

Receiver Algorithms for Satellite-Terrestrial ISAC-RIS Systems

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Abstract—The concept of integrating satellite and terrestrial wireless networks has emerged in recent years as one of the focal points for addressing the high demand for global connectivity. Meanwhile, integrated sensing and communication (ISAC) and reconfigurable intelligent surfaces (RISs) have been studied to enable some of the applications future wireless networks are envisioned to support. To reflect these recent research directions, this paper proposes a satellite-terrestrial integrated network (STIN) model, which comprises an uplink terrestrial ISAC-RIS scenario and a downlink satellite transmission to the ISAC base station. Based on the system model, a mathematical formulation is provided to characterize the communication symbol detection and target estimation problems. Further, the maximum likelihood (ML) detection algorithm is proposed to jointly detect the symbols transmitted by the terrestrial user equipment and satellite. In an interference cancellation scheme, the reflection coefficients of the ISAC target are estimated after symbol detection using the minimum mean-squared error estimation (MMSE) method. The computational complexities of ML and MMSE algorithms are analyzed in terms of the number of real additions and real multiplications involved in their operations. Finally, Monte Carlo simulations are presented to support the findings.

Index Terms—Integrated sensing and communication (ISAC), reconfigurable intelligent surfaces (RIS), satellite-terrestrial integrated network (STIN), sensing parameter estimation.

I. INTRODUCTION

It is expected that in addition to enhanced communication services, the 6th-generation (6G) and beyond 6G wireless technologies will support several high-accuracy sensing applications, including localization and radar sensing [1]. Although there have been parallel advancements in wireless communication and radar sensing technologies over the years, their shared similarities in signal processing algorithms and deployed hardware architecture have motivated significant research in developing an emerging technology known as integrated sensing and communication (ISAC) [2]. ISAC facilitates the coexistence of communication and sensing subsystems on a shared platform to achieve a cost- and spectrally- efficient system [3].

The full potential of ISAC can be achieved if an adequate degree of control over the random wireless channel can be established to enhance the quality of communication signal transmission and that of sensing. To this end, reconfigurable intelligent surfaces (RISs) have garnered significant attention within the research community in recent years due to their low cost and scalability in augmenting the wireless channels

[4]. The opportunity for extra optimization provided by RISs is also crucial in addressing some of the contrasting demands of communication and sensing [5].

To meet the growing global demand for connectivity and user experiences that ISAC-RIS systems would facilitate, considerable research work has recently been conducted on satellite constellations due to their ability to provide greater coverage and serve areas where it may not be feasible to establish terrestrial network services [6], [7]. Such scenarios include backhauling and critical communications for rescue and emergency services in times of natural disasters [8], [9]. An innovative approach to achieve such high-speed global access is by jointly harnessing the wider coverage of satellite systems and the high-capacity infrastructure of terrestrial networks in satellite-terrestrial integrated networks (STINs) [10], also known as satellite-terrestrial networks [11].

The potential of terrestrial ISAC-RIS systems has been investigated in [5], and a joint receiver algorithm was proposed in [12]. However, the scope of these works did not cover satellite applications. The works in [13] and [14] studied the incorporation of ISAC in satellite systems without the inclusion of RIS. In [10], an analytical framework was presented to determine the performance of an ISAC-enabled satellite and an RIS-assisted terrestrial network. The authors also proposed a federated learning technique to tackle the problem of spectral efficiency optimization. However, to the best of our knowledge, there exists a notable gap in the literature with regard to the design of a receiver for the STIN-ISAC-RIS systems.

With the integration of satellite and terrestrial ISAC-RIS systems being envisioned, the need for efficient and reliable signal processing techniques arises. In this paper, we present a set of receiver algorithms to process the received communication and sensing signals in a STIN-ISAC-RIS framework. The key contributions of this paper are listed as follows:

- A scenario incorporating a satellite within a terrestrial ISAC-RIS system is presented. The RIS is optimized to enhance terrestrial communication.
- A mathematical formulation is provided to model the symbol detection and sensing parameter estimation problems in the proposed STIN-ISAC-RIS system.
- The maximum likelihood (ML) detection algorithm is proposed to jointly detect the satellite and user equipment (UE) symbols.

- Using the interference cancellation (IC) method, a minimum mean square error (MMSE) estimator is formulated to calculate the target reflection coefficients.
- The computational complexities of the ML detection algorithm and MMSE estimator are analyzed.
- Monte Carlo simulations are provided to verify the findings.

The rest of the paper is organized as follows: Section II describes the system model and problem formulation. Section III introduces the proposed algorithms. The computational complexities of the proposed algorithms are analyzed in Section IV, whilst Sections V and VI present numerical results and conclusions, respectively.

II. SYSTEM MODEL

Consider a STIN-ISAC-RIS system as shown in Fig. 1, where a full-duplex (FD) ISAC base station (BS) simultaneously receives uplink communication signals from a UE, downlink communication signals from a satellite, and echoes of a sensing signal reflected by the target. Because the transmit and receive antennas of the ISAC BS are collocated, the radar for sensing can be considered a monostatic radar. It is assumed that the self-interference is canceled at the FD ISAC BS prior to processing the joint received signal [15]. A single-input multiple-output (SIMO) system is assumed, in which case the ISAC BS, satellite, and UE each utilize a single transmit antenna, whilst the ISAC BS is equipped with N_r receive antennas. Due to the obstacles present in the terrestrial UE-BS channel, an RIS is deployed on the face of a nearby building to provide virtual line-of-sight paths between the two terminals, as shown in Fig. 1.

In the presence of RIS, the uplink terrestrial communication signal received at the ISAC BS, $\mathbf{y}_1 \in \mathbb{C}^{N_r \times 1}$, consists of signals from the UE-BS channel and the reflected signals from the K RIS elements, which can be expressed as

$$\mathbf{y}_1 = \sqrt{P_{ue}}(\mathbf{h}_1 + \mathbf{H}_2\mathbf{\Theta}\mathbf{h}_3)x_{ue} + \mathbf{n}_{ue}, \quad (1)$$

where $x_{ue} \in \mathbb{C}^{1 \times 1}$ and P_{ue} represent the transmitted UE symbol and communication signal power, respectively. $\mathbf{h}_1 \in \mathbb{C}^{N_r \times 1}$, $\mathbf{H}_2 \in \mathbb{C}^{N_r \times K}$, and $\mathbf{h}_3 \in \mathbb{C}^{K \times 1}$ denote the channel properties of the UE-BS, RIS-BS, and UE-RIS, respectively. $\mathbf{\Theta} = \text{diag}(e^{j\theta_1}, \dots, e^{j\theta_K}, \dots, e^{j\theta_K}) \in \mathbb{C}^{K \times K}$ is a diagonal matrix that represents the RIS phase shifts, where $\theta_k \in [-\pi, \pi)$ is the phase shift introduced by the k -th RIS reflecting element. $\mathbf{n}_{ue} \in \mathbb{C}^{N_r \times 1}$ is the additive white Gaussian noise (AWGN) for the terrestrial communication system with zero-mean and variance of σ_{ue}^2 .

The downlink satellite communication signal received at the ISAC BS, $\mathbf{y}_2 \in \mathbb{C}^{N_r \times 1}$, is formulated as

$$\mathbf{y}_2 = \sqrt{P_{sat}}\mathbf{h}_{sat}x_{sat} + \mathbf{n}_{sat}, \quad (2)$$

where $x_{sat} \in \mathbb{C}^{1 \times 1}$ represents the satellite communication symbols and P_{sat} is the transmitted satellite communication signal power. $\mathbf{h}_{sat} \in \mathbb{C}^{N_r \times 1}$ represents the channel properties

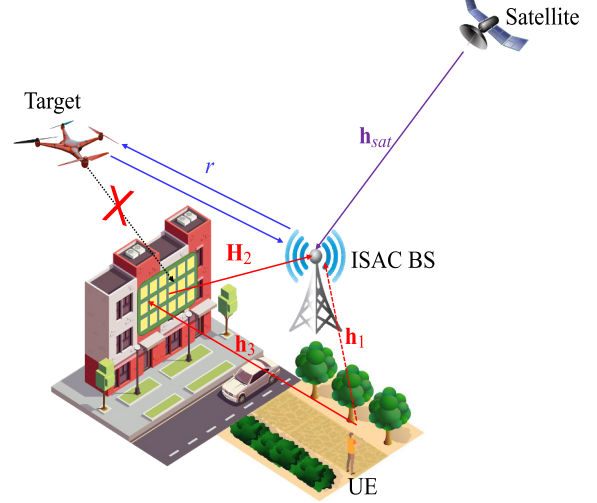


Fig. 1. The proposed STIN-ISAC-RIS system model.

of the satellite-BS link. $\mathbf{n}_{sat} \in \mathbb{C}^{N_r \times 1}$ is the AWGN for the satellite system with zero-mean and variance of σ_{sat}^2 .

The transmitted sensing signal from the ISAC BS is denoted by r . As shown in Fig. 1, it is assumed that the building conceals the RIS from the target. As a result, the reflected echoes of the target that travel towards the RIS are considered negligible. Thus, the sensing signal received at the ISAC BS, represented by $\mathbf{y}_3 \in \mathbb{C}^{N_r \times 1}$, is expressed as

$$\mathbf{y}_3 = \sqrt{P_s}\rho\mathbf{f}(\phi)\mathbf{g}^H(\phi)\mathbf{b}r + \mathbf{n}_s, \quad (3)$$

where P_s is the transmit power of the sensing signal and $(\cdot)^H$ is the conjugate transpose operator. ϕ represents the angle of the target in radians and ρ denotes the target reflection coefficient, which is the sensing parameter of interest in the proposed system. It is assumed that the amplitudes of the received radar pulses from the target follow a Rayleigh distribution (i.e., $\rho \sim \mathcal{CN}(0, 1)$) [16], [17]. $\mathbf{b} \in \mathbb{C}^{1 \times 1}$ is the beamforming vector. $\mathbf{n}_s \in \mathbb{C}^{N_r \times 1}$ is the AWGN for the sensing subsystem with zero-mean and variance of σ_s^2 , being independent of $\mathbf{n}_{ue}$ and $\mathbf{n}_{sat}$. $\mathbf{g}(\phi) \in \mathbb{C}^{1 \times 1}$ and $\mathbf{f}(\phi) \in \mathbb{C}^{N_r \times 1}$ are the transmit and receive steering vectors, respectively [18]. For simplicity, perfect tracking of the target by the radar is assumed, in which case $\mathbf{b} = \mathbf{g}(\phi)$ [16]. The joint received signal at the ISAC BS, $\mathbf{y} \in \mathbb{C}^{N_r \times 1}$ can be written as

$$\mathbf{y} = \dot{\mathbf{h}}_{ue}x_{ue} + \dot{\mathbf{h}}_{sat}x_{sat} + \sqrt{P_s}\rho\mathbf{f}(\phi)\mathbf{g}^H(\phi)\mathbf{b}r + \mathbf{n}, \quad (4)$$

where $\dot{\mathbf{h}}_{ue} = \sqrt{P_{ue}}(\mathbf{h}_1 + \mathbf{H}_2\mathbf{\Theta}\mathbf{h}_3)$, $\dot{\mathbf{h}}_{sat} = \sqrt{P_{sat}}\mathbf{h}_{sat}$, and $\mathbf{n} \sim \mathcal{CN}(0, \sigma^2) = \mathbf{n}_{sat} + \mathbf{n}_{sat} + \mathbf{n}_s$, with $\sigma^2 = \sigma_{ue}^2 + \sigma_{sat}^2 + \sigma_s^2$. The IC technique can be applied to process the communication signal first, where $\mathbf{y}_3$ and $\mathbf{n}$ are considered as aggregate interference and noise [19]. Thus, (4) can be rewritten as

$$\mathbf{y} = \dot{\mathbf{h}}_{ue}x_{ue} + \dot{\mathbf{h}}_{sat}x_{sat} + \mathbf{w}, \quad (5)$$

where $\mathbf{w} = \sqrt{P_s}\rho\mathbf{f}(\phi)\mathbf{g}^H(\phi)\mathbf{b}r + \mathbf{n}$.

III. PROPOSED DETECTION AND ESTIMATION ALGORITHMS

In this section, we propose algorithms to detect the communication symbols and estimate the reflection coefficients of the target in the proposed STIN model. It is worth mentioning that perfect knowledge of the channel state information is assumed at the ISAC BS.

A. Symbol Detection

The ML detection algorithm is proposed to jointly detect the transmitted UE and satellite symbols. This technique solves the detection problem by simultaneously searching the entire constellation spaces of the UE and satellite symbols. The ML detection algorithm finds the pair of the UE and satellite symbols that minimize the Euclidean distance criterion as

$$\begin{aligned} \hat{\mathbf{x}} &= \arg \min \|\mathbf{y} - \mathbf{h}_{ue}x_{ue}^* - \mathbf{h}_{sat}x_{sat}^*\|^2, \\ \text{s.t. } x_{ue}^* &\in \mathcal{C}, x_{sat}^* \in \mathcal{S} \end{aligned} \quad (6)$$

where $\hat{\mathbf{x}} = \{\hat{x}_{ue}, \hat{x}_{sat}\}$ is the estimated set of UE and satellite symbols, and $\mathcal{C}$ and $\mathcal{S}$ represent the constellation sets of the UE and satellite symbols, respectively. Here, x^* denotes a candidate solution. Equation (6) can be expanded as

$$\begin{aligned} \hat{\mathbf{x}} &= \arg \min \|\mathbf{h}_{ue}x_{ue} + \mathbf{h}_{sat}x_{sat} + \mathbf{w} - \mathbf{h}_{ue}x_{ue}^* - \mathbf{h}_{sat}x_{sat}^*\|^2, \\ \text{s.t. } x_{ue}^* &\in \mathcal{C}, x_{sat}^* \in \mathcal{S} \\ &= \arg \min \|\mathbf{h}_{ue}(x_{ue} - x_{ue}^*) + \mathbf{h}_{sat}(x_{sat} - x_{sat}^*) + \mathbf{w}\|^2 \\ &= \arg \min \|\Delta_{ue} + \Delta_{sat} + \mathbf{w}\|^2, \end{aligned} \quad (7)$$

where Δ_{ue} and Δ_{sat} represent the detection errors of the UE and satellite transmissions, respectively. The ML detection algorithm achieves optimum detection performance, which guarantees that in high signal to interference plus noise ratio (SINR) conditions, $\hat{x}_{ue} \rightarrow x_{ue}$ and $\hat{x}_{sat} \rightarrow x_{sat}$. As a result, both Δ_{ue} and Δ_{sat} approach 0. Hence, it can be deduced that the distance metric of the optimum pair of UE and satellite symbols tends to $\|\mathbf{w}\|^2$. A pseudo-code for the ML detection algorithm is presented in Algorithm 1.

B. Estimation of Target Reflection Coefficients

Based on the IC framework in [19], after detection, $\hat{x}_{ue}$ and $\hat{x}_{sat}$ are removed from $\mathbf{y}$ to obtain an estimate of the received sensing signal, $\tilde{\mathbf{y}}_3 \in \mathbb{C}^{N_r \times 1}$ as

$$\begin{aligned} \tilde{\mathbf{y}}_3 &= \mathbf{y} - \mathbf{h}_{ue}\hat{x}_{ue} - \mathbf{h}_{sat}\hat{x}_{sat} \\ &= \sqrt{\beta}\rho\mathbf{f}(\phi)\mathbf{g}^H(\phi)\mathbf{b}\mathbf{r} + \mathbf{n} + \Delta_{ue} + \Delta_{sat}, \end{aligned} \quad (8)$$

with Δ_{ue} and Δ_{sat} becoming negligible in high communication SINR conditions, the MMSE estimator solves the sensing parameter estimation problem in (8) as [16]

$$\hat{\rho} = \mathbf{a}^H [\mathbf{a}^H \mathbf{a} + \sigma^2 \mathbf{I}]^{-1} \tilde{\mathbf{y}}_3, \quad (9)$$

where $\mathbf{a} \in \mathbb{C}^{N_r \times 1} = \sqrt{P_s}\mathbf{f}(\phi)\mathbf{g}^H(\phi)\mathbf{b}$.

IV. COMPUTATIONAL COMPLEXITY ANALYSIS

The computational complexities of the proposed ML detection algorithm and MMSE estimation technique are presented in this section. In the ML detection algorithm, the size of the search space, denoted by $\mathcal{O}_{ML}$, as well as the number of real additions (RA) and real multiplications (RM), $\mathcal{RA}_{ML}$ and $\mathcal{RM}_{ML}$ respectively, are used as metrics for computational complexity. Here, the search space refers to the number of candidate solutions the ML algorithm considers to determine an actual solution. For the MMSE estimation method, the number of RA and RM required, $\mathcal{RA}_{MMSE}$ and $\mathcal{RM}_{MMSE}$, respectively are used as factors to evaluate the complexity.

Algorithm 1 Pseudo-Code of the ML Detection Algorithm

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1: Initialize  $\mathbf{d} = [d_{1,1}, d_{1,2}, \dots, d_{1,M_{ue} \cdot M_{sat}}]$  to store the
   Euclidean distances of UE and satellite symbol combinations;
2: for  $i = 1 : \text{card}(\mathcal{C})$ , do
3:   for  $j = 1 : \text{card}(\mathcal{S})$ , do
4:     Compute  $d_{i,j} = \|\mathbf{y} - \mathbf{h}_{ue}\mathcal{C}_i - \mathbf{h}_{sat}\mathcal{S}_j\|^2, \forall \mathcal{C}, \mathcal{S}$ ;
5:   end for
6: end for
7: Sort  $\mathbf{d}$  in ascending order;
8: Output  $\hat{x}_{ue}$  that corresponds to  $\arg \min(\mathbf{d})$ ;
9: Output  $\hat{x}_{sat}$  that corresponds to  $\arg \min(\mathbf{d})$ ;

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Suppose M_{ue} and M_{sat} represent the modulation order for the UE and satellite symbols, respectively. Because the ML detection algorithm determines a solution by considering all combinations of UE and satellite symbols, then the search space in the proposed SIMO scheme is given by

$$\mathcal{O}_{ML} = M_{ue} \cdot M_{sat}. \quad (10)$$

In equation (6), each product computation of the terms $\mathbf{h}_{ue}x_{ue}$ and $\mathbf{h}_{sat}x_{sat}$ requires $2N_r$ RA and $4N_r$ RM. Next, let $\tilde{\mathbf{y}} = \mathbf{y} - \mathbf{h}_{ue}x_{ue} - \mathbf{h}_{sat}x_{sat}$. Calculating $\tilde{\mathbf{y}}$ involves $4N_r$ RA and no RM since this is only a computation of the difference. The operation $\|\tilde{\mathbf{y}}\|^2$ can be interpreted as the inner product of $\tilde{\mathbf{y}}^H \cdot \tilde{\mathbf{y}}$. Thus, this operation requires $4N_r - 2$ RA and $4N_r$ RM. It should be recalled that the ML detection algorithm performs these calculations for each symbol pair from the UE and satellite, which corresponds to the search space. Consequently, the expressions for the number of RA and RM for ML detection are derived as

$$\mathcal{RA}_{ML} = \mathcal{O}_{ML} \cdot (12N_r - 2), \quad (11)$$

and

$$\mathcal{RM}_{ML} = \mathcal{O}_{ML} \cdot 12N_r. \quad (12)$$

Similarly, the number of RA and RM of the MMSE estimator, $\mathcal{RA}_{MMSE}$ and $\mathcal{RM}_{MMSE}$ respectively, can be calculated as

$$\mathcal{RA}_{MMSE} = 14N_r - 1, \quad (13)$$

and

$$\mathcal{RM}_{MMSE} = 20N_r + 6. \quad (14)$$

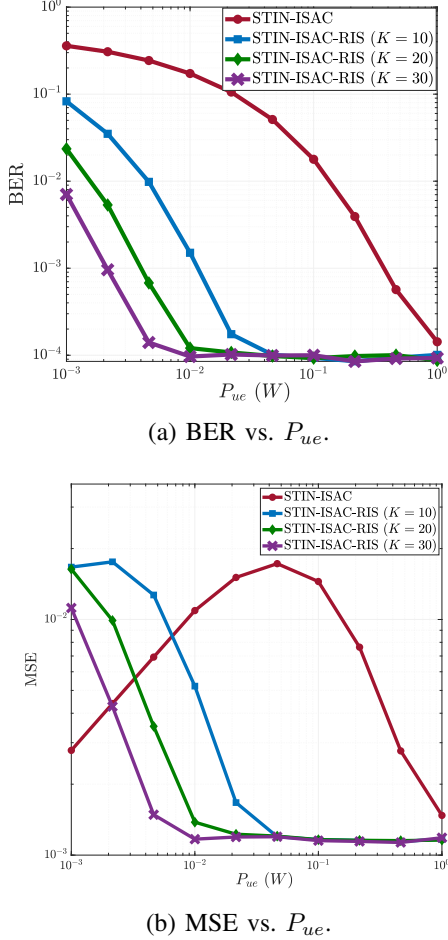


Fig. 2. BER and MSE performance of the STIN-ISAC-RIS system versus varying P_{ue} .

V. NUMERICAL RESULTS

In this section, the performance of the ML detection algorithm and MMSE estimator are presented and assessed in terms of the bit-error rate (BER) and MSE, respectively. In this case, the BER is the average of the error rates in the UE and satellite symbol detection. The sub-band division duplex scheme discussed in [20] is considered. The following parameters are used in the Monte Carlo simulation: $N_r = 8$, $P_s = 1$ W, and $K = 0, 10, 20$, and 30 . x_{ue} and r are both modulated using 4-quadrature amplitude modulation (QAM), whilst x_{sat} is modulated using 8-phase shift keying (PSK) [21]. The RIS phase shifts are optimized using the alternate optimization (AO) technique in [22]. $\mathbf{h}_1$ is modeled as a Rayleigh distribution due to the high scattering environment (i.e., $\mathbf{h}_1 \sim \mathcal{CN}(0, 1)$), whereas $\mathbf{H}_2$ and $\mathbf{h}_3$ are both modeled as Rician fading channels with a Rician factor $\Omega_{dB} = 7$ dB [12]. The satellite channel, $\mathbf{h}_{sat}$ is modeled using the shadowed Rician model in [23]. The maximum value of P_{sat} is set at 10 W [10].

In Fig. 2, P_{ue} is varied within the range of 1 mW to 1 W whilst P_{sat} is fixed at 3 W. Fig. 2(a) shows the

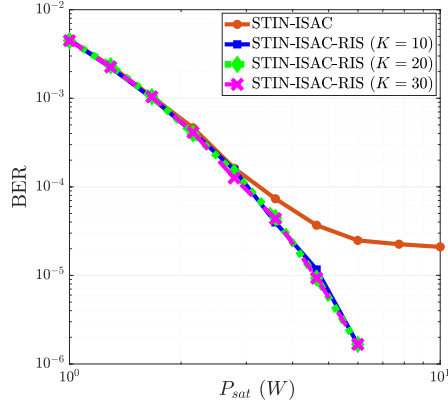
BER performance of the ML detector versus P_{ue} . It can be observed that the STIN-ISAC-RIS systems show superior performance to that of the STIN-ISAC system. Further, by increasing K , a considerable improvement in the BER is noticed. This is mainly due to the communication SINR gain in the terrestrial network in the presence of an increasing number of optimized RIS phase shifts, leading to improved detection of x_{ue} and $\Delta_{ue} \rightarrow 0$ as seen in equation (6). The convergence region in Fig. 2(a) is a result of averaging the varying BER of x_{ue} and nearly constant BER of x_{sat} , arising from a fixed, relatively higher P_{sat} . The MSE performance of the MMSE estimator versus P_{ue} is presented in Fig. 2(b). In the STIN-ISAC scenario, lower values of P_{ue} introduce Δ_{ue} due to low SINR, which degrades the performance of the MMSE estimator. Above $P_{ue} = 0.1$ W in the STIN-ISAC case, the MSE performance improves as a result of Δ_{ue} tending to 0. The UE communication SINR is enhanced in the presence of RIS, leading to significantly reduced Δ_{ue} as K is increased. Consequently, there is a notable improvement in MSE performance for the STIN-ISAC-RIS cases in the region above $P_{ue} = 1$ mW.

Fig. 3 depicts the results of varying P_{sat} while keeping P_{ue} fixed. P_{sat} is varied within the range of 3 W to 10 W, whereas P_{ue} is kept at 1 W. In Fig. 3(a), the presence of RIS within the STIN-ISAC-RIS system contributes to improved BER performance when compared to the STIN-ISAC scenario. The MSE performance in Fig. 3(b) also indicates an improved estimation of ρ in the STIN-ISAC-RIS system. This is because whilst $\Delta_{sat} \rightarrow 0$ owing to an increase in P_{sat} , Δ_{ue} also approaches 0 as a result of the gain introduced by RIS. Hence, $\Delta_{sat} + \Delta_{ue} \rightarrow 0$, which leads to very minimal detection error propagated to the MMSE estimator.

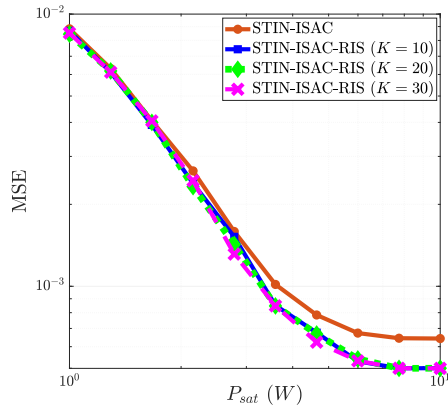
Based on the computational complexity equations in Section IV, the ML detection algorithm requires 3,008 RA and 3,072 RM, as well as a search space size of 32. Similarly, the MMSE estimator requires 111 RA and 166 RM.

VI. CONCLUSION

This paper presented a STIN model whose terrestrial component adopts an ISAC-RIS scenario, which is named STIN-ISAC-RIS. The RIS phase shifts were optimized using the AO method to enhance the terrestrial communication in the presence of the downlink satellite signal. Based on the proposed STIN-ISAC-RIS system model, a mathematical formulation for the joint received signal was presented. The ML detection algorithm was employed to jointly detect both the uplink UE and downlink satellite signals in the STIN-ISAC-RIS system. By adopting an IC approach to process the communication and sensing signals, the MMSE estimator was utilized after detection to calculate the reflection coefficients of a target in the STIN-ISAC-RIS scenario. The results showed that the STIN-RIS-ISAC system offered better BER and MSE performance for communication and sensing, respectively, compared to that of the STIN-ISAC system.



(a) BER vs. P_{sat} .



(b) MSE vs. P_{sat} .

Fig. 3. BER and MSE performance of the STIN-ISAC-RIS system versus varying P_{sat} .

This behavior was due to the SINR gain introduced by the optimized phase shifts of the RIS, which significantly improved the quality of signal detection and also reduced the effect of error propagation. The computational complexities of the ML detection algorithm and MMSE estimator were analyzed, and theoretical formulations were derived for the complexity metrics. The results showed that the ML detection algorithm incurred high computational costs, whereas the MMSE estimator had a reasonable complexity. The derivations for the complexity metrics also serve as benchmarks to compare the complexities of other detection and estimation algorithms in the future.

VII. ACKNOWLEDGEMENT

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