Reliability and QoS Assurance in RIS-assisted Indoor Networks

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***Abstract*—Future smart factories are expected to deploy reliable applications over high-performance indoor wireless channels in the millimeter-wave (mmWave) bands. Since these bands are known to be susceptible to high path losses and Line-of-Sight (LoS) blockages, low-cost Reconfigurable Intelligent Surfaces (RISs) are used to enhance the reliability of wireless links. In this paper, we formulate a combinatorial optimization problem, solved with Integer Linear Programming (ILP) to optimally maintain reliable connectivity by solving the problem of allocating RIS to robots in an indoor wireless network. Our model exploits a new feature of the so-called *nulling interference* from RISs by tuning reflection coefficients. We further consider the system reliability by defining Quality-of-Service (QoS) at receivers in terms of Signal-to-Interference-plus-Noise Ratio (SINR) and connection outages due to insufficient transmission quality. Numerical results for the optimal solution and heuristics show the benefits of optimally deploying RISs by providing continuous connectivity through SINR. We also show that our method can significantly reduce outages due to link quality, while meeting the requirements on system and service reliability.**

***Index Terms*—Interference, millimeter-wave (mmWave), Reconfigurable Intelligent Surface (RIS), reliability, smart factory.**

I. Introduction

Today, the 6G wireless network development is emerging rapidly requiring higher frequencies, such as millimeter-Wave (mmWave) and sub-Terahertz (THz) communications. At the same time, these frequency ranges are susceptible to high path losses and Line-of-Sight (LoS) blockages [1]. To mitigate that, Reconfigurable Intelligent Surfaces (RIS) have been widely projected as breakthrough technology in upcoming 6G networks, to address this issue by alleviating communication problems between base stations and receivers [2]. Currently, applications that require high reliability, such as in 6G campus networks for smart factories, are being tested and deployed, along with other applications domains, such as in vehicular and health care, as well as in the context of ongoing mobile network standards. A smart factory scenario is especially interesting as it typically envisions dynamic industrial robots connected to static Base Stations (BS), or RIS. Each RIS can accommodate multiple robots, whereby attention needs to be paid to the resulting quality of transmission and reliability of wireless links, which is of industrial importance [3].

Despite being a highly controlled environment, smart factory robots can experience wireless link outages due to mobility and interference, which is critical, especially if the outage time exceeds the defined threshold. There are also issues of Signal-to-Interference-plus-Noise Ratio (SINR), due to competing and interfering robots that simultaneously connect to the same BS and RISs. Although RISs have the characteristic of nulling interference for parallel communications at a time [4], their capacity cannot satisfy an increased density of robots. Sustaining reliability of links is still an open challenge. Currently, the problem of optimal RIS allocation for multiple robots, and the related co-channel interference-avoiding strategies in a reliable system are new and unsolved.

We study the optimization driven problem of SINR based link quality, and propose an Integer Linear Programming (ILP) and heuristics to optimize the time that each robot is served by the network under the transmission quality constraints for a reliable system. In particular, to allocate the RISs efficiently in wireless paths, we exploit the alternating projection algorithm for nulling interference solution [4]. This approach allows each RIS to simultaneously serve multiple robots. We show that our optimizations approach can improve the system reliability by minimizing link outages and by reducing robot service failures in smart factories. The performance results also quantify the benefits of exploiting RISs in smart factory, as compared to the smart factories without them.

The remainder of the paper is organized as follows. Section II presents related work. Section III shows the system model. In Section IV, we present the optimization method. In Section V, we show the heuristic method. Section VI shows performance evaluation. Finally, Section VII concludes the paper.

II. Related work

The geometric shape models of conical transmission beams from [5], [6] are used in this paper to identify areas causing

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interference. The geometric analyses, such as beam footprint in mmWave from [2] is used here to identify interfering areas. Studies [7], [8] proposes an interference model based on geometric analyses, which we also use as basis for interference computations. Papers [9], [10] discuss the channel model for RIS-assisted networks, which we also applied in our model. Moreover, paper [11] presents the interference model for indoor THz communications in which any receiver suffers interference from any users, which is also used in this paper. Considering the interference impact of higher frequencies presented in these studies, we integrate the impact values on link quality with SINR as constraints into the ILP for optimal device allocation and the related link reliability strategies.

As discussed in [12], user devices can be subject to a significant performance degradation due to interference, due to uncoordinated directional transmissions. Paper [13] proposes an interference aware routing model in mmWave mesh networks with consideration of RIS devices. Paper [14] proposes solutions to avoid cross-link interference by scheduling transmission among directional links in 6G THz mesh networks with the aim of fully exploiting concurrent transmissions, which we also do in our study. With the same approach, papers [7], [8] propose methods of scheduling transmission to avoid co-channel interference in RIS-assisted THz mesh networks. However, these studies consider a static scenario, which is comparably less complex. Deploying the characteristics of nulling interference from RISs in mesh mmWave/THz networks is missing in the current literature. In this paper, we are exploit this characteristics to enhance a system reliability by reducing connections outages as well as improving link quality for robots in smart factories, which is novel.

This paper extends our previous work [15], which focus on single connection reliability. Here, we focuses on multiple access scenario from robots to RIS in a smart factory scenario. The novelty of this paper is that it integrates the QoS with SINR, as well as the characteristic of nulling interference at RISs into the optimization problem formulation. We reuse some characteristics from [15], such as RIS configuration time, RIS allocation history, and QoS given by connection outage. Regarding the interference nulling solution at each RIS, paper [4] proposes an alternating projection algorithm that allows multiple robots to be simultaneously served without interference, which we also use in this paper. To the best of our knowledge, an analytical scenario for optimal device allocation integrated QoS with SINR and connection outages, as well as and RIS interference nulling characteristic is a new approach.

III. System model

In this section, we present a reference scenario in Section III-A and analytical model of SINR in Section III-B. The reference scenario describes transmission behaviors of the robots in a smart factory used to analyze optimization and heuristic methods in Section IV and Section V, whereas the analytical model of SINR is used to assess transmission link quality for the optimization and heuristic methods.

A. Reference scenario

The reference scenario of smart factory is shown in Fig. 1. We show a set $B = \{b_1, b_2, b_3\}$ of 3 static Base Stations (BSs), a set $I = \{i_1, i_2\}$ of 2 static RISs, and a set $R = \{r_1, r_2, r_3, r_4, r_5, r_6\}$ of 6 dynamic robots. Each robot connects to one BS via either a LoS mmWave channel or a virtual LoS channel facilitated by a RIS if direct LoS links between the BSs and the robot are obstructed. As robots move, the LoS or virtual LoS links change over time, with the time interval of interest $[0, \tau]$ divided into a set $N = \{n = s, n = s+1\}$ of 2 time slots in this example. Each time slot lasts for a duration of $\Delta\tau$; thus, $\tau = |N|\Delta\tau$.

Let us assume that channels are deterministic and known in advance for every location of the robots at any time slot. RISs are mounted on fix locations (e.g., walls) with LoS to BSs. We define the coverage regions for each RIS. In Fig. 1, RIS i_1 and RIS i_2 have the coverage regions limited by the lines a and b, respectively. During time slot $n = s+1$, RIS i_1 can cover robots $\{r_1, r_2, r_3, r_4\}$, whereas RIS i_2 can cover robots $\{r_4, r_5, r_6\}$. Robot r_4 can be covered by both RIS i_1 and RIS i_2. Moreover, assume BSs have coverage regions with all devices in their LoS links. In Fig. 1, during $n = s$, BS b_1 covers all robots $\{r_1, r_2, r_3, r_4, r_5, r_6\}$ and RIS i_1, where these robots moving with certain and trajectories known *a priori*, and that all RISs $\{i_1, i_2\}$ can be covered by BS b_2. If each robot is neither covered by BSs nor by RISs, we consider this a link outage in a time slot measured. Also, a link can experience outage if its SINR is lower than a threshold Ψ_r. If a maximum number of times that a robot can accept consecutive outages is K_r time slots, before we define a service failure for any consecutive outage periods higher or equal to K_r.

Each RIS has E reflecting elements, whereby, based on [4], if E elements are slightly larger than a threshold of $2U(U-1)$, then U communication pairs between BSs and robots can be simultaneously transmitted without interference, by adjusting RIS reflection coefficients. However, to eliminate interference, the arrival angles of signals from robots must be different [4]. If arrival angles overlap, interference nulling is not possible. In Fig. 1, assume that each RIS can accommodate a maximum of $U = 2$ communication pairs simultaneously with nulling interference. Robots r_1 and r_2 in the circle area during time $n = s+1$ have the same arrival angle, and cannot be simultaneously scheduled through RIS i_1. Assume that only robots r_1 and r_3 can be chosen to access simultaneously via RIS i_1 with nulling interference. The RIS configuration from covering one robot to another takes D time slots. If a RIS is available, it can immediately serve the robots, i.e., without reconfiguration delay. BSs on the other time do not induce configuration delay in their corresponding LoS coverage regions.

B. Analytical model of SINR

We now calculate SINR for each robot $r \in R$ with consideration of path loss in mmWave networks. The SINR for each robot r at time slot n, connected via RIS $i \in I$ is:

$$S_{i,r,n} = \frac{P_{i,r,n} G_b G_r}{P_o + \sum_{r\prime \in R \setminus r} \left(\sum_{b \in B} \xi_{b,r'r,n}\right) + \left(\sum_{i' \in I \setminus i} \xi_{i',r'r,n}\right)} \quad (1)$$

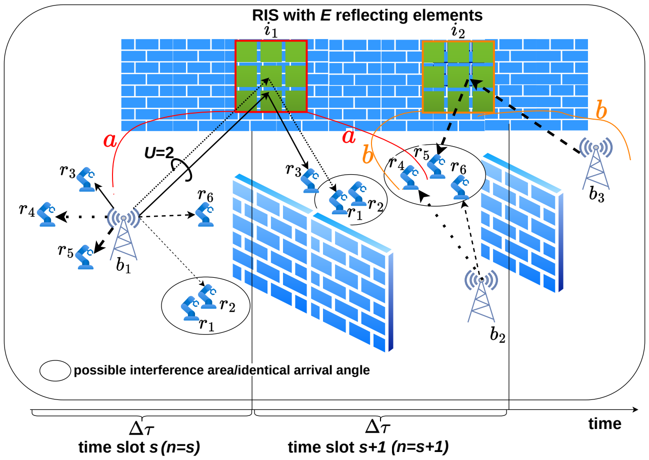


Fig. 1: The reference scenario of a RIS-assisted smart factory.

The transmitting antenna gain G_b [5] of the BS b is:

$$G_b = \frac{2}{1 - cos\left(\frac{\theta}{2}\right)}, \tag{2}$$

where θ is the antenna directivity angle. G_r is the receiving antenna gain of robot r, where $G_b = G_r$. Based on [7], [9], [10], with optimal phase, the signal of each robot r obtained via RIS i at each time slot n is:

$$P_{i,r,n} = P_b |H_{(b,i,n)} \cdot E \cdot H_{(i,r,n)}|^2, \tag{3}$$

where P_b is the transmitting power of BS $b \in B$, E is the number of RIS elements, the channel transfer functions $H_{(b,i,n)}$ between BS b and RIS i at the time slot n and $H_{(i,r,n)}$ between RIS i and robot r at the time slot n is:

$$H = \left(\frac{c}{4\pi f d}\right), \tag{4}$$

where Eq. (4) can be replaced by $H_{(b,i,n)}$ or $H_{(i,r,n)}$, c is the light speed, f is the mmW frequency, and d is the distance; d can be replaced by $d_{b,i,n}$, i.e., distance between BS b and RIS i, or by $d_{i,r,n}$, i.e., between RIS i and robot r, at the time slot n). Also, in Eq. (1), the noise power $P_o = kTV$, where k is the Boltzmann constant, T is the absolute temperature in Kelvin, and V denotes the bandwidth. The undesired interference $\xi_{b,r'r,n}$ from the LoS transmission between BS b and robot r' causing on robot r at the time slot n is:

$$\xi_{b,r'r,n} = \delta_{b,r,n} G_b G_r, \tag{5}$$

where the undesired LoS interference $\delta_{b,r,n}$ without the antenna gain obtained at robot r from BS b at the time n is:

$$\delta_{b,r,n} = P_b |H_{(b,r,n)}|^2, \tag{6}$$

where Eq. (4) is replaced by $H_{(b,r,n)}$, and d is replaced by $d_{b,r,n}$, i.e., distance between BS b and robot r at the time n. The undesired interference $\xi_{i',r'r,n}$ from the virtual LoS link with RIS i' for robot r' causing on robot r at the time n is:

$$\xi_{i',r'r,n} = \delta_{i',r,n} G_b G_r, \tag{7}$$

where the undesired virtual LoS interference $\delta_{i',r,n}$ without the antenna gain obtained at robot r via RIS i' at the time slot n is applied as Eq. (3). As discussed in section III-A, as the robots connected to the same RIS will not get the interference due to either transmission scheduling at different times or interference removed by the solution proposed in [4], we do not consider the interference from those robots in Eq. (1). Finally, the SINR for robot r at the time slot n if directly connected to BS b is:

$$S_{b,r,n} = \frac{P_{b,r,n} G_b G_r}{P_o + \sum_{r' \in R \setminus r} \left(\sum_{b \in B} \xi_{b,r'r,n}\right) + \left(\sum_{i \in I} \xi_{i,r'r,n}\right)}, \tag{8}$$

where the signal power $P_{b,r,n}$ of robot r directly obtained from BS b at the time n is applied as Eq. (6), and the interference $\xi_{b,r'r,n}$ and $\xi_{i,r'r,n}$ are applied as Eqs. (5) and (7), respectively.

IV. Optimization Method

We present an optimal allocation strategy for robots in a smart factory in Section IV-A and the ILP problem formulation in Section IV-B, which are based on the reference scenario in Sections III-A and Section III-B.

A. Optimal allocation strategy

In Fig. 1, if an arrow exists between one robot and a BS/RIS, the related BS/RIS is allocated to that robot. We now analyze the allocation strategy in Fig. 1. During $n = s$, two robots r_1 and r_2 belonging to the circle area may interfere. BS b_1 simultaneously transmits its signal to these two robots if the SINR of robots r_1 and r_2 is larger than or equal to the threshold Ψ_{r_1} and Ψ_{r_2}, respectively. Otherwise, only one of the robots, e.g., r_2, receives the signal from BS b_1 during $n = s$. During time $n = s+1$, considering the coverage region of RIS i_2, it can cover three robots $\{r_4, r_5, r_6\}$. As these three robots have the same arrival angle, only one of them, e.g., r_5 in Fig. 1, is chosen to be allocated by RIS i_2. The remaining two robots r_4 and r_6 are assumed to be simultaneously scheduled with robot r_5 via BS b_2, if the interference among them still satisfies the SINR of these three robots r_4, r_5, and r_6 larger than or equal to the threshold Ψ_{r_4}, Ψ_{r_5}, and Ψ_{r_6}, respectively.

At the same time slot $n = s+1$, and considering the coverage region of RIS i_1, robots $\{r_1, r_2, r_3, r_4\}$ can be served. As robots r_1 and r_2 have the same arrival angle, they cannot be scheduled simultaneously via RIS i_1. As only $U = 2$ robots are simultaneously served via each RIS, there are five options for RIS i_1: $\{r_3, r_1\}$, $\{r_3, r_2\}$, $\{r_3, r_4\}$, $\{r_1, r_4\}$, and $\{r_2, r_4\}$ for simultaneously connecting via RIS i_1. However, since r_4 can be directly connected to BS b_2, the options including this robot can be discarded. From the two options left, $\{r_3, r_1\}$ and $\{r_3, r_2\}$, $\{r_3, r_1\}$ is the best choice because the allocation history of r_2 was already connected to BS b_1 during $n = s$. In this way, we can mitigate the service failures in which each robot expects the outage in less than K_r consecutive time slots. If BS b_2 is allocated to robot r_2 during $n = s+1$, the SINR of robot r_1 may become lower than the threshold Ψ_{r_1}. Therefore, robot r_2 experience an outage during $n = s+1$.

Finally, due to the characteristic of nulling interference [4], the interference never occurs for the robots accessing the same RIS. However, those robots still suffer interference from the robots allocated by other RISs and the BSs with LoS transmission. For example, if robot r_4 is to be allocated by RIS i_1 during $n = s+1$ in Fig. 1, it will not get the interference from robots r_1, r_2, and r_3. However, it still interferes with the received signal of robot r_5 via RIS i_2 and from robot r_6 via the LoS transmission of BS b_2. This can be explained by the fact that the solution to the RIS interference nulling problem is only valid for the robots with access to the RIS itself.

B. ILP Problem Formulation

The input parameters and binary variables are summarized in Table I. The minimization objective is achieved by generating the optimal allocation for robot $r \in R$ on one of the BSs in B, or RISs in I. The objective function that minimizes the total number of connection outages for all of $|R|$ robots over $|N|$ time slots is defined as the following:

$$\min_{\mathbf{W},\mathbf{X},\mathbf{O},\mathbf{Y},\mathbf{C},\mathbf{Z}} \sum_{r\in R}\sum_{n\in N} O_{r,n}, \tag{9}$$

subject to the following constraints:

$$\sum_{b\in B} X_{b,r,n} + \sum_{i\in I} X_{i,r,n} \leqslant 1,\ \forall r \in R, n \in N, \tag{10}$$

where constraint (10) is for each robot r at time slot n, that robot connects to only one BS b / RIS i via the binary variables $X_{b,r,n}/X_{i,r,n}$,

$$\sum_{r\in m} X_{i,r,n} \leqslant 1,\ \forall i \in I, m \in M_{i,n}, n \in N, \tag{11}$$

where constraint (11) is for RIS i at time slot n, there exists a set $M_{i,n}$. Each subset $m \in M_{i,n}$ is a set of robots with the variables $X_{i,r,n}$ that their receiving beams are overlapped together, resulting in conflicts. With the interference nulling solution [4], the robots in m cannot be simultaneously scheduled,

$$\sum_{r\in R} X_{i,r,n} \leqslant U,\ \forall i \in I, n \in N, \tag{12}$$

where according to [4], constraint (12) is for RIS i at time slot n, a maximum of U robots with variable $X_{i,r,n}$ are simultaneously scheduled with nulling interference, which is discussed in Section III,

$$\begin{cases} \dfrac{X_{b,r,n}P_{b,r,n}G_bG_r + \omega}{P_o + \sum_{r'\in R\setminus r}(\varpi + \vartheta)} \geqslant \Psi_r, \forall r \in R, b \in B, n \in N, & \text{(13a)} \\ X_{b,r,n} + Z_{b,r,n} = 1,\ \forall r \in R, b \in B, n \in N, & \text{(13b)} \end{cases}$$

where constraint (13a) shows the link quality of robot r with SINR at time slot n connected to BS b under the allocation selection with variable $X_{b,r,n}$, whereby constraint (13a) can be related to Eq. (8) in Section III-B, $\omega = \mu Z_{b,r,n}$, $\varpi = \sum_{b\in B} X_{b,r',n}\xi_{b,r'r,n}$, and $\vartheta = \sum_{i\in I} X_{i,r',n}\xi_{i,r'r,n}$. The link quality of robot r needs to be satisfied so that SINR $\geq \Psi_r$ (threshold). We define a dummy binary variable $Z_{b,r,n}$ with a constant μ assigned large enough, where with constraint (13b), if $X_{b,r,n} = 1$, $Z_{b,r,n} = 0$; else $Z_{b,r,n} = 1$. With $Z_{b,r,n}$, constraint (13a) is always satisfied, if $X_{b,r,n} = 0$,

$$\begin{cases} \dfrac{X_{i,r,n}P_{i,r,n}G_bG_r + \omega'}{P_o + \sum_{r'\in R\setminus r}(\varpi + \vartheta')} \geqslant \Psi_r, \forall r \in R, i \in I, n \in N, & \text{(14a)} \\ X_{i,r,n} + Z_{i,r,n} = 1,\ \forall r \in R, i \in I, n \in N, & \text{(14b)} \end{cases}$$

where constraint (14a) can be explained as constraint (13a), but robot r is connected to RIS i with variable $X_{i,r,n}$, where constraint (14a) can be referred Eq. (1) in Section III-B, $\omega' = \mu Z_{i,r,n}$, and $\vartheta' = \sum_{i'\in I\setminus i} X_{i',r',n}\xi_{i',r'r,n}$. The binary variable $Z_{i,r,n}$ in constraint (14a) can be referred to $Z_{b,r,n}$ in constraint (13a), where with constraint (14b), if $X_{i,r,n} = 1$, $Z_{i,r,n} = 0$; else $Z_{i,r,n} = 1$,

$$\frac{1}{D}\sum_{\bar{n}=\max\{n-D+1,0\}}^{n} X_{i,r,\bar{n}} \leqslant Y_{i,r,n},\ \forall r \in R, i \in I, n \in N, \tag{15}$$

where constraint (15) states the allocation history of RISs during the last D time slots. If RIS i is allocated to robot r at least once during time interval $[n - D + 1, n]$, the binary variable $Y_{i,r,n} = 1$. Otherwise, $Y_{i,r,n} = 0$,

$$\left(\frac{1}{|R|}\sum_{r\in R} Y_{i,r,n}\right) - \frac{U}{|R|} \leqslant C_{i,n}, \quad \forall i \in I, n \in N, \tag{16}$$

where constraint (16) considers the required time of RIS reconfiguration. If the binary variable $C_{i,n} = 1$, RIS i reallocated during D time slots is not ready. Otherwise, $C_{i,n} = 0$. With (15), RIS i is not available with $C_{i,n} = 1$ at the time slot n, if $Y_{i,r,n} = 1$ at least $U + 1$ different robots r,

$$\sum_{\bar{n}=\max\{n-K_r+1,0\}}^{n} O_{r,\bar{n}} < K_r,\ \forall r \in R, n \in N, \tag{17}$$

where constraint (17) considers the connection status of the robots with the binary variable $O_{r,n}$. If $O_{r,n} = 1$, then the robot r gets an outage at the time slot n. Otherwise, $O_{r,n} = 0$. This constraint defines a service failure for each robot r with K_r time slots. The summation of the outage variable $O_{r,n}$ of each robot r over K_r consecutive time slots should be less than K_r,

$$\begin{cases} O_{r,n} + \sum_{i\in I} W_{i,r,n} + \sum_{b\in B} X_{b,r,n} \geq 1, \forall r \in R, n \in N, & \text{(18a)} \\ W_{i,r,n} \leqslant X_{i,r,n}, \forall i \in I, r \in R, n \in N, & \text{(18b)} \\ W_{i,r,n} \leqslant 1 - C_{i,n}, \forall i \in I, r \in R, n \in N, & \text{(18c)} \end{cases}$$

where constraint (18a) states that if each robot $r \in R$ at time slot n is directly connected to BS b via the variable $X_{b,r,n}$ or is allocated to the RIS i in case of that available RIS i via the binary variable $W_{i,r,n}$, which its constraints are presented in constraint (18b) and constraint (18c). If $W_{i,r,n} = 1$, each robot r at each time slot n is allocated to the ready RIS i. Otherwise, $W_{i,r,n} = 0$. In Eq. (18a), if there exists an allocation for robot r at the time slot n, then $O_{r,n} = 0$. Otherwise, $O_{r,n} = 1$. The complexity of the ILP solution is given by:

$$O(|I|\cdot|R|\cdot|N|\cdot[|R|(|B|+|I|)+D]+|I|\cdot|N|\cdot|M_w|\cdot|m_w|+ |R|\cdot|B|\cdot|N|\cdot[|R|(|B|+|I|)]+|R|\cdot|N|\cdot[|B|+|I|+K_r]), \tag{19}$$

TABLE I: List of input parameters and binary variables of ILP program.

Input	Meaning
R	Set of robots.
N	Set of time slots.
B	Set of BSs.
I	Set of RISs.
$M_{i,n}$	Set of subsets m with robots conflicted at RIS i at time n.
U	Robots simultaneously allocated at RIS.
Ψ_r	SINR threshold for robot r.
ξ	Interference on robot r at n caused by comm. between BS b / RIS i and robot r', $\xi = \{\xi_{b,r'r,n}, \xi_{i,r'r,n}\}$.
P	Power with no gain obtained at robot r via BS b / RIS i at n, $P = \{P_{b,r,n}, P_{i,r,n}\}$.
G	Antenna gain of BS b / robot r, $G = \{G_b, G_r\}$.
P_o	Noise power.
D	RIS configuration time.
K_r	Outage time slot threshold for robot r.
μ	Large constant, e.g., $\mu = 10^9$.
Variables	**Meaning**
X	Allocation of BS b / RIS i to robot r at n, X = 0/1: unallocated/allocated, $X = \{X_{b,r,n}, X_{i,r,n}\}$.
$W_{i,r,n}$	Allocation of RIS i to robot r at time n as well as availability of RIS i at time n, $W_{i,r,n}$ = 0/1: unallocated/allocated.
$O_{r,n}$	Connection status of robot r at time n, $O_{r,n}$ = 0/1: connection/outage.
$Y_{i,r,n}$	Allocation history of RIS i to robot r at n, $Y_{i,r,n}$ = 0/1: unallocated/allocated at least once during $[n-D+1, n]$.
$C_{i,n}$	Availability status of RIS i at time n, $C_{i,n} = 0/1$: available/unavailable.
Z	Dummy variable: $Z = \{Z_{b,r,n}, Z_{i,r,n}\} = 0/1$.

With constraint (10), we need $|N| \cdot |R|(|B| + |I|)$ steps to search allocations for robots. There are $|I| \cdot |N| \cdot |M_w| \cdot |m_w|$ steps to find transmission scheduling solutions for RIS interference nulling in constraint (11), where $m_w \in M_w$ is the worst case, represented for $m \in M_{i,n}$ in constraint (11). We need $|I| \cdot |R| \cdot |N|$ steps to choose a maximum of U robots simultaneously served through each RIS in constraint (12). We need $|R| \cdot |B| \cdot |N| \cdot [|R|(|B| + |I|)]$ steps to consider SINR threshold in constraint (13a) and $|R| \cdot |B| \cdot |N|$ steps for dummy variables in constraint (13b). We need $|R| \cdot |I| \cdot |N| \cdot [|R|(|B| + |I|)]$ steps to consider SINR threshold in constraint (14a) and $|R| \cdot |I| \cdot |N|$ steps for dummy variables in constraint (14b). The RIS allocation history in constraint (15) needs $|R| \cdot |I| \cdot |N| \cdot D$ steps. In constraint (16), we need $|I| \cdot |N| \cdot |R|$ steps to identify the status of RISs. The service failure of robots is considered in constraint (17) with $|R| \cdot |N| \cdot K_r$ steps. There are $|R| \cdot |N| \cdot (|B| + |I|)$ steps in constraint (18a). Finally, we need $|I| \cdot |R| \cdot |N|$ steps for both constraints (18b) and (18c).

V. Heuristic method

In this section, we present a heuristic method for the reference scenario described in Section III-A, where the SINR calculations are referred to Section III-B and the input parameters are also used from Table I. The pseudo-code of the proposed heuristic is presented in Algorithm 1.

Algorithm 1 Heuristic

INPUT: input parameters from Table I.
for $n = 1 : |N|$ **do**
  for $r = 1 : |R|$ **do** ▷ Robots allocation
    X_n = AddAllocationSP(r,B,I,n);
  end for
  for $i = 1 : |I|$ **do** ▷ Non-LoS (RIS) constraints
    for $j = 1 : |M_{i,n}|$ **do**
      $m = M_{i,n}[j]$;
      X_n = SelectRandom(X_n,$r \in m$,i,n);
    end for
    X_n = SelectRandom(X_n,U,i,n);
    for $r = 1 : |R|$ **do**
      $S_{i,r,n}$ =SINR(i, r, n); ▷ Eq. (1)
      if $S_{i,r,n} \geqslant \Psi_r$ **then**
        X_n = Select(X_n,r,i,n);
      end if
      AllocationHistory(r,i,n,D); ▷ Constraint (15)
    end for
    if CheckReadyRIS(i, n) **then** ▷ Constraint (16)
      X_n = Select(X_n,r,i,n);
    end if
  end for
  for $b = 1 : |B|$ **do** ▷ LoS (BS) constraints
    for $r = 1 : |R|$ **do**
      $S_{b,r,n}$ =SINR(b, r, n); ▷ Eq. (8)
      if $S_{b,r,n} \geqslant \Psi_r$ **then**
        X_n = Select(X_n,r,b,n);
      end if
    end for
  end for
  $\overline{X}\_n = R \setminus X\_n$;
  $Outage\_n = \overline{X}\_n$;
end for
OUTPUT: $\sum_{n=1}^{|N|} |Outage\_n|$;

The idea behind the heuristic is to the take the model formulation from Section IV-B into consideration, but removing or simplifying some steps. The heuristic starts by connecting each robot to one BS/RIS with the shortest path, based on constraint (10). To remove interference at a RIS, the heuristic method selects randomly at most one robot from the set of robots whose receiving beams from the same RIS are overlapping (constraint (11)). Also, due to the limited capacity of each RIS (constraint (12)), the heuristic selects randomly a maximum of U robots to be simultaneously served by that RIS. Then, the heuristic checks the SINR QoS for LoS and non-LoS communications (constraints (13a) and (14a)). To identify an available RIS, it calculates the RIS allocation history (constraint (15)). Based on the allocation history, it can identify the available status of each RIS (constraint (16)). Finally, the heuristic decides if a robot is either allocated or unallocated (outage) (constraints 18a, 18b, and 18c). Moreover, since the heuristic method always connects robots to BSs/RISs over the shortest paths, the allocation strategy from constraint (17) cannot be applied. Thus, reducing the complexity for the allocation strategy selection. Therefore, the solutions provided by the heuristic are not optimal.

We now present the pseudo-code (Algorithm 1) in detail. Our algorithm considers a scenario with $|N|$ time slots (line 2). Let X_n be a vector of robots allocated to BS b or RIS i at the time slot n, whereas $\overline{X\_n}$ is a vector of robots unallocated at the time slot n. Each robot r is only allocated to one $b \in B$ or one $i \in I$ with the Shortest Path (SP) at the time slot n via the function X_n =AddAllocationSP(r,B,I,n), i.e., in lines 3-5. From lines 6-22, we consider constraints for the robot allocations with each RIS i. As discussed on constraint (11) in Section IV-B for the condition to remove interference at a RIS [4], with a set $M_{i,n} = \{M_{i,n}[j] \mid j \in [1, |M_{i,n}|]\}$ at RIS i at the time slot n, each subset of robots $m = M_{i,n}[j]$ for which the receiving beams at robots in the same subset m are overlapped, only one robot is connected to RIS i. For heuristic method, we select randomly at most one robot $r \in m$ in each subset $m = M_{i,n}[j]$ from the allocation vector X_n at the RIS i at the time slot n via the function SelectRandom(X_n,$r \in m$,i,n) (lines 7-10), where the remaining robots in m become unallocated. On the other hand, as analyzed in constraint (12), due to the capacity of RIS i being limited by a maximum of U robots simultaneously served, the heuristic selects randomly a maximum of U robots simultaneously served by that RIS i from the allocation vector X_n at the time slot n via the function SelectRandom(X_n,U,i,n) (line 11). In addition, each robot r is selected for the allocation at RIS i from the allocation vector X_n at the time slot n so that its SINR $S_{i,r,n} \geqslant \Psi_r$ via the function Select(X_n,r,i,n) (lines 14-16), where $S_{i,r,n}$ is calculated by the function SINR(i, r, n) at line 13 referred to Eq. (1), as discussed in constraint (14a). However, for each RIS from the allocation vector X_n, we need to check whether that RIS is ready or not. In line 17, at the time slot n, we calculate the allocation history of each robot r with the RIS i during the last D time slots via the function AllocationHistory(r,i,n,D) as in constraint (15). As a result, based on that allocation history from all robots at the time slot n, we can check the availability of RIS i via the function CheckingReadyRIS(i, n) as in constraint (16) (line 19). Each allocation of RIS i is only performed for robot r at the time slot n from the allocation vector X_n via the function Select(X_n,r,i,n), if that RIS is ready, as discussed similarly in constraints (18b) and (18c) (line 20).

For LoS communications, each robot r is selected for allocation at BS b from the allocation vector X_n at time slot n, so that its SINR $S_{b,r,n} \geqslant \Psi_r$ via the function Select(X_n,r,b,n) (lines 23-30), where $S_{b,r,n}$ is calculated by the function SINR(b, r, n) at line 25, Eq. (8). With the allocation vector X_n obtained, we derive the vector $\overline{X\_n}$ of the robots that are not allocated at time slot n, line 31. Hence, we obtain an $Outage\_n$ vector of robots that are not allocated at the time slot n (line 32). The total number of outages over $|N|$ time slots is equal to $\sum_{n=1}^{|N|} |Outage\_n|$ (line 34). The complexity of Algorithm 1 is given by:

$$\begin{aligned} &O(|N| \cdot [|R| + |I| \cdot (|M_w| + |R|) + |B| \cdot |R|]), \\ &= O(|N| \cdot [|I| \cdot |M_w| + |R| \cdot (|I| + |B|)]), \end{aligned} \tag{20}$$

where $M_{i,n} = M_w$ is the worst case of a RIS i at the time slot n, lines 6-7. Note that since the heuristic has no optimal allocation strategy for each robot over different time slots in the past and present, all of the functions in the pseudo-code (Algorithm 1) compute simple equations and thus are $O(1)$.

TABLE II: List of input parameters and binary variables of ILP program.

Input	Meaning
$\lvert B \rvert = 2$	Number of BSs.
$\lvert I \rvert = 8$	Number of RISs.
$E = 200$	Number of RIS elements [4].
$\lvert N \rvert = 50$	Number of time slots.
$\theta = 10^o$	Beamwidth [1].
$V = 20 \cdot 10^6$ Hz	Bandwidth [16].
$T = 290$ Kelvin	Absolute temperature [16].
$P_b = 1$ mW	Power of BS.
$f = 28 \cdot 10^9$ Hz	Frequency [16], [17].

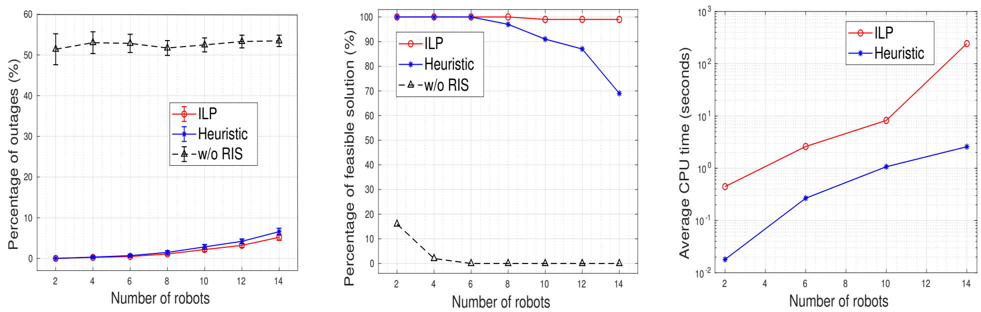
VI. Performance evaluation

We evaluate the performance of the reference scenario of a smart factory presented in Section III-A, with the optimal allocation from Section IV-A and the SINR calculation from Section III-B. The numerical results are obtained by means of solving the optimization problem from Section IV-B by using the *intlinprog* function from Matlab and running the heuristics from Section V. All inputs are summarized in Table II. With $E = 200$ elements, each RIS allows a maximum of $U = 10$ robots being simultaneously served [4].

We randomly generate both the placements and the movement of robots in a factory setting. Each robot moves during five time slots in the same direction before changing course. We also generate a list of all RISs and BSs coverage areas in which a robot is in any given time slot. Each BS/RIS emits signals in conical beams with a beamwidth of θ degrees [5], [6]. Hence, we can calculate the footprint diameter ϕ of the conical beam from a BS/RIS to a robot with the distance d as [2], $\phi = 2tan\left(\frac{\theta}{2}\right)d$. If any robots are within any undesired footprint, they are considered as receiving an interfering signal. The analytical results are run for 100 random independent scenarios for each case, so we get the average values with confidence intervals of 95%.

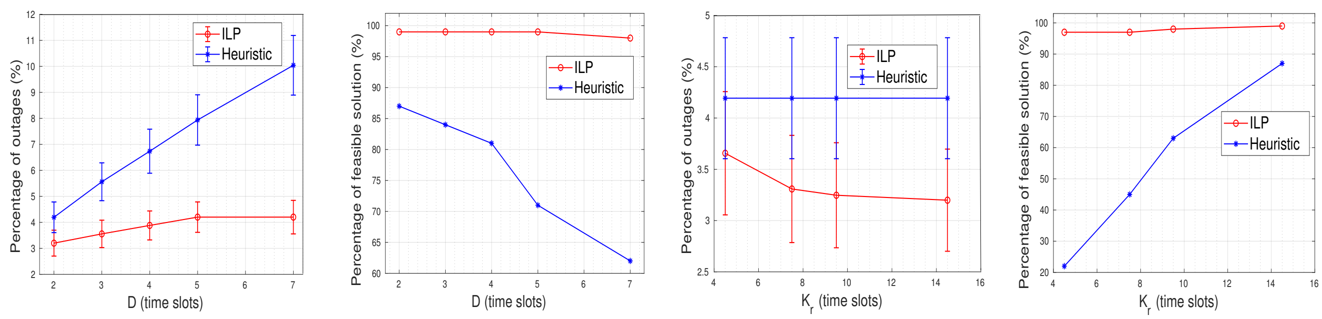
We define the percentage of outages as the ratio of the total number of outages to the product of the total number of time slots and the number of robots. Also, the percentage of feasible solutions may happen due to an infeasible scenario or the proposed heuristic failing to find a solution.

Fig. 2 shows the percentage of outages and feasible solutions. We set $K_r = [14, 15]$ time slots and threshold $\Psi_r = [9, 10]$ for robots (averages $K_r = 14.5$ and $\Psi_r = 9.5$), RIS configuration time $D = 2$ time slots, and $U = 2$ robots simultaneously served by a RIS. For comparison, a scenario without RIS (w/o RIS) is also analyzed. The percentage of



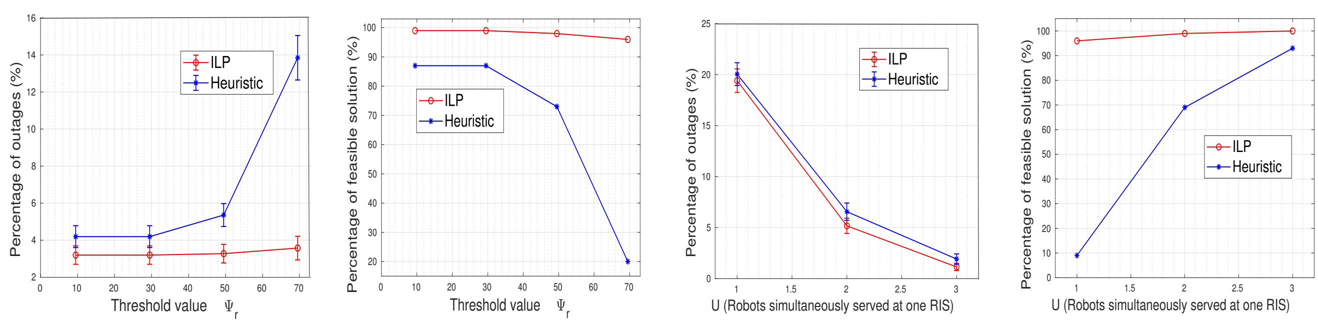
(a) Outage level (b) Feasible solutions (c) Time complexity

Fig. 2: Outages, feasibility and complexity: $K_r \in [14, 15]$ time slots, $\psi_r \in [9, 10]$, $D = 2$ time slots, and $U = 2$ robots simultaneously served at each RIS.



(a) $K_r = 14; 15$ time slots (b) $K_r = 14; 15$ time slots (c) $D = 2$ time slots (d) $D = 2$ time slots

Fig. 3: Percentage of outages and feasible solutions: $\psi_r \in [9, 10]$, $U = 2$ robots simultaneously served at each RIS, and $R = 12$ robots.



(a) $U = 2$ robots and $R = 12$ robots (b) $U = 2$ robots and $R = 12$ robots (c) $\Psi_r = 9; 10$ and $R = 14$ robots (d) $\Psi_r = 9; 10$ and $R = 14$ robots

Fig. 4: Percentage of outages and feasible solutions: $D = 2$ time slots and $K_r \in [14, 15]$.

outages in Fig. 2(a) remains fairly constant w/o RIS with increasing number of robots, because this case only depends on the number of robots inside the BS coverage areas, which is around $(50, 60)\%$. This results in low feasibility in almost all scenarios, even under 20% in case of fewer robots $|R| = 2$ in Fig. 2(b). With RISs, both the ILP and heuristic methods significantly reduce the percentage of outages and enhance the percentage of feasible solutions. This shows the advantage in using low-cost RISs to improve system reliability. As expected, the ILP method outperforms the heuristic method, as shown in Fig. 2(a) and in Fig. 2(b), due to its optimal RIS allocation strategy. Regarding feasibility (Fig. 2(b)), the ILP method achieves up to 99% with $|R| = 14$ robots, whereas the heuristic method achieves under 70%, an evidence of the hardness of this problem. Due to its competition for RIS connections, it is expected that the percentage of outages and infeasible solutions increases with the number of robots. With less competition among robots ($|R| \leq 6$), there is no difference (percentage of feasible solutions) between the ILP and heuristic. Finally, the average CPU execution time of the algorithms is shown in Fig. 2(c), where the expected exponential CPU time of the ILP is evinced by the one-order-of-magnitude time leap between 10 and 14 robots. For more robots, the ILP becomes impractical. On the other hand, the CPU time of the heuristic scales smoothly, decreasing its steepness with the addition of more robots.

The impact of the reconfiguration time D on the performance is shown in Fig. 3(a) and Fig. 3(b), for $|R|$ = 12 robots. The percentage of outages and infeasible solutions increases with increasing D due to increasing the unavailability period of an RIS after reallocation. The heuristic feasibility decreases linearly as D increases maintaining above 60%, whereas the ILP feasibility just decreases slightly. The impact of the maximum outage time K_r (a QoS requirement) on the performance is shown in Fig. 3(c) and Fig. 3(d), with $|R|$ = 12 robots. The average K_r plotted are K_r = $[4.5; 7.5; 9.5; 14.5]$. The percentage of outages of the heuristic remains constant for all K_r, because it does not consider the allocation strategy for robots (constraints (17) and (18a) in Section IV-B). Hence, the heuristic is independent on the values of K_r and consequently shows less feasibility. For the ILP, with increasing K_r, we can find solutions with a lower percentage of outages (Fig. 3(c)) and infeasible solutions (Fig. 3(d)) because QoS requirements of K_r are low. In this analysis, the heuristic cannot handle the majority of scenarios, especially for lower K_r values.

In Fig. 4(a) and Fig. 4(b), we analyze the impact of the SINR threshold (a QoS requirement) on performance, where $|R|$ = 12 robots. The average values Ψ_r plotted are Ψ_r = $[9.5; 29.5; 49.5; 69.5]$. It is harder to find more feasible solutions with increasing Ψ_r in Fig. 4(b) because the SINR requirements are more stringent, resulting in a higher percentage of outages (Fig. 4(a)), specially for the heuristic. Due to optimal interference avoiding and RIS allocation strategies, ILP solution does not show major difference with increasing Ψ_r. Finally, we analyze the performance impact of U robots being served simultaneously at each RIS in Fig. 4(c) and Fig. 4(d), with $|R|$ = 14. We find fewer outages and infeasible solutions with increasing U because each RIS allows more robots to schedule transmission simultaneously. Thus, it becomes easier to find more feasible solutions. We stop at U = 3 because the ILP achieves up to 100% feasibility (Fig. 4(d)). This also means that, for the scenario with 14 robots, we could employ RIS devices with fewer reflecting elements (smaller U), which allows for a more cost effective RIS deployment.

VII. Conclusion

We formulated a novel combinatorial optimization problem, of which solution can optimally maintain connectivity in smart factory with robots, by optimally allocating RISs to robots. Our model exploited the characteristics of nulling interference from RISs by tuning RIS reflection coefficients. We also considered connection outages due to insufficient transmission quality service, and especially signal-to-interference-plus-noise ratio (SINR), which is novel. Numerical results showed the benefits of RISs in reducing the number of link outages. We also showed that interference-avoiding strategies were necessary to optimize the performance.

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