RIS: Spatial-Wideband Effect Analysis and Off-Grid Channel Estimation

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Abstract: As a critical candidate technology for 5G-advanced and 6G, reconfigurable intelligent surfaces (RIS) have received extensive attention from academia and industry. RIS has the promising features of passiveness, reconfigurable ability, and low cost. RIS channel estimation faces the challenges of high matrix dimension, passive estimation, and spatial-wideband effect. In this article, we analyze the impact of the spatial-wideband effect on the RIS channel to account for the propagation delay across RIS elements and estimate sparse channel parameters such as angle and gain through a super-resolution compressive sensing (CS) algorithm. The simulation results explore the influence of the spatial-wideband effect on the RIS channel and verify the effectiveness of the proposed algorithm.

Keywords: RIS; channel estimation; spatial-wideband effect; compressed sensing

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1 Introduction

With the acceleration of 5G commercialization, research on 5G-advanced and 6G communication systems is in full swing. The scarcity of wireless spectrum resource has become severe[1], and the increasing network coverage, cost and energy efficiency requirements become a pain point restricting the mobile communication industry. New expediting study for innovative solutions is in urgent need. The reconfigurable intelligent surface (RIS), a cross-fusion of information metamaterials and mobile communications[2], is a new and revolutionary wireless communication enhancement technology. Its basic principle is to construct an intelligent and controllable environment by manipulating the electromagnetic property of metamaterials through digital programming with low-cost hardware architecture and tremendous flexibility.

It is necessary to obtain accurate channel state information (CSI) to support the promising capabilities of the RIS, such as expanding coverage, increasing transmission freedom, and conducting environmental perception and positioning. Different from the massive multiple input multiple output (MIMO), the RIS changes the electromagnetic wave propagation with segmented channels[3]. As RIS elements are passive and massive, it becomes challenging to estimate the channel.

Many channel estimation algorithms have been designed for RIS-assisted communications. In Ref. [4], a channel estimation method based on the ON-OFF approach is introduced, splitting the RIS into multiple elements and performing channel estimation separately for each element. In Ref. [5], the high-frequency scenario is considered, the low-rank property of the RIS channel is exploited, and a matrix filling problem is designed for channel estimation. The hybrid RIS architecture with sensing and signal processing ability is considered in Ref. [6], and the sparseness is utilized to obtain high-resolution channel parameters. To make full use of the collected data, a potential solution is to use the artificial intelligence (AI) method for channel estimation[7]. In addition, the position information is helpful for designing a low-complexity channel estimation method to obtain critical information such as the direction of arrival (DOA).

Moreover, as a RIS is usually large, new channel characteristics appear and affect channel estimation accuracy. New algorithms and protocols need to be designed to carry out practical channel estimation and avoid complicated onboard signal processing operations. Most existing works are based on the channel model directly extended from the traditional MIMO channel model[8], and the propagation delay is usually neglected. Different RIS elements receive signals with different path delays when a far-field signal impinges on the RIS. The delay between different elements can reach the same order of magnitude as the symbol interval, and different RIS elements will receive different amplitudes and phases of the identical symbol or even distinct symbols for the same sampling period. This phenomenon is called spatial-wideband effect. The frequency-wideband effect caused by multipath delay spread is considered in recent studies, while the spatial-wideband effect is always ignored. As a result, the beam generated for different frequencies cannot point toward the same direction, and reciprocally, the estimated incident angles are inaccurate if only the frequency-wideband effect is considered.

In Ref. [9], the influence of the spatial-wideband effect on the massive MIMO channel is discussed, and the transceiver is redesigned for orthogonal frequency-division multiplexing (OFDM) systems. In Ref. [10], the discrete-time channel for the hybrid mmWave massive MIMO system with the spatial-wideband effect is modeled and the wideband channel is estimated through the Newtonized fully corrective forward greedy selection-cross validation-based algorithm. The authors of Ref. [11] develop a spatial-wideband channel model for lens antenna arrays and design a fast angle estimation algorithm to establish point-to-point mappings between the spatial-frequency patterns and the strongest discrete Fourier transform beam containing the incident angle. Nevertheless, few work has considered the spatial-wideband channel model for RIS, and high-resolution RIS channel estimation approach is lacking.

In this paper, we analyze the frequency-dependent spatial-wideband effect for RIS-assisted communications and present a high-resolution channel estimation algorithm based on off-grid sparse Bayesian learning (SBL) approach. Simulation results are provided to verify the correctness of the spatial-wideband effect and the effectiveness of the proposed compressive sensing (CS) algorithm. Moreover, the challenges and promising directions of RIS future research are discussed.

2 Spatial-Wideband Channel Analysis

The array steering vector commonly used in MIMO is,

$$\boldsymbol{a}(\varphi) = \left[1, \quad e^{j2\pi d\sin\varphi/\lambda} \quad \dots \quad e^{j2\pi(N-1)d\sin\varphi/\lambda}\right], \tag{1}$$

where d is the antenna spacing, φ is the angle of arrival and λ is the wavelength. When the number of array elements is enormous and the transmission bandwidth is wide, for example, in a typical RIS-assisted communication, new affecting factors need to be considered.

In this paper, the millimeter frequency band is considered, the RIS is deployed in fixed locations such as building walls without mobility, and the BS is deployed at a high location with almost no obstacles around. The line-of-sight (LoS) path transmission between BS and RIS is usually stable and dominates the energy of the channel. In this way, the LoS assumption is adopted for the channel between BS and RIS. For RIS-assisted communications, the LoS channel can be obtained with prior knowledge of the location information and simple RIS signaling. The BS-RIS channel parameters can be conveyed to user equipment (UE) through the control channel for RIS-UE channel estimation. Multiple RIS-UE channel estimations are performed within a single BS-RIS channel estimation period as the BS-RIS channel changes slowly.

The RIS-UE channel with spatial-wideband effect is analyzed. For multipath propagation, the passband signal received by the (m,n)-th element of RIS is

$$\tilde{y}_{m,n}(t) = \left(\sum_{l=0}^{L-1}\beta_l e^{j2\pi f_c\left(t-\tau_{l,m,n}\right)}\delta\left(t-\tau_{l,m,n}\right)\right)\times s(t) + w_{m,n}(t), \tag{2}$$

where L is the path number, f_c is the carrier frequency, β_l is the l-th path gain, and $\tau_{l,m,n}$ is the delay of the l-th path received by the (m,n)-th RIS element. Since RIS is a two-dimensional planar structure, we have

$$\tau_{l,m,n} = \tau_l + m\frac{\psi^1}{f_c} + n\frac{\psi^2}{f_c}, \psi^1 = \frac{d\sin\varphi\cos\phi}{\lambda_c}, \psi^2 = \frac{d\cos\varphi}{\lambda_c}, \tag{3}$$

where τ_l denotes the delay of path l for the first RIS element, and $\varphi \in [0, 2\pi)$ and $\phi \in [0, \pi)$ are the azimuth and elevation angles.

As a result, the received baseband signal by the (m,n)-th RIS element in the time domain is

$$y_{m,n}(t) = \left(\sum_{l=0}^{L-1}\bar{\beta}_l e^{-j2\pi f_c\left(m\frac{\psi_l^1}{f_c}+n\frac{\psi_l^2}{f_c}\right)}\delta\left(t-\tau_l-m\frac{\psi_l^1}{f_c}-n\frac{\psi_l^2}{f_c}\right)\right)\times s(t) + w_{m,n}(t), \tag{4}$$

where $\bar{\beta}_l = \beta_l e^{-j2\pi f_c\tau_l}$ is the equivalent path gain for path l. Correspondingly, the received signal in the frequency domain is

$$y_{m,n}(f) = \left(\sum_{l=0}^{L-1}\bar{\beta}_l e^{-j2\pi f_c\left(m\frac{\psi_l^1}{f_c}+n\frac{\psi_l^2}{f_c}\right)} e^{-j2\pi f\left(m\frac{\psi_l^1}{f_c}+n\frac{\psi_l^2}{f_c}\right)}\right)s(f) + w_{m,n}(f) = \left(\sum_{l=0}^{L-1}\bar{\beta}_l e^{-j2\pi\left(m\psi_l^1+n\psi_l^2\right)\left(1+\frac{f}{f_c}\right)}\right)s(f) + w_{m,n}(f). \tag{5}$$

The frequency domain signals received on all RIS elements can be written in a matrix form as

$$\boldsymbol{Y}(f) = \left(\sum_{l=0}^{L-1}\bar{\beta}_l\boldsymbol{A}_R\left(\left(1+\frac{f}{f_c}\right)\psi_l^1, \left(1+\frac{f}{f_c}\right)\psi_l^2\right)\right)s(f) + \boldsymbol{W}(f), \tag{6}$$

where $\boldsymbol{A}_R$ is the uniform rectangular spatial-domain steering matrix with $\boldsymbol{A}_R(m,n) = e^{-j2\pi\left(m\psi_l^1+n\psi_l^2\right)\left(1+\frac{f}{f_c}\right)}$. Vectorization is performed, resulting in

$$\check{\mathbf{y}}(f) = \left(\sum_{l=0}^{L-1}\bar{\beta}_l\boldsymbol{a}_R\left(\left(1+\frac{f}{f_c}\right)\psi_l^1, \left(1+\frac{f}{f_c}\right)\psi_l^2\right)\right)s(f) + \boldsymbol{w}(f) = \boldsymbol{g}(f)s(f) + \boldsymbol{w}(f). \tag{7}$$

N-point OFDM modulation is adopted to overcome frequency selective fading, and the received signal can be arranged as

$$G = \left[g(0) \quad g(\Delta f) \quad \dots \quad g((N-1)\Delta f) \right] = \sum_{l=0}^{L-1} \bar{\beta}_l \boldsymbol{a}_R \left(\left(1 + \frac{f}{f_c}\right)\psi_l^1, \left(1 + \frac{f}{f_c}\right)\psi_l^2 \right) \boldsymbol{b}^T(\tau_l), \tag{8}$$

where $\boldsymbol{b}(\tau) = \left[e^{-j2\pi f \tau_l} \quad \dots \quad e^{-j2\pi(f + (N-1)\Delta f)\tau_l} \right]$.

For the spatial-narrowband case, the frequency-selective effect induced by the multipath delay spread is considered, while the spatial-selective effect is ignored. The approximation $s\left(t - \tau_l - m\frac{\psi_l^1}{f_c} - n\frac{\psi_l^2}{f_c}\right) \approx s(t - \tau_l)$ holds and the propagation delay across the RIS can be neglected. The spatial-narrowband channel can be represented by

$$\boldsymbol{G}_{Narrow} = \sum_{l=0}^{L-1} \bar{\beta}_l \boldsymbol{a}_R (\psi_l^1, \psi_l^2) \boldsymbol{b}^T(\tau_l). \tag{9}$$

It can be observed that, for spatial-narrowband signals, a fixed beam can be generated with no frequency dependence. However, the generated beam has slight variations of the antenna radiation pattern correlated with the frequency for spatial-wideband signals. This is the main difference between spatial-wideband and spatial-narrowband channels.

When a RIS is large enough and the signal bandwidth is wide enough, the physical propagation delay is non-negligible. The spatial-wideband effect brings challenging channel estimation difficulties and seriously affects system performance. Moreover, the inherent passive characteristics of the RIS pose the same phase shift for all frequencies. Thus, RIS elements cannot adapt to different received signal phases, and the spatial-wideband effect cannot be compensated. It is necessary to carefully design channel estimation and beamforming schemes for RIS with the spatial-wideband effect.

Through the above analysis, we have obtained the expression of the RIS-UE channel considering the spatial-wideband effect. The spatial-wideband OFDM channel can be represented by parameters including the angle, delay, and path gain. Once these parameters are obtained, the overall channel can be obtained easily.

For simplification, the received OFDM signal can be written as

$$\boldsymbol{y} = \sum_{l=0}^{L-1} \bar{\beta}_l vec\left[\boldsymbol{a}_R \left(\left(1 + \frac{f}{f_c}\right)\psi_l^1, \left(1 + \frac{f}{f_c}\right)\psi_l^2 \right) \boldsymbol{b}^T(\tau_l) \right] s + \boldsymbol{n} = \sum_{l=0}^{L-1} \bar{\beta}_l \boldsymbol{c}(\psi_l^1, \psi_l^2, \tau_l) s + \boldsymbol{n}, \tag{10}$$

where $\boldsymbol{c}(\psi_l^1, \psi_l^2, \tau_l) = vec\left[\boldsymbol{a}_R \left(\left(1 + \frac{f}{f_c}\right)\psi_l^1, \left(1 + \frac{f}{f_c}\right)\psi_l^2 \right) \boldsymbol{b}^T(\tau_l) \right]$.

Moreover, to estimate the RIS-UE channel from the received OFDM signal, a simple idea is to select part of the received signal to recover those parameters, avoiding the high dimension disadvantage.

3 Off-Grid CS Based Channel Estimation

To estimate the RIS channel with severe spatial-wideband effect, we design an off-grid SBL algorithm to estimate the channel parameters $\hat{\boldsymbol{\phi}}, \hat{\boldsymbol{\varphi}}, \hat{\boldsymbol{\tau}}$, and $\hat{\boldsymbol{\beta}}$. It should be noted that, according to the obtained parameters, we can not only recover the pilot channel but also recover the channel on all subcarriers and extrapolate it to the channel of the complete RIS.

On-grid CS algorithms such as orthogonal matching pursuit (OMP)[12] are hard to achieve satisfying performance with low complexity as the number of channel parameters is enormous. The SBL algorithm is adopted to achieve super-resolution parameter estimation performance. A parameterized dictionary with a varying grid is utilized to overcome the grid mismatch problem. According to Ref. [13], uniform distribution is adopted as a priori distribution for angle and delay parameters. In this way, the channel estimation problem can be transformed into maximizing the posterior probability of multidimensional variables of angle, delay, and channel gain jointly.

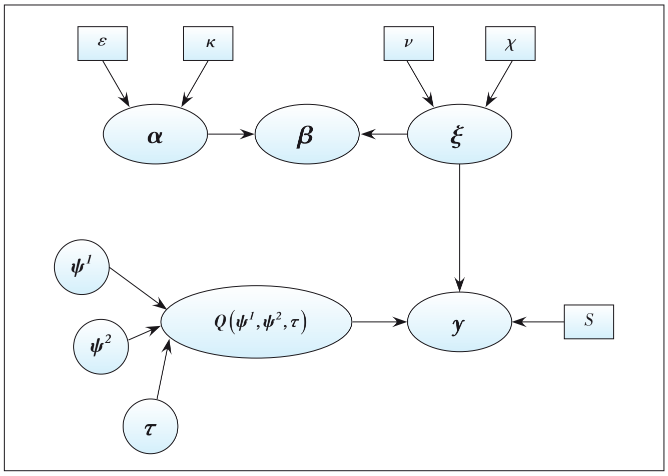
Define the dictionary as $\boldsymbol{Q}(\boldsymbol{\psi}^1, \boldsymbol{\psi}^2, \boldsymbol{\tau}) = \left[\boldsymbol{c}(\psi_1^1, \psi_1^2, \tau_1) \quad \dots \quad \boldsymbol{c}(\psi_D^1, \psi_D^2, \tau_D) \right]$, where D is the path number and the parameters of each column are variable. As the path number is unknown, D is set to be a relatively large value initially and adjusted by deleting or adding a new column $\boldsymbol{c}(\psi_t^1, \psi_t^2, \tau_t)$.

The posterior probability distribution function (PDF) of the received spatial-wideband OFDM signal is

$$p(\boldsymbol{y} | \boldsymbol{\psi}^1, \boldsymbol{\psi}^2, \boldsymbol{\tau}, \boldsymbol{\beta}, \xi) = CN\left((S^T \otimes \boldsymbol{I}) \times \boldsymbol{Q}(\boldsymbol{\psi}^1, \boldsymbol{\psi}^2, \boldsymbol{\tau}) \boldsymbol{\beta}, \xi^{-1} \boldsymbol{I} \right). \tag{11}$$

The Bayesian network of the RIS-UE channel model is shown in Fig. 1. The prior distribution assumption for noise inverse variance is gamma distribution. The channel gain obeys the two-layer prior model, where the first layer is the zero-mean Gaussian distribution w. r. t. hyperparameter vector α and the second layer follows gamma distribution $\Gamma(\cdot | \varepsilon, \kappa)$ that connects $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ as $p(\boldsymbol{\beta} | \boldsymbol{\alpha}, \xi) = CN(\boldsymbol{0}, \xi \boldsymbol{A}), p(\alpha_i) = \Gamma(\alpha_i | \varepsilon, \kappa)$ and $\boldsymbol{A} = diag(\boldsymbol{\alpha})$. Moreover, those angle-related parameters and delay parameters are assumed to be uniformly distributed.

The type II sparse Bayesian learning estimator[13] is adopted and the associated problem becomes the search for



▲ **Figure 1. Bayesian network for reconfigurable intelligent surface (RIS)-user equipment (UE) channel**

$\left\{\hat{\boldsymbol{\psi}}^1,\hat{\boldsymbol{\psi}}^2,\hat{\tau},\hat{\boldsymbol{\alpha}},\hat{\xi}\right\}$ utilizing the maximum a posteriori (MAP) criterion. The channel parameters can be inferred from

$$\left\{\hat{\boldsymbol{\psi}}^1,\hat{\boldsymbol{\psi}}^2,\hat{\tau},\hat{\boldsymbol{\alpha}},\hat{\xi}\right\} = \arg\max \ln p\left(\boldsymbol{\psi}^1,\boldsymbol{\psi}^2,\tau,\boldsymbol{\alpha},\xi \middle| \boldsymbol{y}\right)$$
$$\propto \arg\max \ln p\left(\boldsymbol{y} \middle| \boldsymbol{\psi}^1,\boldsymbol{\psi}^2,\tau,\boldsymbol{\alpha},\xi\right) p\left(\boldsymbol{\psi}^1\right) p\left(\boldsymbol{\psi}^2\right) p(\tau)\, p(\boldsymbol{\alpha})\, p(\xi). \tag{12}$$

After calculation, we find that the marginal likelihood obeys Gaussian distribution as

$$p\left(\boldsymbol{y} \middle| \boldsymbol{\psi}^1,\boldsymbol{\psi}^2,\tau,\boldsymbol{\alpha},\xi\right) = CN\left(\mathbf{0},\xi^{-1}\boldsymbol{C}\right), \tag{13}$$

where $\boldsymbol{C} = \boldsymbol{C}_{-i} + \alpha_i \boldsymbol{c}\left(\psi_i^1,\psi_i^2,\tau_i\right)\boldsymbol{c}^H\left(\psi_i^1,\psi_i^2,\tau_i\right)$ and $(\cdot)_{-i}$ represent a new matrix with the component related to the i-th path removed. Defining $L\left(\boldsymbol{\psi}^1,\boldsymbol{\psi}^2,\tau,\boldsymbol{\alpha},\xi\right) = \ln p\left(\boldsymbol{y} \middle| \boldsymbol{\psi}^1,\boldsymbol{\psi}^2,\tau,\boldsymbol{\alpha},\xi\right)$, the MAP criterion is equivalent to maximize L.

It can be inferred from Eq. (13) that L can be split into one part that is related to the i-th path and the other parts related to the other paths. An iterative approach can be utilized to find the desired solution for each path separately. The detail can be summarized as:

1) The noise variance is obtained by setting the partial derivative of L w.r.t. ξ to be zero.

2) For path i, the hyperparameter α_i can be obtained by choosing a value to make the partial derivative w.r.t. α_i to be zero.

3) The estimated $\boldsymbol{\psi}^1,\boldsymbol{\psi}^2$ and τ are obtained separately through the gradient descent or Newton method.

Although the globally optimal condition cannot be guaranteed, the proposed off-grid SBL algorithm can achieve a continuous convergence of the objective function and obtain a locally optimal solution. As the proposed algorithm processes continuous angle and delay directly, it can effectively overcome the grid mismatch problem and achieve super-resolution estimation accuracy.

4 Simulation Results

In this section, the channel estimation performance is analyzed. The RIS adopted is composed of 16×16 elements, and 4×4 elements are selected for channel estimation. The number of OFDM subcarriers is 64, and 8 or 16 subcarriers are selected for channel estimation. The central frequency is 60 GHz and the bandwidth is 1 GHz.

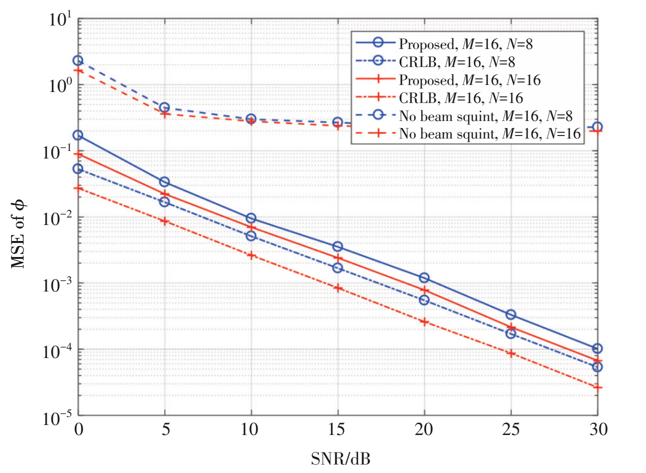
In Fig. 2, we simulate the estimated mean square error (MSE) of ϕ, which is defined as $MSE_\phi = \left|\phi - \hat{\phi}\right|^2$ and ϕ is measured in angles. Firstly, the angle estimation performance of the one that does not consider spatial-wideband effect is abysmal. It does not decrease with the signal-to-noise ratio (SNR), remaining a value larger than 0.1 even for noiseless cases. This proves the existence of the spatial-wideband effect in addition to the frequency-wideband effect, verifying the correctness of the proposed RIS-assisted channel model. Secondly, it can be found that the proposed off-grid SBL channel estimation algorithm achieves a better angular MSE performance that decreases approximately linearly with SNR. Moreover, the proposed algorithm approaches the Cramer-Rao lower bound (CRLB). The superiority of the proposed method is verified, although the global optimal cannot be guaranteed. Increasing the number of subcarriers used for channel estimation can improve angle estimation accuracy. The estimation of ϕ and τ have similar results, and the detail is omitted due to space limitations.

In Fig. 3, the normalized MSE of the RIS-UE channel for all RIS elements, which is defined as $MSE_{\boldsymbol{H}} = \left|\boldsymbol{H} - \hat{\boldsymbol{H}}\right|^2 \Big/ \left|\boldsymbol{H}\right|^2$, is analyzed. The MSE performance of those ignoring the spatial-wideband effect is worse than the proposed algorithm and does not improve with higher SNR. In addition, the MSE of the proposed algorithm decreases continuously with SNR, and the error floor that exists for the on-grid OMP algorithm can be overcome. Though very fine grids make the channel estimation performance of OMP better, it becomes numerically unstable and computationally unacceptable and can hardly beat the proposed off-grid one.

5 Foresight of Challenges

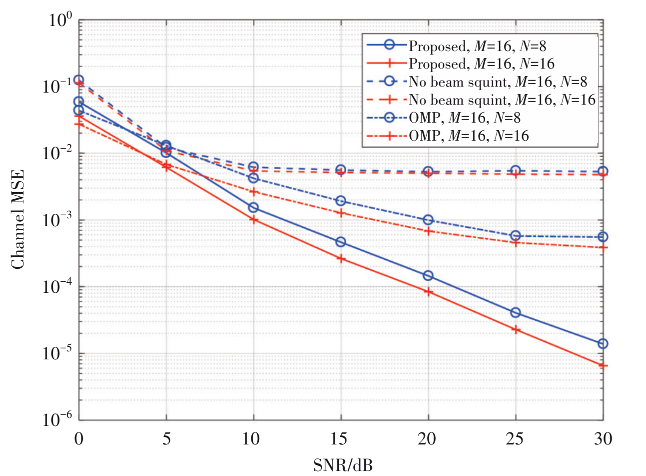
5.1 Channel Modeling

Most of the existing channel modeling methods follow the wireless channel models of 3GPP and ITU. However, the new challenges brought by the novel characteristics of RIS are ignored, and the lack of RIS wireless channel measurement becomes a tremendous challenge for the current stage. It is urgent to develop a thoroughgoing RIS channel model considering various fading factors. In addition, it is necessary to reasonably model hardware non-ideal factors such as the mutual coupling between sub-wavelength RIS elements and verify it



CRLB: Cramer-Rao lower bound SNR: signal-to-noise ratio
MSE: mean square error

▲**Figure 2. MSE of angle parameter ϕ**



MSE: mean square error SNR: signal-to-noise ratio
OMP: orthogonal matching pursuit

▲**Figure 3. Channel estimation MSE versus SNR**

through practical channel measurement.

The electromagnetic mutual coupling means that when multiple antennas are close to each other, the electric field of one antenna will affect the current distribution of other antennas and generate a voltage at its terminals, thereby affecting the performance of the antenna array. To realize the intelligent control of the environment, a RIS is usually composed of tens of thousands of electromagnetic elements, with the element interval being less than half a wavelength. The mutual coupling within RIS is severe, and the radiation pattern is affected dramatically. If no compensation is performed, the system performance will be decreased. The commonly used electromagnetic coupling analysis methods are the method of moment approach[14] and the mutual coupling model based on S parameters[15]. However, the hardware implementation of the RIS is diverse, including structures based on PIN tubes, varactor diodes, liquid crystals, etc. How to reasonably model the impedance of RIS needs in-depth research.

5.2 Near-Field Analysis

In MIMO communications, it is assumed that the signals received by the antenna array are parallel. However, this approximation only holds when the receiving array is in the far-field of the transmitting array. The case is different for a RIS as the near-field condition occurs more frequently. The transmission characteristics of spherical waves need to be considered, and near-field research needs to be promoted urgently.

According to different transmission distances, the receiving area is divided into the reactive near-field, near-field and far-field, and the boundaries are $0.6\sqrt{D_a^3/\lambda}$ and $2D_a^2/\lambda$ respectively, with D_a being the array aperture. As the array aperture for the RIS is usually large, the signals received by different RIS elements have different transmission distances and different effective receiving areas, and polarization mismatch errors are inevitable[16]. These factors cause significant differences in the signal received by different RIS elements, making the RIS near-field analysis more complicated than MIMO. The performance analysis and design optimization of near-field communications are helpful for understanding the characteristics and potential advantages of RIS-assisted communications.

5.3 Multi-User Transmission

A significant feature of RIS is that the electromagnetic element can only produce a certain phase adjustment at a particular moment[17], and it is difficult for RIS to achieve ideal multi-beams for multi-user transmission. One solution is maximizing a criterion and achieving a tradeoff by optimizing the RIS phase shift matrix. However, this solution is complicated and generally difficult to generate beams with precise directivity, restricting its value in actual products. Other solutions include RIS segmentation service for multi-users, matching BS-RIS and RIS-UE beam pairs to obtain suitable beams supporting multi-users, etc. However, the inherent performance loss due to the amplitude restriction of RIS element is difficult to compensate. Different subcarriers incident into the same RIS will cause different RIS electromagnetic responses, and different beams will be generated due to the spatial-wideband effect. Reasonable use of these properties may bring new inspiration to multi-user RIS-assisted transmission.

After the introduction of RIS, the communication system will face many challenges such as a more complex propagation environment, an increase in factors affecting channel capacity, etc. RIS needs to perform different functions according to different requirements, such as beamforming, energy focusing and near-field broadcasting[18]. Studying the maximum capacity, energy efficiency, or optimization of other indicators under various schemes will be a hot spot for future research.

5.4 Standardization

Standardization is an essential connection from technology to application. Although the research on RIS is still in the development stage, it is indispensable to study the impact of RIS standardization. At present, there are various channel estimation and beamforming approaches in academia, while the most basic question considered by the industry is how to standardize and apply them.

As a simple version of RIS is hoped to be deployed in 5G-advanced network, the standardization of RIS is just around the corner. The points to be standardized for RIS include the use cases and requirements, RIS channel modeling, air interface design, and the RIS network architecture. The standardization mainly includes near-field and far-field channel modeling, time slot structure design, channel and signaling design, channel measurement design, feedback design, and related protocol process design. The possible air interface designs include reference signaling, channel feedback signaling, codebook, control signaling, etc.

6 Conclusions

The spatial-wideband effect is inevitable in the RIS channel, and the communication quality will be affected seriously if the spatial-wideband effect is not handled well. To deal with this problem, we reanalyze the wideband RIS channel representation and design an off-grid SBL method to estimate the sparse channel parameters. The estimation of the channel parameters through the activation of some RIS elements is realized and the complete channel is restored successfully. The simulation results prove the effectiveness of the off-grid SBL algorithm. Finally, the challenges to be dealt with for RIS-assisted communications are discussed.

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