






Angle of Arrival Based Signal Classification in Intelligent Reflecting Surface-Aided Wireless Communications

Haolin Tang¹✉, Yanxiao Zhao¹, and Wei Wang²

¹ Department of Electrical and Computer Engineering, Virginia Commonwealth University, Richmond, VA 23284, USA

{tangh4, yzhao7}@vcu.edu

² Department of Computer Science, San Diego State University, San Diego, CA 92115, USA

wwang@sdsu.edu

Abstract. Intelligent Reflecting Surface (IRS) has been recognized as a promising technology for future wireless communications. It can reconfigure the radio signal propagation environment and improve the performance of wireless networks. However, this attractive strength of the IRS is grounded on a commonly perceived assumption that the IRS is able to distinguish the incoming signals so that IRS can be controlled to either improve or reduce the total received signal strength at a receiver. The signal differentiation issue for IRS is overlooked in the literature. To tackle this challenge, this paper proposes a solution that integrates an Angle of Arrival (AoA) algorithm into IRS systems. First, we propose a new idea that IRS can work as smart antenna by a hybrid architecture, i.e., all elements are passive except for a few active sensing elements. The active elements can collaboratively serve as a smart antenna. Second, the MUSIC (Multiple Signal Classification) AoA algorithm is applied to this hybrid IRS architecture to classify the incoming signal directions due to its advantages of simple implementation and high resolution. Last, extensive simulations are conducted to evaluate the classification performance of the proposed method under various scenarios. The simulation results demonstrate the effectiveness and accuracy of our approach.

Keywords: Intelligent reflecting surface · Spectrum sensing · Angle of arrival · MUSIC · Signal classification

1 Introduction

In the last decade, we have witnessed the rapid evolution of wireless communication which has become an essential part of our daily lives than ever before. Academia, industries and governments are continually making every effort to further enhance the performance of Fifth-Generation (5G) and Next Generation

(NextG) wireless networks. Recently, Intelligent Reflecting Surface (IRS) as a new emerging and promising technology has been investigated and adopted for wireless communications due to its capability of reconfiguring wireless communication environment. IRS typically consists of a large number of low-cost passive reflecting elements, which are able to reflect the incident wireless signal with an adjustable phase shift. The reflected signals by IRS can be constructively or destructively added at the receiver by jointly adjusting the phase shifts of all reflecting elements [1–4]. Consequently, the desired signal will be enhanced or the undesired signal (e.g., jamming signal) will be suppressed at the receiver. In recent research of IRS-aided wireless communications, the majority works focus on the optimization of the phase shift coefficient at the IRS taking some constraints (e.g., total transmit power, the existence of eavesdroppers, etc.) into consideration [5–8]. However, these works are based on a strong assumption that the IRS knows the sources of its received signals. For instance, an IRS receives an intended signal or a jamming signal along with some signals from unknown sources. The IRS needs to strengthen the intended signal or mitigate the jamming signal for the legitimate receiver by adjusting the phase shift dynamically. This service essentially depends on the fact that the IRS distinctly knows the sources of each signal in advance.

From the above mentioned, we conclude that it is imperative to develop a new approach to help IRS to determine which signal is to be reflected in order to enhance or suppress accordingly. In this paper, we address this problem and propose a promising classification method based on incoming signal's Angle of Arrivals (AoA) for IRS-aided system. The new idea is to enable IRS as smart antenna by proposing a hybrid IRS architecture, which consists of dominant passive elements, and a small number of active sensing elements, so that it works as a smart antenna array. Consequently, the active sensing elements enable the IRS to detect the arrival angles of all incoming signals. Therefore, if the location information of signal sources is known in advance, the IRS is able to determine whether its received signals are from the known sources or not.

The contributions of this paper can be summarized as follows.

- We propose a new idea that enables IRS to work as a smart antenna in a hybrid architecture where all the elements are passive except for a few active sensing elements, which are linearly arranged. The small number of active elements work collaboratively to act as a linear antenna array.
- The MUSIC (MULTiple SIGNAL Classification) AoA algorithm is employed to classify the signals from different sources since it has several advantages, e.g., higher resolution and less implementation cost. MUSIC algorithm plots a spatial spectrum in which the peaks indicate the arrival angles from distinct signal sources.
- Various simulations are conducted for evaluations and the results demonstrate the MUSIC AoA algorithm effects in the most simulation scenarios. The relation between the number of the active elements and the performance is investigated. In addition, the detectable angle difference is discussed.

The remainder of the paper is organized as follows. Section 2 briefly reviews the recent deployments of the IRS in wireless communications and introduce the AoA estimation. Section 3 proposes a new IRS architecture and formulate the MUSIC AoA based signal classification approach. Simulations in different scenarios are conducted to evaluate the classification performance in Sect. 4.

2 Related Works

2.1 Intelligent Reflecting Surface-Aided Wireless Communication

IRS has been proposed to reduce energy consumption and improve the performance of wireless communications [4]. Basically, IRS is a planar surface which is constructed by a large number of reconfigurable reflecting elements and is controlled by a smart controller [9]. The IRS reflecting elements thus can change the phases and/or amplitudes of the incident signals, thereby enhancing desired signals or mitigating undesired signals. IRS is typically used to enhance secrecy rate or Signal-to-Noise Ratio (SNR) of the communication system and hence to protect the quality of wireless communications between legitimate users [7]. [1] presents an IRS-aided wireless communication system for security where an Access Point (AP) sends confidential messages to a user in the presence of an eavesdropper. To improve the secrecy rate of the communication system, an optimization algorithm is proposed by jointly designing the AP's transmit beamforming and the IRS's reflect beamforming. In [5], IRS is used for mitigating inter-cell interference in cellular communication system. They also analyze the IRS placement optimization problem to make the most use of IRS. An IRS assisted Guassian Multiple-Input Multiple-Output (MIMO) wiretap channel is carefully considered in [10]. They propose an alternative joint optimization algorithm to optimize the transmit covariance at transmitter and phase shift coefficient at IRS to maximize the secrecy rate. In short, the majority of recent IRS-related research focuses on optimizing the IRS with some constraints to improve the overall performance of wireless communications. However, there is an overlooked problem in the above deployments of the IRS. In a practical wireless signal propagation environment, the IRS may receive signals not only from the desired transmitter but also from other unknown sources. The successful implementation of the IRS thus depends on whether the IRS is able to identify the source of the incoming signals.

2.2 Angle of Arrival Estimation

AoA estimation methods allow a device to identify the arrival angle of the incident signals by examining the differences in the received signal across the antenna elements [11]. Spectrum sensing-based AoA methods, including Bartlett, MUSIC and Capon methods, have been studied extensively [12–14]. In this paper, the MUSIC AoA based sensing approach is selected to classify the sources of the incoming signals, because MUSIC algorithm provides high precision measurement and measures multiple signals simultaneously [15]. Furthermore, it can

achieve real-time processing using high-speed processing technology. The MUSIC algorithm works by conducting characteristic decomposition for the covariance matrix associated with any array output data, resulting in a signal subspace orthogonal to the noise subspace that corresponds to the signal components. Then the two orthogonal subspaces are used to construct a spectrum function to estimate the arrival angle of the incident signals.

3 System Model and Proposed Methodology

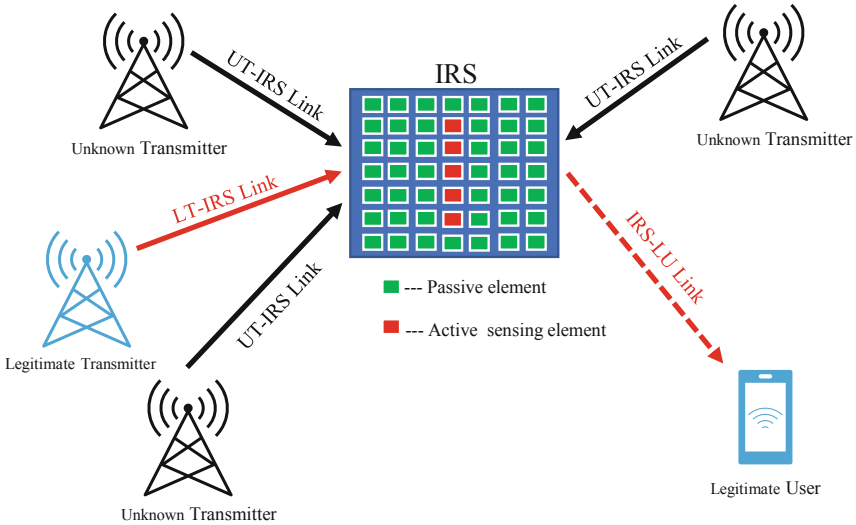


Fig. 1. Illustration of an IRS-aided communication, including a legitimate transmitter and user, and the unknown transmitters. IRS is deployed to improve the communication performance between the legitimate transmitter and user.

3.1 System Model

As discussed previously, we propose to enable IRS to distinguish signals from different sources by measuring their arrival angles. To implement this, we adopt a hybrid IRS architecture which is constructed by dominant passive reflecting elements along with a small number of active sensing elements. In particular, the active elements have two functional modes: (i) spectrum sensing mode where they work as a set of multiple connected adaptive array antennas (i.e., smart antenna), and (ii) reflecting mode where they merely reflect the incoming signals passively. Consider an IRS-aided wireless communication network, as depicted in Fig. 1, including a legitimate transmitter, a legitimate user and the unknown transmitters (e.g., malicious users or attackers). The IRS with the proposed

architecture is deployed to improve the communication performance between the legitimate transmitter and user. Specifically, the IRS receives the signal from the legitimate transmitter (via LT-IRS link) and signal from the unknown transmitters (via UT-IRS links). The IRS is required to identify the signal from the legitimate transmitter and then reflect the signal to the legitimate user (via IRS-LU link). We assume all the transmitters are equipped with omni-directional antennas, while the IRS has M active sensing elements which comprise a smart antenna array. The direction or angle information of the legitimate transmitter is assumed available, which can be acquired by many methods. For instance, if the location of the legitimate transmitter is denoted as (x_1, y_1) and the location of the IRS is denoted as (x_2, y_2) . It is straightforward to calculate the actual angle observed at the IRS is $\theta = \arctan \frac{|y_1 - y_2|}{|x_1 - x_2|}$ from the legitimate transmitter. In such a communication system, an AoA based method can be applied to estimate the angle of the incoming signals. Therefore, a decision whether the signal originates from the legitimate transmitter or not can be made by comparing the estimated and actual arrival angles. For instance, if the angle from the legitimate transmitter to the IRS, denoted by θ_i , is given in advance and the estimated angle of an incoming signal is denoted by $\hat{\theta}_i$. We can determine the incoming signal is from the legitimate transmitter when $|\theta_i - \hat{\theta}_i| \leq \Delta\phi$ holds, where $\Delta\phi$ indicates the detectable angle difference and will be discussed in Sect. 4.

3.2 AoA Based Signal Classification

With the hybrid architecture described in Fig. 1, IRS is able to behave as smart antenna, so that AoA based spectrum sensing approaches are feasible to estimate the angles of incoming signals [14, 16]. This subsection first briefly introduces typical AoA technology, then MUSIC AoA is selected for signal classification in our paper since it provides a higher resolution, less computation, and better robustness.

Assume there are D signal sources from the legitimate transmitter and the unknown transmitters to the IRS, and let $\mathbf{s}(t) = [s_1(t), s_2(t), \dots, s_D(t)]^\top$ represents the vector of source signal values from D sources at a discrete time t . At this time, the active elements of the IRS are on the spectrum sensing mode and we assume the M active sensing elements lays on the IRS linearly with equal spacing, denoted by d . Such that the active elements construct a liner antenna array with M identical elements. Each active sensing element receives signals from all D sources along with the noise. At the i^{th} ($i = 1, 2, \dots, M$) element, the received signal thus can be expressed as

$$x_i(t) = \sum_{k=1}^D a_{ik}(t)s_k(t) + n_i(t), \quad (1)$$

where $a_{ik}(t)$ is the steering factor from the source k to the active element i and $n_i(t)$ represents the additive white Gaussian noise. We can rewrite this equation into a compact matrix form as

$$\mathbf{x} = \mathbf{A}\mathbf{s} + \mathbf{n}, \quad (2)$$

where $\mathbf{x}(t) = [x_1(t), x_2(t), \dots, x_M(t)]^\top$ is an $M \times 1$ vector of the received signal and additive noise. Here $\mathbf{A} = [\mathbf{a}(\theta_1), \dots, \mathbf{a}(\theta_k)]$ is an $M \times D$ Vandermonde matrix of steering vectors $\mathbf{a}(\theta_k) = [1, e^{-j2\pi\lambda \sin(\theta_k)/d}, \dots, e^{-j2\pi(M-1)\lambda \sin(\theta_k)/d}]^\top$. \mathbf{n} is an $M \times 1$ vector of the channel noise.

Thus, the $M \times M$ array correlation matrix of \mathbf{x} can be expressed as

$$\mathbf{R}_{xx} = \mathbb{E}[\mathbf{x} \cdot \mathbf{x}^H] = \mathbb{E}[(\mathbf{A}\mathbf{s} + \mathbf{n}) \cdot (\mathbf{A}\mathbf{s} + \mathbf{n})^H] = \mathbf{A}\mathbf{R}_{ss}\mathbf{A}^H + \sigma_n^2\mathbf{I}_D, \quad (3)$$

where \mathbf{R}_{ss} represents the correlation matrix of the source signal vector \mathbf{s} and σ_n^2 indicates the noise variance. \mathbf{I}_D is a $D \times D$ identity matrix and H indicates the operation of conjugate transpose.

The purpose of the AoA estimation is to construct a function that determines the angles of the incoming signals using Pseudo spectrum, $P(\theta)$. Several off-the-shelf approaches are available to construct $P(\theta)$. We select the MUSIC AoA algorithm due to its advantages in higher resolution, less computation, and better robustness.

Let \mathbf{u}_i be one of the eigenvector of \mathbf{R}_{xx} corresponding to the eigenvalue σ_i^2 , where $i = 1, 2, \dots, M$. Then,

$$\mathbf{R}_{xx}\mathbf{u}_i = \mathbf{A}\mathbf{R}_{ss}\mathbf{A}^H\mathbf{u}_i + \sigma_n^2\mathbf{I}_D\mathbf{u}_i = \sigma_i^2\mathbf{u}_i. \quad (4)$$

Here $M > D$ such that $\sigma_i^2 > \sigma_n^2 > 0$ for $i = 1, 2, \dots, D$ and $\sigma_i^2 = \sigma_n^2$ for $i = D + 1, \dots, M$. Thus, we conclude

$$\mathbf{A}\mathbf{R}_{ss}\mathbf{A}^H = \begin{cases} (\sigma_i^2 - \sigma_n^2)\mathbf{u}_i, & \text{if } i = 1, 2, \dots, D \\ 0, & \text{if } i = D + 1, \dots, M. \end{cases} \quad (5)$$

We can split the M -dimensional vector space into two subspaces since $\mathbf{A}\mathbf{R}_{ss}\mathbf{A}^H$ has D positive real eigenvalues and $(M - D)$ zero eigenvalues. The eigenvectors corresponding to the positive eigenvalues span the signal subspace, \mathbf{U}_s . The eigenvectors corresponding to the zero eigenvalues are orthogonal to the signal space and span the null subspace, \mathbf{U}_n . The MUSIC algorithm searches for all arrival angles θ , and the spatial spectrum over the angle space is given by

$$P_{MUSIC}(\theta) = \frac{1}{\mathbf{a}^H(\theta_k)\mathbf{U}_n}. \quad (6)$$

Specially, the steering vector $\mathbf{a}(\theta_k)$ is only in the signal space which results in $\mathbf{a}^H(\theta)\mathbf{U}_n = 0$. From the Eq. 6, we can conclude that $P_{MUSIC}(\theta)$ shows a peak when $\theta = \theta_k$. It indicates that a peak should only appear at the angle from which a signal originates. Therefore, finding the estimated arrival angle corresponds to finding the peak in the spatial spectrum. That is, the angle of incoming signal is estimated as

$$\hat{\theta} = \arg \max_{\theta} P_{MUSIC}(\theta). \quad (7)$$

Comparing the estimated arrival angle $\hat{\theta}$ with the angle of legitimate transmitter known in advance, we can classify the signal sources and determine which signal

is from the legitimate transmitter or the unknown transmitters. After the signal classification, the active elements of the IRS will be on the reflecting mode and collaborate with the passive elements to reflect the identified signal from the legitimate transmitter to the legitimate user.

4 Numerical Results

This section evaluates the performance of the AoA based signal classification method in two scenarios for IRS-aided wireless communications. The impact of factors such as the number of active sensing elements on the IRS and the angle of signal sources is investigated. The first scenario analyzes the relationship between the classification accuracy and the number of active sensing elements in the MUSIC AoA algorithm. We consider that there are four signal sources, including a legitimate transmitter and three unknown transmitters, in an IRS-aided wireless communication system. The corresponding angles to the IRS are $\theta_1 = -20^\circ$, $\theta_2 = -10^\circ$, $\theta_3 = 10^\circ$, and $\theta_4 = 20^\circ$, respectively. In addition, we conduct simulations for 5, 10 and 15 active sensing elements. Figure 2 shows the MUSIC AoA algorithm spectrum results. It shows four peaks (angles of the source signals) exactly at $\theta_1 = -20^\circ$, $\theta_2 = -10^\circ$, $\theta_3 = 10^\circ$, and $\theta_4 = 20^\circ$. This demonstrates the MUSIC AoA algorithm can classify the incoming signals successfully with high accuracy. If we know the actual angle from the legitimate

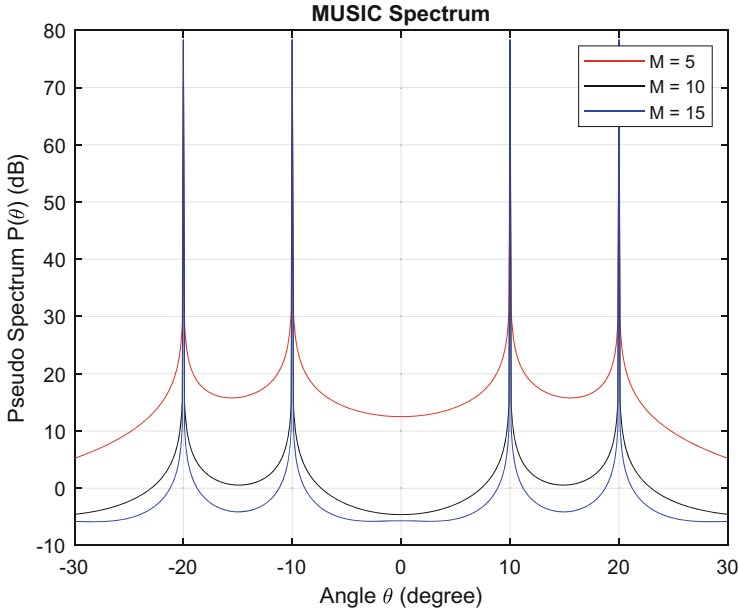


Fig. 2. Illustration of pseudo spectrum $P_{MUSIC}(\theta)$ with 5, 10 and 15 active sensing elements on IRS for four signal sources ($\theta_1 = -20^\circ$, $\theta_2 = -10^\circ$, $\theta_3 = 10^\circ$).

transmitter to the IRS is $\theta = 10^\circ$ in advance, the result suggests that the signal from the legitimate transmitter is identified accurately. The IRS can reflect the identified signal accordingly to the legitimate user. Specially, if the direction or angle information of the three unknown transmitters is accessible, the signals from them can also be recognized successfully which indicates the MUSIC AoA algorithm can classify multiple signals simultaneously. Moreover, we can conclude the relation between the classification accuracy and the number of the active sensing elements from the spectrum results. With more active sensing elements, classification accuracy increases.

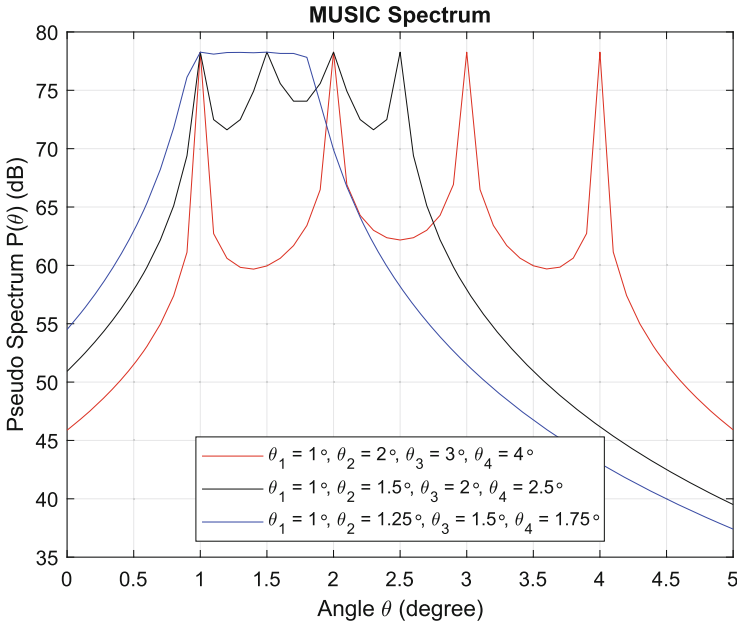


Fig. 3. Illustration of pseudo spectrum $P_{MUSIC}(\theta)$ with 5 active sensing elements on IRS for four signal sources with three angles sets.

In the second scenario, we explore the detectable angle difference $\Delta\phi$ for the MUSIC AoA approach when the signal sources are close to each other. The number of the active sensing elements on IRS is configured as $M = 5$. Similar with the first scenario, four signal sources are considered. We conduct simulations for three sets of angles, i.e. $(\theta_1 = 1^\circ, \theta_2 = 2^\circ, \theta_3 = 3^\circ, \theta_4 = 4^\circ)$, $(\theta_1 = 1^\circ, \theta_2 = 1.5^\circ, \theta_3 = 2^\circ, \theta_4 = 2.5^\circ)$ and $(\theta_1 = 1^\circ, \theta_2 = 1.25^\circ, \theta_3 = 1.5^\circ, \theta_4 = 1.75^\circ)$. The angle differences of the three angles sets are $1^\circ, 0.5^\circ$ and 0.25° , respectively. Figure 3 exhibits the results, from which it can be observed that four peaks appear distinctly and indicates the angles of source signals accurately for the first set. From the results for the second set, it shows that the MUSIC AoA algorithm can still detect all signal sources in spite of the lower resolution.

However, the four signals are detected as the same in the results of the last angles set. The MUSIC AoA algorithm fails to detect the signal sources when the angles become very closer. This failure may lead a threat to the legitimate user. For instance, if a malicious attacker exists closely with the legitimate transmitter, the IRS can not identify the signal sources and thus may reflect the attacking signals to the legitimate user.

Overall, MUSIC AoA based signal classification method can detect and classify multiple signal sources effectively when the signal sources are separated sufficiently far and we suggest the detectable angle difference $\Delta\phi = 1^\circ$.

5 Conclusions

In this paper, we have pointed out an overlooked issue of signal differentiation using IRS in current research of IRS-aided wireless communications. In an IRS-aided environment, the IRS should have the ability to identify the signal sources so that it knows how to control phase shifts of reflecting elements correspondingly. To tackle this challenge, we propose a new idea that enable IRS to perform signal differentiation by adopting a hybrid IRS architecture, which consists of dominant passive elements and a few of active sensing elements. These active elements can serve as a linear antenna array. We then propose to utilize the active sensing elements to help an IRS to classify the signals between the legitimate transmitter and unknown transmitters leveraging an AoA based method. The MUSIC algorithm was selected for the AoA estimation and the performance was tested in two scenarios. The simulation results demonstrated that MUSIC AoA based signal classification is effective in general, except when the angles of sources are highly close to each other.

Acknowledgment. This research is partially supported by Commonwealth Cyber Initiative (CCI) and Virginia Commonwealth University (VCU) Presidential Research Quest Fund (PeRQ) award.

References

1. Cui, M., Zhang, G., Zhang, R.: Secure wireless communication via intelligent reflecting surface. *IEEE Wirel. Commun. Lett.* **8**(5), 1410–1414 (2019)
2. Shen, H., Wei, X., Gong, S., He, Z., Zhao, C.: Secrecy rate maximization for intelligent reflecting surface assisted multi-antenna communications. *IEEE Commun. Lett.* **23**(9), 1488–1492 (2019)
3. Sun, Y., An, K., Luo, J., Zhu, Y., Zheng, G., Chatzinotas, S.: Intelligent reflecting surface enhanced secure transmission against both jamming and eavesdropping attacks. *IEEE Trans. Veh. Technol.* **70**(10), 11017–11022 (2021)
4. Qingqing, W., Zhang, R.: Intelligent reflecting surface enhanced wireless network via joint active and passive beamforming. *IEEE Trans. Wireless Commun.* **18**(11), 5394–5409 (2019)
5. Hashida, H., Kawamoto, Y., Kato, N.: Intelligent reflecting surface placement optimization in air-ground communication networks toward 6G. *IEEE Wirel. Commun.* **27**(6), 146–151 (2020)

6. Qingqing, W., Zhang, R.: Towards smart and reconfigurable environment: intelligent reflecting surface aided wireless network. *IEEE Commun. Mag.* **58**(1), 106–112 (2019)
7. Wu, Q., Zhang, S., Zheng, B., You, C., Zhang, R.: Intelligent reflecting surface-aided wireless communications: a tutorial. *IEEE Trans. Commun.* **69**, 3313–3351 (2021)
8. Xianghao, Yu., Dongfang, X., Sun, Y., Ng, D.W.K., Schober, R.: Robust and secure wireless communications via intelligent reflecting surfaces. *IEEE J. Sel. Areas Commun.* **38**(11), 2637–2652 (2020)
9. Zhang, Z., Lv, L., Wu, Q., Deng, H., Chen, J.: Robust and secure communications in intelligent reflecting surface assisted NOMA networks. *IEEE Commun. Lett.* **25**(3), 739–743 (2020)
10. Dong, L., Wang, H.-M.: Secure MIMO transmission via intelligent reflecting surface. *IEEE Wirel. Commun. Lett.* **9**(6), 787–790 (2020)
11. Khan, A., Wang, S., Zhu, Z.: Angle-of-arrival estimation using an adaptive machine learning framework. *IEEE Commun. Lett.* **23**(2), 294–297 (2018)
12. Balanis, C.A.: *Antenna Theory: Analysis and Design*. John Wiley & Sons, Hoboken (2015)
13. Fried, D.L.: Differential angle of arrival: theory, evaluation, and measurement feasibility. *Radio Sci.* **10**(1), 71–76 (1975)
14. Gross, F. *Smart antennas for wireless communications*. McGraw-Hill Professional (2005)
15. Xie, J., Fu, Z., Xian, H.: Spectrum sensing based on estimation of direction of arrival. In: *International Conference on Computational Problem-solving*, pp. 39–42. IEEE (2010)
16. Zhao, Y., Huang, J., Wang, W., Zaman, R.: Detection of primary user's signal in cognitive radio networks: angle of arrival based approach. In: *2014 IEEE Global Communications Conference*, pp. 3062–3067. IEEE (2014)