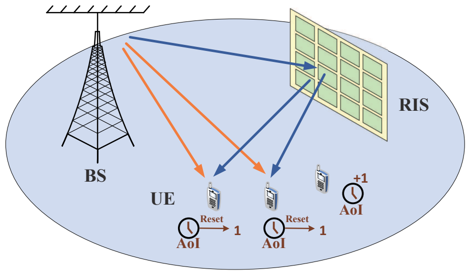

Fig. 1. An illustration of the system model.

$$y_{k,t} = (\mathbf{h}_{\mathrm{d},k}^H + \mathbf{h}_{\mathrm{r},k}^H \mathbf{\Phi}_t \mathbf{G}) \sum_{k\in\mathcal{K}_t} \mathbf{w}_{k,t} s_{k,t} + n_{k,t}, \tag{3}$$

where $n_{k,t} \sim \mathcal{CN}(0, \sigma^2)$ is the additive white Gaussian noise at UE k at time slot t. The signal-to-interference-plus-noise ratio (SINR) received by UE k at time slot t is given by

$$\gamma_{k,t} = \frac{\left|(\mathbf{h}_{\mathrm{d},k}^H + \mathbf{h}_{\mathrm{r},k}^H \mathbf{\Phi}_t \mathbf{G})\mathbf{w}_{k,t}\right|^2}{\sum_{j\in\mathcal{K}_t\setminus\{k\}} \left|(\mathbf{h}_{\mathrm{d},k}^H + \mathbf{h}_{\mathrm{r},k}^H \mathbf{\Phi}_t \mathbf{G})\mathbf{w}_{j,t}\right|^2 + \sigma^2}. \tag{4}$$

The requirement of each UE on the received signal quality is given by $\gamma_{k,t} \geq \gamma_{th}$, where γ_{th} is the minimum tolerable SINR.

B. Channel Model

In this system, we assume that the knowledge of the channel state information (CSI) is available by channel estimation [17, 18]. Due to the small wavelength, the mmWave channels have limited scattering effects. Therefore, we adopt the Saleh-Valenzuela (SV) channel model. Assume that the channels will not change within T time slots. The BS-RIS channel gain $\mathbf{G}$ can be written as

$$\begin{aligned}\mathbf{G} = \sqrt{\frac{N_T M}{L_{\mathrm{g}}}} \Big(& \tilde{\alpha}_0 \mathbf{a}_r \left(M, \phi_{RIS,0}^r, \zeta_{RIS,0}^r\right) \mathbf{a}_t^H \left(N_T, \psi_{BS,0}^t\right) \\ & + \sum_{i=1}^{L_{\mathrm{g}}-1} \tilde{\alpha}_i \mathbf{a}_r \left(M, \phi_{RIS,i}^r, \zeta_{RIS,i}^r\right) \mathbf{a}_t^H \left(N_T, \psi_{BS,i}^t\right) \Big),\end{aligned} \tag{5}$$

where L_{g} denotes the total number of paths, the 0-th path is the LOS path with complex gain $\tilde{\alpha}_0$, and the i-path ($i \neq 0$) is the i-th NLOS path with complex gain $\tilde{\alpha}_i$. Also, $\mathbf{a}_r(\cdot)$ and $\mathbf{a}_t(\cdot)$ denote the normalized angle steering vector functions at the transmitter and the receiver, respectively [19]. We assume the transmit antennas at the BS form a uniform linear array (ULA) configuration and the RIS adopts a uniform planar array (UPA) structure. $\phi_{RIS,i}^r$ and $\zeta_{RIS,i}^r$ represent the azimuth and elevation angles of arrival associated with the RIS, respectively, and $\psi_{BS,i}^t$ denotes the angle of departure from the BS.

Similarly, the RIS-UE channel gain $\mathbf{h}_{\mathrm{r},k}$ can be written as

$$\begin{aligned}\mathbf{h}_{\mathrm{r},k} = \sqrt{\frac{M}{L_{\mathrm{r}}}} \Big(& \tilde{\beta}_0 \mathbf{a}_t \left(M, \phi_{RIS,0}^t, \zeta_{RIS,0}^t\right) \\ & + \sum_{i=1}^{L_{\mathrm{r}}-1} \tilde{\beta}_i \mathbf{a}_t \left(M, \phi_{RIS,i}^t, \zeta_{RIS,i}^t\right) \Big),\end{aligned} \tag{6}$$

where L_{r} denotes the total number of paths of $\mathbf{h}_{\mathrm{r},k}$, $\tilde{\beta}_0$ denotes the complex gain of the LOS path while $\tilde{\beta}_i$ $(i \neq 0)$ denotes the complex gain of the i-th NLOS path, $\phi^t_{RIS,i}$ and $\zeta^t_{RIS,i}$ represent the azimuth and elevation angles of departure associated with the RIS, respectively.

For the BS-UE channel gain $\mathbf{h}_{\mathrm{d},k}$, we assume that there is no LOS path. It is given by

$$\mathbf{h}_{\mathrm{d},k} = \sqrt{\frac{N_T}{L_{\mathrm{d}}}} \sum_{i=1}^{L_{\mathrm{d}}} \tilde{\varrho}_i \mathbf{a}_t \left(N_T, \psi^t_{BS,i} \right), \tag{7}$$

where L_{d} denotes the total number of paths of $\mathbf{h}_{\mathrm{d},k}$ and $\tilde{\varrho}_i$ denotes the complex gain of the i-th NLOS path.

C. Weighted AoI Definition

In this work, we use AoI to portray the information freshness. Consider a *generate-at-will* model, in which the BS can generate a new packet carrying the latest time-sensitive messages for each target UE at the beginning of any interest time slot [20]. We assume that the generation of packets relies on the scheduling strategy. In other words, if $u_{k,t} = 1$, the BS generates a packet for UE k at the beginning of time slot t and then transmits the packet to it during the time slot. For UE k, successful delivery of the packet at time slot t is conditioned on two realizations: i) $u_{k,t} = 1$; ii) $\gamma_{k,t} \geq \gamma_{th}$. We use $d_{k,t}$ to represent whether there is a successful delivery to UE k at time slot t, which is given by

$$d_{k,t} = \begin{cases} 1, & \text{if } u_{k,t} = 1 \text{ and } \gamma_{k,t} \geq \gamma_{th}, \\ 0, & \text{otherwise.} \end{cases} \tag{8}$$

Then, let $\mathcal{A}_{k,t}$ denote the AoI of UE k at time slot t. The AoI will grow linearly with no packet successfully received by UE k, otherwise it drops to 1. The evolution of the AoI can be given by

$$\mathcal{A}_{k,t} = \begin{cases} 1, & \text{if } d_{k,t} = 1, \\ \mathcal{A}_{k,t-1} + 1, & \text{otherwise.} \end{cases} \tag{9}$$

For simplicity, we assume that the initial AoI $\mathcal{A}_{k,0} = 1$ for all k.

In addition, we consider the number of packets required for UE k, which is denoted by q_k. The received packets of UE k up to the end of time slot t_s can be calculated as $\sum_{t=1}^{t_s} d_{k,t}$. To characterize whether the transmission requirement of UE k has been satisfied over T time slots, we define the penalty factor as

$$\rho_k = \begin{cases} \rho_{max}, & \text{if } q_k^{\pi} = \sum_{t=1}^{T} d_{k,t} < q_k, \\ 1, & \text{otherwise.} \end{cases} \tag{10}$$

Further, if $\sum_{t=1}^{t_s} d_{k,t} = q_k$ $(t_s < T)$, which means the requirement of UE k is satisfied in the first t_s time slots, we consider that the transmission task of UE k in the current superframe has been completed and let $\mathcal{A}_{k,t} = 0$ for $t = t_s + 1, \cdots, T$.

Thus, the average weighted AoI of UE k over T time slots can be given by $\mathcal{A}_k = \frac{1}{T} \sum_{t=1}^{T} \rho_k \omega_k \mathcal{A}_{k,t}$, where ω_k represents the importance of UE k.

III. PROBLEM FORMULATION AND DECOMPOSITION

In this section, we first formulate the optimization problem and then decompose it into two sub-problems.

A. Problem Formulation

Considering both the freshness of received information and the transmission requirements of UEs, we aim to minimize the average weighted AoI for K UEs. Let us denote $\mathbf{U}$, $\mathbf{W}$, and $\mathbf{\Phi}$ as the sets of scheduling parameters, precoding vectors, and RIS configurations over T time slots, respectively, which are defined as $\mathbf{U} = \{u_{k,t} | \ \forall t \in \mathcal{T}, \forall k \in \mathcal{K}\}$, $\mathbf{W} = \{\mathbf{w}_{k,t} | \ \forall t \in \mathcal{T}, \forall k \in \mathcal{K}\}$, and $\mathbf{\Phi} = \{\mathbf{\Phi}_t | \ \forall t \in \mathcal{T}\}$. The joint optimization problem can be formulated as

$$\mathcal{OP}: \min_{\mathbf{U},\mathbf{W},\mathbf{\Phi}} \ \frac{1}{KT} \sum_{k=1}^{K} \sum_{t=1}^{T} \rho_k \omega_k \mathcal{A}_{k,t} \tag{11a}$$

$$s.t. \ (1), (2)$$

$$u_{k,t} \in \{0, 1\}, \forall k \in \mathcal{K}, t \in \mathcal{T}, \tag{11b}$$

$$\varphi_{m,t} \in \mathcal{F}, \ \forall m \in \mathcal{M}, t \in \mathcal{T}. \tag{11c}$$

It can be easily observed that problem $\mathcal{OP}$ contains both continuous variable $\mathbf{w}_{k,t}$ and discrete variables $u_{k,t}$ and $\mathbf{\Phi}_t$. Besides, the objective function of $\mathcal{OP}$ is nonlinear, and the problem includes nonlinear constraints. Thus, it is a mixed-integer nonlinear programming (MINLP) problem, which is hard to solve. In addition, the three optimization variables are coupled in $\mathcal{OP}$. To facilitate the solution, we first decompose the problem.

B. Problem Decomposition

In $\mathcal{OP}$, it is noted that unlike $u_{k,t}$, the effects of $\mathbf{w}_{k,t}$ and $\mathbf{\Phi}_t$ on the weighted AoI are indirect. Specifically, they essentially affect the generation of scheduling strategies by changing the SINR performance of the system at each time slot, which next affects the AoI. Therefore, we decouple $\mathcal{OP}$ into the following two subproblems:

1) Precoding and RIS Design Subproblem: Considering the power constraint in (2), we focus on how to satisfy the SINR requirements of the scheduled UEs at each time slot with less power consumption by the joint design of precoding and RIS phase shifts. When the scheduling strategy is given, the subproblem can be written as

$$\mathcal{OP}1: \min_{\mathbf{w}_t, \mathbf{\Phi}_t} \ \sum_{k \in \mathcal{K}_t} ||\mathbf{w}_{k,t}||^2 \tag{12a}$$

$$s.t. \ \varphi_{m,t} \in \mathcal{F}, \ \forall m \in \mathcal{M}, \tag{12b}$$

$$\gamma_{k,t} \geq \gamma_{th}, \ \forall k \in \mathcal{K}_t, \tag{12c}$$

where $\mathbf{w}_t \in \mathbb{C}^{N_T \times K_t}$ is the precoding matrix at time slot t.

2) Scheduling Strategy Design Subproblem: When the precoding matrix and the RIS phase shifts under the given scheduling strategy are known, $\mathcal{OP}$ is reduced to

$$\mathcal{OP}2: \min_{\mathbf{U}} \ \frac{1}{KT} \sum_{k=1}^{K} \sum_{t=1}^{T} \rho_k \omega_k \mathcal{A}_{k,t} \tag{13a}$$

$$s.t. \ \sum_{k=1}^{K} u_{k,t} = K_t \leq K_{max}, \ \forall t \in \mathcal{T}, \tag{13b}$$

$$\sum_{k \in \mathcal{K}_t} ||\mathbf{w}_{k,t}||^2 \leq P, \ \forall t \in \mathcal{T}, \tag{13c}$$

$$u_{k,t} \in \{0, 1\}, \forall k \in \mathcal{K}, t \in \mathcal{T}. \tag{13d}$$

IV. WEIGHTED AOI MINIMIZATION

In this section, we first propose a joint design method for precoding and RIS phase shifts for a given scheduling strategy, and then design the scheduling policy to minimize the average weighted AoI.

A. Precoding and RIS Design

We first focus on the design of precoding and RIS phase shifts for $\mathcal{OP}1$. For precoding scheme $\mathbf{w}_t$, we adopt a zero-force (ZF)-based linear precoder to eliminate the multi-user interference. The precoding matrix is given by $\mathbf{w}_t = \mathbf{H}_t(\mathbf{H}_t^H\mathbf{H}_t)^{-1}\mathbf{P}_t^{\frac{1}{2}}$ [21]. $\mathbf{H}_t^H = \mathbf{H}_\text{d}^H + \mathbf{H}_\text{r}^H\mathbf{\Phi}_t\mathbf{G}$ denotes the channel matrix at time slot t with $\mathbf{H}_\text{r}^H = [\mathbf{h}_{\text{r},k_1}, \cdots, \mathbf{h}_{\text{r},k_{K_t}}]^H$ and $\mathbf{H}_\text{d}^H = [\mathbf{h}_{\text{d},k_1}, \cdots, \mathbf{h}_{\text{d},k_{K_t}}]^H$, where $\mathcal{K}_t = \{k_1, \cdots, k_{K_t}\}$ represents the set of scheduled UEs at time slot t. $\mathbf{P}_t = \text{diag}(p_{k_1}, \cdots, p_{k_{K_t}})$ is the received power matrix in which p_k represents the received power at UE k. Thus, the transmit power can be rewritten as $P_T = \sum_{k\in\mathcal{K}_t} ||\mathbf{w}_{k,t}||^2 = \text{tr}(\mathbf{P}_t^{\frac{1}{2}}(\mathbf{H}_t^H\mathbf{H}_t)^{-1}\mathbf{P}_t^{\frac{1}{2}})$, and Constraint (12c) can be transformed into $p_k/\sigma^2 \geq \gamma_{th}$, $\forall k \in \mathcal{K}_t$.

Note that the optimal solution of $\mathcal{OP}1$ corresponds to the case when Constraint (12c) is met with equality. Thus we have $p_k = \sigma^2\gamma_{th}$, $\forall k \in \mathcal{K}_t$. Then, $\mathcal{OP}1$ can be reduced to

$$\mathcal{OP}3 : \min_{\mathbf{\Phi}_t} \ \text{tr}(\mathbf{P}_t^{\frac{1}{2}}(\mathbf{H}_t^H\mathbf{H}_t)^{-1}\mathbf{P}_t^{\frac{1}{2}}) \tag{14a}$$

$$s.t. \ \varphi_{m,t} \in \mathcal{F}, \ \forall m \in \mathcal{M}. \tag{14b}$$

Now the power minimization problem only depends on the RIS design. Considering the discrete phase shift values, we adopt a local search method to optimize the RIS phase shifts. Specifically, we successively optimize each RIS element while fixing the phase shifts of the remaining $M-1$ elements. We traverse all the possible phase shifts from $\mathcal{F}$ for each element and select the phase shift corresponding to the minimum transmit power as its optimized phase shift. Then we use it for the phase shift optimization of other RIS elements until all the phase shifts are optimized. The details of the precoding and RIS design method are shown as Algorithm 1.

B. Weighted AoI Minimization

For $\mathcal{OP}2$, we need to design a scheduling strategy to minimize the average weighted AoI, which depends on the AoI performance of each UE and the satisfaction of UE transmission requirements. This imposes two requirements on the design of the scheduling strategy: 1) the strategy shall satisfy the transmission requirements of as many UEs as possible; 2) the strategy shall achieve a good AoI performance. Motivated by this, we propose a heuristic scheduling algorithm which is presented in Algorithm 2.

Specifically, let $\mathcal{K}_s$ denote the set of UEs that have not received enough packets. First, at each time slot, we check the satisfaction of each UE's transmission requirement and obtain $\mathcal{K}_s$ as in lines 3-8. Then, we calculate the priority value of each UE in $\mathcal{K}_s$. Considering both AoI and q_k, we design the priority value as

$$\delta_{k,t} = \omega_k \left(\frac{q_{\min}\left(\rho_{\max} - 1\right)}{q_k} + t - t_{k,\text{la}} \right), \tag{15}$$

where $q_{\min} = \min\limits_{k\in\mathcal{K}}\{q_k\}$ represents the minimum requirement among all the UEs, $t_{k,\text{la}}$ denotes the time slot when UE k was last scheduled before time slot t. The former item in (15) is related to UE requirements. We prioritize the UEs with lower requirements, which helps to satisfy more UEs' requirements in a fixed time interval. The latter item $(t - t_{k,\text{la}})$ denotes the AoI reduction at UE k if the UE is scheduled at time slot t. The UE with a higher AoI reduction has a higher priority.

Algorithm 1 Precoding and RIS Design

```
Input: $\mathbf{G}$; $\mathbf{H}_\text{r}^H$; $\mathbf{H}_\text{d}^H$; $M$; $b$; $\mathcal{K}_t$; $t$; $\sigma^2$; $\gamma_{th}$
Output: $\mathbf{w}_t$; $\mathbf{\Phi}_t$; $P_T^*$
Initialization: randomly generate $\mathbf{\Phi}_t$
Calculate the received power of scheduled UEs by $p_k = \sigma^2\gamma_{th}$ and obtain $\mathbf{P}_t$;
for $m = 1 : M$ do
    $P_T^* = +\infty$;
    for $p_s = 1 : 2^b$ do
        Update $\mathbf{\Phi}_t$ with $\varphi_{m,t} = (p_s - 1)\frac{2\pi}{2^b}$;
        Calculate $\mathbf{w}_t$ by $\mathbf{w}_t = \mathbf{H}_t(\mathbf{H}_t^H\mathbf{H}_t)^{-1}\mathbf{P}_t^{\frac{1}{2}}$;
        Calculate $P_T$ by $P_T = \text{tr}(\mathbf{P}_t^{\frac{1}{2}}(\mathbf{H}_t^H\mathbf{H}_t)^{-1}\mathbf{P}_t^{\frac{1}{2}})$;
        if $P_T < P_T^*$ then
            $P_T^* = P_T$, $\varphi_{m,t}^* = \varphi_{m,t}$;
        end if
    end for
    Update $\mathbf{\Phi}_t$ with $\varphi_{m,t}^*$;
end for
Calculate $\mathbf{w}_t$ by $\mathbf{w}_t = \mathbf{H}_t(\mathbf{H}_t^H\mathbf{H}_t)^{-1}\mathbf{P}_t^{\frac{1}{2}}$.
Calculate $P_T^*$ by $P_T^* = \text{tr}(\mathbf{P}_t^{\frac{1}{2}}(\mathbf{H}_t^H\mathbf{H}_t)^{-1}\mathbf{P}_t^{\frac{1}{2}})$.
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Algorithm 2 Weighted AoI Minimization

```
Input: $\mathcal{K}$; $\mathcal{T}$; $q_k$; $\rho_{max}$; $\omega_k$; $K_{max}$; $P$
Output: $\mathbf{U}^*$, $\mathbf{W}^*$, $\mathbf{\Phi}^*$
Initialization: $u_{k,t} = d_{k,t} = 0, \forall k \in \mathcal{K}, t \in \mathcal{T}$; $q_k^\pi = 0, \forall k \in \mathcal{K}$; $t_{k,\text{la}} = 0, \forall k \in \mathcal{K}$; $\mathcal{K}_s = \mathcal{K}$
 1: for each time slot $t$ do
 2:     $\mathcal{K}_t = \emptyset$, $K_t = 0$;
 3:     for each UE $k$ in $\mathcal{K}_s$ do
 4:         Calculate $q_k^\pi$;
 5:         if $q_k^\pi \geq q_k$ then
 6:             $\mathcal{K}_s = \mathcal{K}_s - \{k\}$;
 7:         end if
 8:     end for
 9:     Calculate the priority values of the UEs in $\mathcal{K}_s$ using (15);
10:     Sort the UEs in $\mathcal{K}_s$ in decreasing order by priority value;
11:     for each UE $k$ $(1 \leq k \leq |\mathcal{K}_s|)$ do
12:         if $K_t < K_{max}$ then
13:             $u_{k,t} = 1$, $\mathcal{K}_t = \mathcal{K}_t \cup k$;
14:             Obtain $\mathbf{w}_t$, $\mathbf{\Phi}_t$, and $P_T^*$ using Algorithm 1;
15:             if $P_T^* \leq P$ then
16:                 $K_t = K_t + 1, t_{k,\text{la}} = t, d_{k,t} = 1, \mathbf{w}_t^* = \mathbf{w}_t, \mathbf{\Phi}_t^* = \mathbf{\Phi}_t$;
17:             else
18:                 $u_{k,t} = 0$, $\mathcal{K}_t = \mathcal{K}_t - \{k\}$;
19:             end if
20:         end if
21:     end for
22: end for
23: Output $\mathbf{U}^* = \{u_{k,t}|\ \forall t \in \mathcal{T}, \forall k \in \mathcal{K}\}$, $\mathbf{W}^* = \{\mathbf{w}_t^*|\ \forall t \in \mathcal{T}\}$, and $\mathbf{\Phi}^* = \{\mathbf{\Phi}_t^*|\ \forall t \in \mathcal{T}\}$.
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Following the calculation of the priority value, we test each

UE in the descending order of priority as in lines 11-21. If the number of UEs in $\mathcal{K}_t$ is less than K_{max}, the current UE k is added to $\mathcal{K}_t$. Then, Algorithm 1 is adopted to optimize the precoding and the RIS phase shifts to obtain the minimum transmit power P_T^*. The current scheduling policy is retained only when P_T^* does not exceed P. After the iterations for T time slots, we can obtain the overall scheduling strategy and the corresponding precoding and RIS design scheme, thus solving $\mathcal{OP}$.

V. SIMULATION RESULTS AND DISCUSSIONS

In this section, we evaluate the performance of the proposed algorithm under various representative parameter settings. The BS and the RIS are located at (2 m, 0 m) and (0 m, 40 m), respectively. Eight UEs are uniformly distributed in a circle centered at (10 m, 40 m) with a radius of 5 m. The height of the BS, the RIS, and the UEs are set to 10 m, 2.5 m, and 1.5 m, respectively. The complex gain in (5)-(7) follows $\mathcal{CN}(0, 10^{-0.1\kappa})$, where the path loss is $\kappa = a + 10b\log_{10}(\tilde{d}) + \xi$, where $\tilde{d}$ is the distance between the transmitter and the receiver, and $\xi \sim \mathcal{N}(0, \sigma_\xi^2)$ denotes the large-scale fading. The values of a, b, and σ_ξ are set as $a = 61.4$, $b = 2$, and $\sigma_\xi = 5.8$ dB for the LOS channel and $a = 72$, $b = 2.92$, and $\sigma_\xi = 8.7$ dB for NLOS channels [10]. The Rician factor, representing the ratio of the energy in the LOS path to the sum of the energy in all the NLOS paths, is set to 13.2 dB for the BS-RIS and RIS-UE channels.

In addition, we set the number of time slots T to 50. The maximum number of concurrently scheduled UEs K_{max} is set to 4. The importance of all the UEs is set to 1. According to the different packet requirements of UEs, we divide UEs into three types: H-UE, M-UE, and L-UE. The packet requirement of the three types of UEs is 40, 30, and 20, respectively. We assume that there are 2 H-UEs, 3 M-UEs, and 3 L-UEs in the system. Note that the time slot resource cannot satisfy the requirements of all the UEs. Other parameters are set as listed in Table I. We also compare the proposed algorithm with two baseline schemes: **1) Random-RIS**: RIS phase shifts are randomly generated in this algorithm; **2) No-RIS**: there is no RIS in the system, and only the BS-UE link exists.

First, we investigate the impact of the penalty factor ρ_{max}. Fig. 2 plots the number of satisfied UEs versus ρ_{max} with $M = 256$ and $\gamma_{th} = 10$ dB. One can observe that for both Random-RIS and No-RIS, increasing ρ_{max} leads to the system satisfying the transmission requirements of more UEs. For the proposed algorithm, the increase of the number of satisfied UEs becomes stable when ρ_{max} is more than 5. At this time, except for the two H-UEs, all the other six UEs are satisfied. Another observation is that the proposed algorithm outperforms the other two schemes. This is because the deployment and proper design of RIS improve the link quality and allow more UEs to be served in a time slot.

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Maximum transmit power P	38 dBm
Noise power σ^2	-90 dBm
Carrier frequency f_c	28 GHz
Number of paths L_g, L_d, L_r	$4, 4, 4$
Number of transmit antennas N_T	64
Quantization bits of RIS b	3

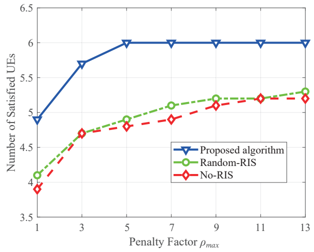

Fig. 2. Number of satisfied UEs versus penalty factor ρ_{max}.

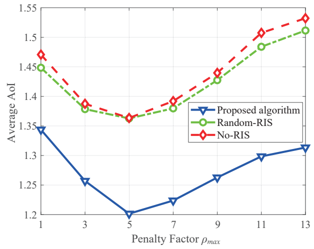

Fig. 3. Average AoI over T time slots versus penalty factor ρ_{max}.

Fig. 3 shows the effect of ρ_{max} on the average AoI with the same parameters as in Fig. 2. The results indicate that the proposed algorithm achieves the minimum average AoI, evidencing the benefits of RIS in terms of information freshness enhancement. Additionally, as ρ_{max} increases, the difference in priority value between UEs with varying requirements increases. Consequently, UEs with lower requirements will be more likely to be scheduled early, while the AoI of UEs with higher requirements simultaneously increases. When $\rho_{max} \leq 5$, the AoI reduction for UEs with lower requirements exerts a more significant impact on the average AoI, thereby causing a decrease in the curves of all three schemes as ρ_{max} increases. Conversely, when $\rho_{max} > 5$, the AoI increase for UEs with higher requirements dominates, leading to an increase in the curves as ρ_{max} increases.

Fig. 4 illustrates the average weighted AoI versus the number of RIS elements M with $\rho_{max} = 5$ and $\gamma_{th} = 10$ dB. We can observe that for the proposed algorithm, the average weighted AoI decreases with the increase of M. The reason is that increasing M enhances the SINR performance of the system. When M is sufficiently large, the first K_{max} UEs with the highest priority value for each time slot can be scheduled, thereby stabilizing the average weighted AoI. In comparison, due to the failure to generate effective reflection beams, the increase of M has less effect on the average weighted AoI for the Random-RIS scheme. It is also noted that as M increases, the proposed algorithm exhibits more pronounced advantages over the other two schemes, which reflects the benefits of the joint optimization with RIS.

Finally, in Fig. 5, we examine the average weighted AoI under different SINR threshold γ_{th} with $\rho_{max} = 5$ and $M = 256$. When γ_{th} is small, all the three schemes can schedule K_{max} UEs with the highest priority at each time slot, and so they have the same average weighted AoI performance. However, with the increase of γ_{th}, the number of UEs allowed for concurrent scheduling reduces, thus leading to an increase in the average weighted AoI for all the three schemes. Nevertheless, due to the proper joint optimization, the proposed algorithm can effectively mitigate the degradation of the average weighted AoI compared to the other two schemes.

VI. CONCLUSIONS

In this paper, we investigated to minimize the average weighted AoI in the RIS-assisted downlink mmWave system, which was defined as a function of AoI and UE transmission requirement satisfaction. Considering the multi-user interference and the transmit power constraint, we first designed precoding and RIS phase shifts to minimize the transmit power required to satisfy the transmission requirements of the scheduled UEs. Then, a heuristic scheduling strategy was proposed to minimize the average weighted AoI. Simulation results showed that the proposed algorithm effectively reduced the AoI and improved the number of satisfied UEs by deploying RIS and performing joint optimization. The performance of the proposed algorithm was closely tied to the selection of the penalty factor. Additionally, compared with the other two schemes, our approach offered considerable benefits in minimizing the system's average weighted AoI for varying numbers of RIS elements and SINR thresholds.

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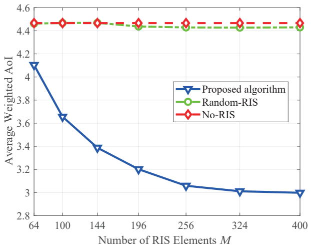

Fig. 4. Average weighted AoI versus the number of RIS elements M.

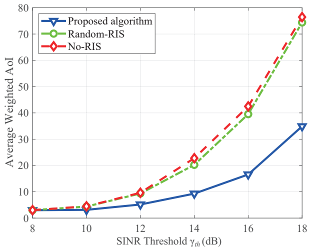

Fig. 5. Average weighted AoI versus SINR threshold γ_{th}.

REFERENCES

[1] R. D. Yates, Y. Sun, D. R. Brown, S. K. Kaul, E. Modiano, and S. Ulukus, "Age of information: An introduction and survey," *IEEE J. Sel. Areas Commun.*, vol. 39, no. 5, pp. 1183–1210, May 2021.

[2] A. Muhammad, I. Sorkhoh, M. Samir, D. Ebrahimi, and C. Assi, "Minimizing age of information in multiaccess-edge-computing-assisted IoT networks," *IEEE Internet Things J.*, vol. 9, no. 15, pp. 13 052–13 066, Aug. 2022.

[3] J. Liu, X. Wang, B. Bai, and H. Dai, "Age-optimal trajectory planning for UAV-assisted data collection," in *Proc. IEEE INFOCOM WKSHPS*, Honolulu, HI, USA, Apr. 2018, pp. 553–558.

[4] A. Alabbasi and V. Aggarwal, "Joint information freshness and completion time optimization for vehicular networks," *IEEE Trans. Serv. Comput.*, vol. 15, no. 2, pp. 1118–1129, Mar. 2022.

[5] J. Lee, D. Niyato, Y. L. Guan, and D. I. Kim, "Learning to schedule joint radar-communication with deep multi-agent reinforcement learning," *IEEE Trans. Veh. Technol.*, vol. 71, no. 1, pp. 406–422, Jan. 2022.

[6] Z. Gao, S. Liu, Y. Su, Z. Li, and D. Zheng, "Hybrid knowledge-data driven channel semantic acquisition and beamforming for cell-free massive MIMO," *IEEE J. Sel. Topics Signal Process.*, early access, 2023.

[7] Z. Gao, Z. Wan, D. Zheng, S. Tan, C. Masouros, D. W. K. Ng, and S. Chen, "Integrated sensing and communication with mmWave massive MIMO: A compressed sampling perspective," *IEEE Trans. Wireless Commun.*, vol. 22, no. 3, pp. 1745–1762, Mar. 2023.

[8] Y. Niu, Y. Li, D. Jin, L. Su, and A. V. Vasilakos, "A survey of millimeter wave communications (mmWave) for 5G: opportunities and challenges," *Springer Wirel. Netw.*, vol. 21, no. 8, pp. 2657–2676, Apr. 2015.

[9] Q. Wu, S. Zhang, B. Zheng, C. You, and R. Zhang, "Intelligent reflecting surface-aided wireless communications: A tutorial," *IEEE Trans. Commun.*, vol. 69, no. 5, pp. 3313–3351, May 2021.

[10] P. Wang, J. Fang, X. Yuan, Z. Chen, and H. Li, "Intelligent reflecting surface-assisted millimeter wave communications: Joint active and passive precoding design," *IEEE Trans. Veh. Technol.*, vol. 69, no. 12, pp. 14 960–14 973, Dec. 2020.

[11] Y. Chen, B. Ai, H. Zhang, Y. Niu, L. Song, Z. Han, and H. V. Poor, "Reconfigurable intelligent surface assisted device-to-device communications," *IEEE Trans. Wireless Commun.*, vol. 20, no. 5, pp. 2792–2804, May 2021.

[12] X. Fan, M. Liu, Y. Chen, S. Sun, Z. Li, and X. Guo, "RIS-assisted UAV for fresh data collection in 3D urban environments: A deep reinforcement learning approach," *IEEE Trans. Veh. Technol.*, vol. 72, no. 1, pp. 632–647, Jan. 2023.

[13] M. Samir, M. Elhattab, C. Assi, S. Sharafeddine, and A. Ghrayeb, "Optimizing age of information through aerial reconfigurable intelligent surfaces: A deep reinforcement learning approach," *IEEE Trans. Veh. Technol.*, vol. 70, no. 4, pp. 3978–3983, Apr. 2021.

[14] A. Muhammad, M. Elhattab, M. Shokry, and C. Assi, "Leveraging reconfigurable intelligent surface to minimize age of information in wireless networks," in *Proc. IEEE ICC*, Seoul, Korea, Republic of, May 2022, pp. 2525–2530.

[15] W. Lyu, Y. Xiu, S. Yang, P. L. Yeoh, Y. Li, and Z. Zhang, "Weighted sum age of information minimization in wireless networks with aerial IRS," *IEEE Trans. Veh. Technol.*, vol. 72, no. 4, pp. 5390–5394, Apr. 2023.

[16] M. Sherman, S. Shao, X. Sun, and J. Zheng, "Optimizing AoI in UAV-RIS assisted IoT networks: Off policy versus on policy," *IEEE Internet Things J.*, vol. 10, no. 14, pp. 12 401–12 415, Jul. 2023.

[17] M. Ke, Z. Gao, Y. Wu, X. Gao, and R. Schober, "Compressive sensing-based adaptive active user detection and channel estimation: Massive access meets massive MIMO," *IEEE Trans. Signal Process.*, vol. 68, pp. 764–779, Jan. 2020.

[18] Z. Gao, M. Wu, C. Hu, F. Gao, G. Wen, D. Zheng, and J. Zhang, "Data-driven deep learning based hybrid beamforming for aerial massive MIMO-OFDM systems with implicit CSI," *IEEE J. Sel. Areas Commun.*, vol. 40, no. 10, pp. 2894–2913, Oct. 2022.

[19] O. E. Ayach, S. Rajagopal, S. Abu-Surra, Z. Pi, and R. W. Heath, "Spatially sparse precoding in millimeter wave MIMO systems," *IEEE Trans. Wireless Commun.*, vol. 13, no. 3, pp. 1499–1513, Mar. 2014.

[20] Y. Sun, E. Uysal-Biyikoglu, R. D. Yates, C. E. Koksal, and N. B. Shroff, "Update or wait: How to keep your data fresh," *IEEE Trans. Inf. Theory*, vol. 63, no. 11, pp. 7492–7508, Nov. 2017.

[21] Q. Wu and R. Zhang, "Beamforming optimization for wireless network aided by intelligent reflecting surface with discrete phase shifts," *IEEE Trans. Commun.*, vol. 68, no. 3, pp. 1838–1851, Mar. 2020.