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Perspective method for reconfigurable intelligent surface design for NOMA transmission: Theoretical study

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The method (paradigm) presented here was inspired by two basic ideas: the assumption of the MIMO-RIS-NOMA communication channel as a dispersive channel with fading, and the representation of the latter by means of the generalized Kronecker channel model (GKCM), applying the “orthogonalization approach” based on utilization of the “universal” eigen basis in the form of prolate spheroidal wave functions (PSWFs). In other words, the essence of the approach is representing the MIMO-RIS-NOMA channel by means of a finite set of artificially created orthogonal trajectories for wave propagation, which are connected by the coupling matrix (CM) of the RIS. The goal for RIS (through the selection of specific CM elements) is to provide a decoding system for the NOMA users with the required SNR values for each user to guarantee successful decoding processing. A theoretical analysis of this paradigm is presented.

KEYWORDS

dispersive channel, fading, reconfigurable intelligent surface (RIS), wireless communication, orthogonalization

1 Introduction

In the transmission system design process, the professional community faces a well-known problem: the need to increase the spectrum efficiency of the system according to the drastically growing user demand and associated content. To satisfy those demands, there has been the development of the Internet of Everything, Intelligent Cities, *etc.*, together with progress in technology in general. There are also several opportunistic ideas proposed, including the shift from OMA to NOMA, MIMO (massive MIMO), and blockchain radio access network (B-RAN), among others. Great interest has recently been devoted to the RIS-NOMA design.

Essentially, RIS-NOMA is based on the idea of intelligent reconfiguration of the propagation environment to provide the best conditions for NOMA **user decoding** and minimize multiuser interference (MAI) or, more generally, to adapt the system structure to allow the best use of its potential spectrum abilities. Comprehensive surveys of the results obtained thus far in RIS-NOMA have been published (Ding et al., 2022; Hou et al., 2019; and Yang et al., 2021, see also references therein). Based on these studies, the combination of RIS-NOMA seems to be rather opportunistic and is able to significantly improve the transmission's throughput. Moreover, it provides improved security, automation of network control with AI-deep learning, *etc.* However, the idea of the artificial influence on the propagation environment of the communication channel to improve the characteristics of information transmission is not new. In this regard, it is reasonable to

invoke the ideas of the “West Ford” project (Kennedy, 1969). The West Ford project was proposed by R. Kennedy (MIT) in the late 1950s and early 1960s as an artificially created “wave guide” for the improvement of very long-distance (overseas) HF communications.

From fundamental analogies, RIS might be considered a “replica” of the West Ford idea, adapted to mobile wireless communications. In some sense, RIS is an aggregate of the properly “tuned” set of partial “West Ford’s” reflectors in order to finally provide the optimum decoding conditions for all NOMA users.

In the next section, how the ideas of Kennedy (1969) can be theoretically adopted and developed as a new paradigm for RIS-NOMA design will be discussed; it is assumed that, for user decoding, the ideas from Kontorovich (2022) are applied.

The paper is organized as follows: Section 2 is dedicated to a description of the idea behind the RIS-NOMA design paradigm. In Section 3, the sketch of the calculus of the elements of the coupling matrix (CM) for RIS control is outlined. Section 4 is dedicated to the calculus of the principal characteristics of noise immunity and spectrum efficiency of information transmission with the application of the proposed paradigm for RIS design. The conclusions appear in Section 5.

2 Description of the main idea

Prior studies indicate that RIS-NOMA transmission systems have been analyzed for many, and very important, cases (Ding et al., 2022; Hou et al., 2019; Yang et al., 2021; etc.); however, the analysis has been mainly limited to special cases of system design, such as SISO-RIS-NOMA and MISO-RIS-NOMA. The MIMO-RIS-NOMA case has rarely been investigated (see references).

In this section, the general case of MIMO-RIS-NOMA¹ is analyzed following ideas from Kennedy (1969) and applying space–time channel orthogonalizations (Alcocer-Ochoa et al., 2006; Kontorovich et al., 2008; Parra-Michel et al., 2009, etc., and references therein). In this regard, and in order to be “consequent,” the MIMO-RIS-NOMA system can be considered a MIMO system (or, more concretely, a MIMO analog channel) with fading and dispersion applied for power NOMA transmission.

It is considered natural to model this MIMO channel with the help of the generalized Kronecker channel model (GKCM), as proposed in prior studies (Alcocer-Ochoa et al., 2006; Kontorovich et al., 2008; Parra-Michel et al., 2009; see also references therein). Moreover, the “angle model” described in Parra-Michel et al. (2009) might be used as well.

Next, as mentioned in Ding et al. (2022), “secondary” users for NOMA transmission are usually located in small clusters surrounding each RIS of the MIMO-RIS-NOMA; therefore, it is reasonable to suppose that users (members of a cluster) may initially operate in different transmission power regimes or with similar transmission powers. In any case, propagation conditions for all may be assumed as physically “sparse” and RIS has to support the

optimum conditions for their “decoding” (identification) at the receiving terminal.

RIS provides a “passive beamforming” for those users (Hou et al., 2019; Hou et al., 2020; Yang et al., 2021; Imene et al., 2022) as well, but, physically, its modeling depends on the wave reflection mechanism of RIS. If the number of RIS reflectors is large (Ding et al., 2022; Hou et al., 2019; Yang et al., 2021) and the number of propagation trajectories is large as well, then the “angle model” from Parra-Michel et al. (2009) becomes difficult to apply, even though it is reasonable to invoke the more general GKCM model (Alcocer-Ochoa et al., 2006; Kontorovich et al., 2008), which has an efficiency that follows from the limited number of “non-physical” or artificial trajectories for practical application (Alcocer-Ochoa et al., 2006; Kontorovich et al., 2008; Parra-Michel et al., 2009; and references therein). According to the “structure” of the GKCM, the idea of “passive beamforming” might be implemented from the CM of the GKCM (see next section), which provides the “propagation tracks” for each NOMA transmission user.

The GKCM is essentially a model of the generic Gaussian channel based on the space–time orthogonalization principle, using a limited set of two-dimensional **separable** PSWFs with envelope PDFs as eigenfunctions (as Rayleigh, Rice, and Nakagami, etc.) for each partial artificial trajectory (eigenfunction) (see *block diagram for MIMO from Alcocer-Ochoa et al., 2006*).

The RIS algorithm is a synthesis of the **predefined** “connections” between eigenfunctions at the transmission and reception terminals in order to provide the required conditions for a power NOMA user’s decoding. Therefore, the outgoing material might be considered a synthesis of the CM (refer to the following paragraph) of RIS for the power NOMA-MIMO transmission system and the theoretical basis for passive beamforming for artificial trajectories.

It must be stressed that the theoretical synthesis of the CM of the GKCM is not the final step in the MIMO-RIS-NOMA design. In fact, RIS is mainly implemented as a block of many reflectors (analog to passive “MIMO” antennas), which are controlled by the specific RIS controller (Ding et al., 2022; Hou et al., 2019; Yang et al., 2021; etc.). This controller adapts the RIS processing to the propagation conditions (environment) to support the final goal, which is “best decoding” for all users. The latter is a specific “replica” of an attempt to generalize the implementation of “reflectors” for the artificial trajectory’s propagation scenario.

Moreover, the implementation of reflectors is clearly not a unique way to implement RIS. A different approach to implementing RIS might be based on the synthesis of inhomogeneous surfaces with reflecting properties that are adequate to the CM and can be adaptively controlled by AI by means of metamaterials (IEEE Staff, 2022). Detailed comments related to RIS implementation are not included here; future discussion and development of a “bridge” between a synthesized CM and an implementation of RIS are needed.

3 Sketch for the calculus of the elements of the coupling matrix design

Let us assume the existence of $i = \overline{1, k}$ RIS located in different sites (which are associated with a MIMO transmission system); each

¹ See Ding et al. (2022), MIMO-RIS-NOMA can be considered when each node is equipped with multiple antennas, or there are multiple RISs; see Abrardo et al. (2021) for an example.

site is assigned to several users $j = \overline{1, m_i}$. Each user at the location requires a fixed SIR (h^2) at the receiving terminal of the SICs of the MIMO systems in order to be properly identified as a NOMA user. A graphical interpretation of this is provided in Abrardo et al. (2021).

To avoid any future confusion, a selected site notation for h_j^2 that forms a variation series will be used:

$$h_1^2 < h_2^2 < \dots < h_{m_i}^2. \quad (1)$$

If the members of the series are rather “sparse,” i.e., $\{h_j^2\}$ are rather close at (1), then conditions for power NOMA are unacceptable (see, for example, evaluations provided by Kontorovich (2022) and the references therein).

Then, an “interleaving” principle (or analog to it) might be applied to form the series (1) from **different sites** associated with $i = \overline{1, k}$ RISs, which requires an additional “deciphering” procedure at the MIMO receiving terminal (to form a set of users’ SIRs). In order to make the outgoing material more “friendly,” let us consider (1) as an initial point for the analysis.

Next, let us assume that those h_j^2 from (1) provide a satisfactory identification of the users of the site by any known methods (Kontorovich, 2022; etc.) and that it is true for all users from any site. Also, it is assumed in the following that the set of signals from all “ k ” RIS are **orthogonal** between themselves, which is a first approximation for simplification of the MIMO processing algorithms. Neglecting the orthogonality of the signal sets from “different” RIS dramatically increases the system’s complexity.

At this point, it is time to invoke the GKCM model for the MIMO transmission with RIS from one of the previously selected sites. When MIMO deals with “ N ” transmitting and “ M ” receiving antennas (N_T, N_R) representing the “ N ” transmitting and “ M ” receiving SISO broadband channels (in general), the channel Matrix $\mathbf{H}(t, \tau)$ (Alcocer-Ochoa et al., 2006; Kontorovich et al., 2008) is:

$$\mathbf{H}(t, \tau) = \int_{-\infty}^{\infty} \mathbf{H}(t, f) \exp(j2\pi f\tau) df, \quad (2)$$

where t, τ , and f are time, delay, and frequency, respectively; matrixes $\mathbf{H}(t, \tau)$ and $\mathbf{H}(t, f)$ are of size $N \times M$.

The impulse response matrix $\mathbf{H}(t, \tau)$ is assumed to have its complex elements as samples of scalar Gaussian random fields, which are adequate (with an arbitrary set of means and variances) for Rayleigh, Rice, and Nakagami, etc., channel fading.

Also, based on prior studies (Alcocer-Ochoa et al., 2006; Kontorovich et al., 2008), it follows that, at both transmitting and receiving terminals, the assumption of PA can be successfully approximated by the statistically equivalent (in a covariance sense) n -ULA arrays (where n is the number of arrays).

Taking the latter into account, the matrix $\mathbf{H}(t, \tau)$ in (2) can be represented in the following way (Alcocer-Ochoa et al., 2006; Kontorovich et al., 2008):

$$\mathbf{H}(t, \tau) = \mathbf{V}_{Tx} [\tilde{\mathbf{\Omega}} \cdot \mathbf{G}(t, \tau)] \mathbf{V}_{Rx}^H, \quad (3)$$

where super index H indicates the Hermitian transpose of the matrix, $\tilde{\mathbf{\Omega}}$ is the element-wise square root of the **coupling matrix** $\mathbf{\Omega}$, which physically represents how the eigenmodes of the transmit

and receive correlation matrix (in this case PSWF) are connected through the scattering environment of the RIS, and \mathbf{V}_s with certain indexes are “orthogonalization matrixes.”

As a first approximation, $\mathbf{\Omega}$ might be considered a **diagonal** with elements:

$$\Omega_{mn} = \langle |\mathbf{V}_{Tx_n}^H \theta \mathbf{V}_{Rx_n}^*|^2 \rangle, \quad (4)$$

where n is an index of {PSWF} associated with the n th user and θ might be associated with power azimuth spectrum (PAS)—directions on RIS, or mutual “losses” of the connected eigenmodes (IEEE Staff, 2022).

The coupling matrix $\mathbf{\Omega}$ shows how the eigenmodes of Tx and Rx are connected through RIS. From the n -ULA approximation for Tx and Rx with the assumption of a rectangular aperture in an angular domain for each array (see also (11) and (12) from Kontorovich et al. (2008)), one can see that evaluation of PSWF parameters and eigenvalues is well-known and might be obtained *a priori*.

For a first approximation, the Ω_{mn} can be calculated as:

$$\Omega_{mn} \cong \lambda_n^2 \langle \phi_{n_{Tx}}^2 \phi_{n_{Rx}}^2 \rangle, \quad (5)$$

where $\phi_n(\cdot)$ are PSWFs.

Then, assuming (5) and that the n th user from (1) belongs only to n th eigenfunctions from both the Rx and Tx sides, then h_n^2 :

$$h_n^2 = \bar{\phi}_{n_{Tx}}^2 \bar{\phi}_{n_{Rx}}^2 \Omega_{mn} \lambda_n^2. \quad (6)$$

From the required h_n^2 , one can easily find Ω_{mn} , which is the aim of the RIS controller algorithm. From Kontorovich (2022) and from (6), the required SNR for the users has to be around 13–15 dB in order to maintain good decoding at SIC, as well as signal/interference for undesired users.

Briefly, the general view or the “paradigm” of the reconfigurable MIMO-RIS-NOMA transmission might be formulated as the calculus of “passive beamforming” weights based on orthogonalized artificial trajectories (PSWF) of the MIMO channel model and its CM.

4 MIMO-RIS-NOMA evaluation based on Kennedy (1969)

For the evaluation of RIS-NOMA-MIMO paradigm characteristics, it might be reasonable to accept the approach for evaluation of the (upper and lower) boundaries for certain “global” characteristics of the information transmission, as exact analytical solutions might be cumbersome (Abrardo et al., 2021; Do et al., 2021). For evaluation of the boundaries, it might be adequate to take the fundamental information-theoretic approach, based on the results of Shannon, Fano, etc., first applied in (Kennedy, 1969).

First, one can assume that OMA + NOMA transmission applying RIS-MIMO (when the number of users and antennas in MIMO is relatively large) accounts for channel fading and dispersion as an aggregate **equivalent Gaussian channel** modeled by GKCM. This aggregate equivalent channel from the information theory point of view might be characterized by average transmission rate and noise immunity boundaries (Kennedy, 1969), as presented hereafter.

Second, for this channel, the **average** transmission rate is well-known:

$$R = \frac{1}{T_s} \log_2 m \text{ b/s}, \tag{7}$$

where T_s is the average (for all users) symbol interval and the same for m as modulation order. This channel (“equivalent” for the whole system) is purely hypothetical, but it might be useful for first approximation evaluations.

Third, for RIS-NOMA-MIMO, the transmission rate (for independent transmission for all users) grows asymptotically up to:

$$R_\Sigma = \sum_{k=1}^n R_k, \tag{8}$$

where $\{R_k\}$ are individual user rates and n is the number of users.

If the “equivalent” T_s in (7) (with m -fixed) is diminishing drastically, the average SNR \bar{h}^2 and noise immunity are decreasing as well.

Then, according to Kennedy (1969), one can obtain two different, but rather close, boundaries BER or P_{err} :

$$P_{err} \leq K_2 \exp(-h^2 E), \tag{9}$$

$$P_{err} \geq K_1 \exp(-T_s C E), \tag{10}$$

where C is the Shannon channel capacity (see 13), and K_1 and K_2 are approximation coefficients (Kennedy, 1969).

One might consider that (9) and (10) have the same sense, as do the well-known Chernoff boundaries, but it is not the case. In contrast to the Chernoff boundaries, the inequalities of (9) and (10) were obtained, not through statistical limits, but through fundamental properties of information transmission that might be more relevant to the case presented here.

For (9) and (10), the approximation parameters and coefficients are:

$$E = \frac{1}{2} - \frac{R_\Sigma}{C}, 0 \leq \frac{R_\Sigma}{C} \leq \frac{1}{4}$$

$$E = 1 - \sqrt{\frac{R_\Sigma}{C}}, \frac{1}{4} < \frac{R_\Sigma}{C} \leq 1,$$

$$K_2 = \frac{1}{\sqrt{2\pi h^2}}, 0 \leq \frac{R_\Sigma}{C} \leq \frac{1}{4}$$

$$K_2 = \frac{1}{\sqrt{2\pi h^2}} \left\{ \frac{1}{1 - \sqrt{\frac{R_\Sigma}{C}}} + \frac{\sqrt{C/R_\Sigma}}{2\sqrt{\pi h^2} \left(2\sqrt{\pi h^2} \left(2\sqrt{R_\Sigma/C} - 1 \right) \right)} \right\}, \frac{1}{4} < \frac{R_\Sigma}{C} \leq 1, \tag{11}$$

$$K_1 = \frac{1}{4\pi h^2} \left(1 - \frac{2}{h^2} \right)^2, 0 \leq \frac{R_\Sigma}{C} \leq \frac{1}{4}$$

$$K_1 = \frac{1}{16\pi h^2} \frac{\sqrt{C/R_\Sigma}}{1 - \sqrt{\frac{R_\Sigma}{C}}} \left[1 - \frac{1}{2h^2} \left(\frac{C}{R_\Sigma} \right) \right] \left[1 - \frac{1}{2h^2 \left(1 - \sqrt{R_\Sigma/C} \right)^2} \right], \frac{1}{4} < \frac{R_\Sigma}{C} \leq 1. \tag{12}$$

For the calculation of the Shannon channel capacity in the previous formulas, there might be two options.

- for the equivalent channel (Kennedy, 1969): $C = 1.44 \frac{\bar{h}^2}{T_s}$, or more precisely:
- the well-known channel capacity for the MIMO channel is:

$$C = \log_2 \left[\det \left(\mathbf{I}_{N_R} + \frac{\bar{h}^2}{N_T} \mathbf{H} \mathbf{H}^H \right) \right], \tag{13}$$

where $(\cdot)^H$ represents, as before, the Hermitian transpose, \mathbf{I}_{N_R} is an identity matrix of N_R order, N_R, N_T are the numbers of antenna arrays at the receiving and transmitting terminals, and \mathbf{H} corresponds to (3) with the coupling matrix $\mathbf{\Omega}$, which was obtained by means of the RIS design (see (4) and so on). Thus, the noise immunity and spectrum efficiency evaluations are completed (in the average sense) and it can provide the “order” of certain figures to “backup” further simulation results.

Finally, to illustrate whether the presented method can be considered as “prospective,” one can obtain upper boundaries for BER (P_{err}) and BPCU (see Ding et al., 2022; the bit rate achieved for channel use) for the GKCM Gaussian equivalent channel for the MIMO- RIS-NOMA system.

Assuming average SNR, as shown in Kontorovich (2022): \bar{h}^2 as 12–15 dB, R/C close to 1 (for prospective 6G), and applying (9), it is easy to obtain an average P_{err} less than 10^{-2} and BPCU more than 20, which is rather optimistic.

5 Conclusion

The presented material might be a prospective paradigm for MIMO-NOMA RIS design transmission systems, based on the original ideas published previously (Kennedy, 1969; Alcocer-Ochoa et al., 2006; Kontorovich et al., 2008; Parra-Michel et al., 2009). Proposed solutions for RIS design are mainly based on the RIS reflectors “tuning” to the propagation scenario, with one exception found in Yigit et al. (2022), but it seems completely different compared to this material. The approach presented previously provides an artificially “created” MIMO channel for the successful final separation of the NOMA users at the receiving terminal of the MIMO system.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

The author listed has made substantial, direct, and intellectual contributions to the work and approved it for publication.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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