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Intelligent Reconfigurable surface technique for Multiple Antenna Communication System

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Abstract

The throughput growth of the coming wireless communication schemes requires the deployment of more base stations at a lower power use. We were inspired by the newly recommended Reconfigurable Intelligent Surface technique (RIS) to address this issue. Specifically, this study mainly concerns the joint precoding system design challenge regarding improving the throughput at the base station (or the access point) and IRS stages. An iteration strategy called MMSE-MP has been developed, procedures a minimum mean squared error precoder (MMSE) approach for the Digital-BF and the Matching Pursuit (sparse approximation algorithm) for the Analog precoding, to cope with this complex challenge. For the reflecting element phase shift matrix, the algorithm uses the arrival/departure angles of the LOS rays at the IRS elements. Basically, the joint problem of optimizing the analog and the digital precoder was transformed into a one-variable matrix reconstruction, i.e., sparsity-constrained signal-recovery optimization. The simulation outcome confirms that there is nearly 66.5% spectral enhancement if comparing with the classic network without IRS for a certain power scenario of the scheme.

Keywords: digital to analog precoding, intelligent recon-figurable surface (IRS), minimum mean squared error precoder (MMSE), Matching pursuit (sparse approximation) method.

الخلاصة: ان زيادة الطلب على معدل اعلى لتدفق البيانات في أنظمة الاتصال اللاسلكية القادمة يستوجب نشر المزيد من أبراج الارسال التي تعمل بمعدل قدرة أقليلة. في هذا البحث تم توظيف تقنية السطوح الذكية القابلة للتشكيل (RIS) وذلك لمعالجة هذه المشكلة. على وجه التحديد، هذا البحث يتناول تصميم موجه الحزمة عند برج الارسال والسطوح الذكية بنفس الوقت والذي يضمن أفضل مقدار لتدفق البيانات للنظام. تم تطوير إستراتيجية التكرار التي تسمى MMSE-MP، واعتماد طريقةMMSE في تصميم تشكيل الحزمة الرقمي اضافة الى خوارزمية التقريب المتفرقة من أجل التعامل مع هذا التحدي المعقد.
بالنسبة لمصفوفة السطوح الذكية فان الخوارزمية تستخدم زوايا الوصول والمغادرة لمساراتLOS عند هذه السطوح، هذه الخوارزمية بالأساس تقوم بتحويل المهمة المترابطة الخاصة بإيجاد تصميم لموجه الحزمة الرقمي الى مهمة منفصلة لكل متغير على حدة، تؤكد نتائج المحاكاة أن هناك ما يقرب من 66.5 ٪ من التحسين الطيفي عند المقارنة بالشبكة الكلاسيكية التي لا تستخدم تقنية السطوح الذكية القابلة للتشكيل (RIS) وذلك لظروف معينة تضمن مقارنة عادلة بين الحالتين.

1. INTRODUCTION

The growing rate of information requirements for future and current wireless networks (6G networks) are highly concerned with energy utilization [1-2]. As a result, the efficiency of energy (EE) essentially denotes using less energy to perform the same purpose. In order to organize a green, sustainable cellular network, EE has been establishing itself as a critical performance indicator [3-4]. Between the transceiver techniques which considered through studies in references [5-10] for communication that prioritizes environmental sustainability; the commonly named Reconfigurable Intelligent Surface technique (RIS) is a cutting-edge hardware technique that shows great promise in reducing the energy consumption associated with communication systems. [11-15]. These Intelligent Surfaces is made up of reasonable passive components and is intended to transform a wireless environment into a generally desired span or channel. Through applying the RIS in wireless communication systems, enhancements in the quality of user-received signals are gained by transmitting control signals from the Access Point (AP) or the base station to the controller of the RIS array (see figure 1 for details). RIS works as a reflector, and as a result, compared to traditional amplify-and-forward (AF) relays, these Intelligent Surfaces require a reduced amount of energy. [7]. However, using energy-efficient RIS technique efficiently presents some challenges, extending from the channel sounding task to network optimization [16], which is discussed in many extant workings, containing [17]– [19]. In [17], the researchers examined the practicable rates (near-optimal) in the downlink of the RIS based communication system as a substitute for considering immediate channel state information (CSI) availability.

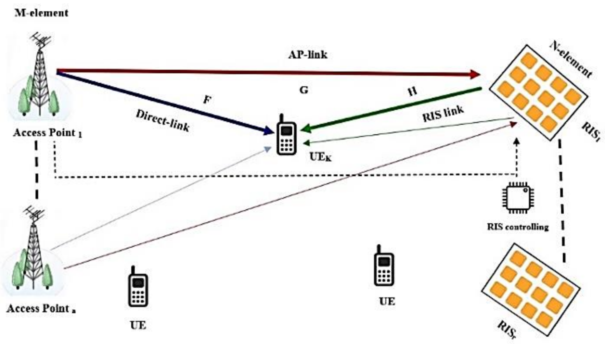

Figure 1: reconfigurable smooth surface based MIMO system.

In [18], a new approach for the "multiuser multiple-input single-output" (MISO) system energy efficiency optimization was presented by the authors, which involves adjusting the RIS phase shifts reflector and the base stations transmitted power (BSs). Instead of the SDR "semidefinite relaxation" approach, the authors in [19], achieved a low-complexity tech to solve the "nonconvex-quadratic-constrained quadratic problem" (NC-QCQP) program. An alternating improvement rule for deciding the locally optimum point for the problem of power allocation in a single-user MISO communication system was proposed by the authors in [20], however, it was not found suitable for the problem of Weighted Sum Rate (WSR) maximization in multiuser systems due to an increase in complexity of the equipment. In [21], the authors examined RIS-based multi-point communication (coordinated multipoint joint transmission (CoMP JT)) from multiple BS to raise the minimum achieved data rate of the users at the edge of the cell. They transform the procedure of the max-min non-convex formula into the convex-associated one via the strategy of mean-square error, which relaxes the work into a near-optimal and effective iterative approach. In [22], the authors discussed the use of RIS to enhance matched multipoint transmission from multiple access points (Aps), with the goal of optimizing the minimal local rate for remote users. They simplify the complexity of the problem by utilizing the sub-gradient technique. In [23], the authors address the issue of RIS-aided MIMO based on the Theory of Duality and Quadratic methods. Where the design challenge for the suggested system (joint precoding) is designed to attain a near-optimum data rate for all the system's users. They divide the joint precoding design via the Quadratic formula and the duality theorem.

Unlike the methodology used in [22], which relies on the sub-gradient method "mean-square error", in our proposed algorithm we extend the sparse precoding approach in [9] into the BS-MIMO system where the sparse approximation problem can be solved via building of the basis and Matching pursuit. The significance of the article's contributions is listed in the following,

- This work introduces the concept of downlink in wireless networks, where multiple users (each user has a single antenna) can communicate with a base station that has multiple antennas. A passive RIS utilizing reflection precoding is employed with the aid of the utilization of intelligent surfaces that have a relatively small number of reflective elements.

- To enhance the QoS for all the users and be inspired by the techniques signified in [9], we try spatially sparse precoder for the milli-meter wave MIMO systems to meet the formulated requirements.

Notations: scalar constants were represented by capital letters such as (M,…, N). scalar variables were represented by Small latter's such as (k,…..r). Bold small letters were used for representation of vector variables e.g., h_k denotes the k^{th} component of the channel h. In addition, Bold capital letters were employed for representation of matrix variables. diag (•) represents the diagonal of the matrix, tr(.) and (.) H means, respectively, the matrixes' trace and conjugate transpose (Hermitian). As well as we use C, Rel, ⊗ represents for complex, real number, and Kronecker product, respectively.

2. SYSTEM MODEL

In this section, the channel and system model for the supposed mmWave system were presented, and later the problem of hybrid beamforming will be formulated. Specifically, the Multiple-Input Multiple-Output mmWave system is shown in Figure 2, in which the transmit antennas number is denoted by N_{at}, the RF chains number at the transmitter is represented by N_{RF} and the data streams number is indicated by N_{st}. The message to be transmitted can be expressed as [23],

$$m = V_{PB}\, V_{BB}\, s \;\ldots\; (1)$$

Where, $V_{BB} \in (N_{at} * N_{st)} and, V_{PB} \in (N_{RF} * N_{st)}$ are digital and analog beamform vectors, respectively. As a power constraint, these vectors obey the norm of squared Frobenius as follows [25],

$$\|V_{PB}\, V_{BB}\|_F^2 = N_{st} \;\ldots.\; (2)$$

Also, $s \in \mathbb{C}^{N_{st} \times 1}$ is the vector which transmitted by N_{st} statistics streams and with the following restriction [20],

$$\Xi\{ss^{\mathrm{H}}\} = \Xi\{|\mathrm{s}|^2\} = \frac{1}{\mathrm{N_{St}}}\, \mathbf{I}_{\mathrm{N_{st}}} \;\ldots (3)$$

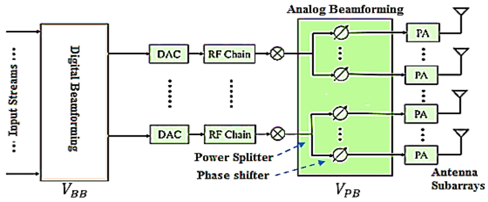

Figure 2. The hybrid beamforming in the Multiple-Input Multiple-Output based mmWave system.

Consequently, the received signal next to the decoding function can be formulated as following [25],

$$y = P_t^{1/2} \,.\, U_{BB}^H U_{PB}^H \;H\; V_{PB} V_{BB} \,.\, s + U_{BB}^H U_{PB}^H\, \boldsymbol{z} \;\ldots.\; (4)$$

where $U_{BB} \in (N_{RR} * N_{st})$, is base-band precoding vector of the receiver, N_{RR} stands for the receiver RF-chains number, $U_{PB} \in (N_{ar} * N_{RR})$, is passband receiver precoding, N_{ar} is the antennas' number of the receiver, P_t represents the total power of transmission, and $\boldsymbol{z}$ denotes the noise power. Now, in (nats/sec), the spectral effectiveness of the scheme can be described (with aid of the Shannon's theorem) as follows,

$$\eta_{SE} = \ln\left(\left|I_{N_{St}} + \frac{P_t}{\sigma_n^2 \,.\, N_{st}}\, H\; V_{BB}\, V_{PB}\; V_{PB}^H\, V_{BB}^H\; H^H\right|\right) \ldots (5)$$

where, $(\cdot)^H$ stands for the matrix conjugated transposition, and the operation $|\cdot|$ stands for the matrix determinant.

The System Channel Model; It is generally reasonable that the mmWave rays obeys a dispersed model containing several paths and dispersions, i.e., like the bundled channel model of ray's cluster (Saleh Valenzuela) [21]. Keeping generality intact, let's assume there is a array of square planar antenna equipped by an N components on the transmitter and receiver sides, respectively, $N_{cluster}$ denotes the number of clusters, and N_{path} is the rays or paths' number in each cluster, then the channel matrix is $H \in \mathbb{C}^{N_{ar} \times N_{at}}$in eq.(4) can be formulated as [22],

$$\mathbf{H} = \left(\frac{N_{ar} \,.\, N_{at}}{N_{path} \,.\, N_{cluster}}\right)^{\frac{1}{2}} * \sum_{i \in N_{cluster}} \sum_{j \in N_{path}} \xi_{ij} \,.\, \mathbf{g}_r(\theta_{ij})\;\; \mathbf{g}_t(\phi_{ij})^H \quad \ldots (6)$$

where, $\sum_{i \in N_{cluster}} \sigma_{ij}^2$ denotes stabilization factor of the model that certify the mean of $\|H\|_F^2$ is equal to $N_{ar}.N_{at}$, $\xi_{ij} \in \mathbb{CN}(0, \sigma_{ij}^2)$ is the gain of the *j*-th path (in the *i*-th scatters' set) with complex gaussian distribution. $\mathbf{g}_t(\phi_{ij})$ indicates the transmit antenna's response vectors (with ϕ_{ij} azimuth departure angle (AoD)). $\mathbf{g}_r(\theta_{ij})$ indicates the receive antenna's response vectors (with θ_{ij} is the angle of arrival (AoA)). We analyze traditional $(M * M)$ square planar uniform array (figure 4), where the response can be developed as following,

$$\mathbf{g}(\theta_{ij},\phi_{ij}) = \frac{1}{M}\left[1,\dots,\exp\left(\frac{2\pi d}{\lambda}\left[a.\sin\theta_{ij}\sin\phi_{ij}+b.\cos\phi_{ij}\right]\right)\right]^{T}, \qquad \forall\, a,b \in \{0,1,\dots M\} \quad \dots(7)$$

Where d and λ are the antenna's element spacing and the signal's wavelength, correspondingly.

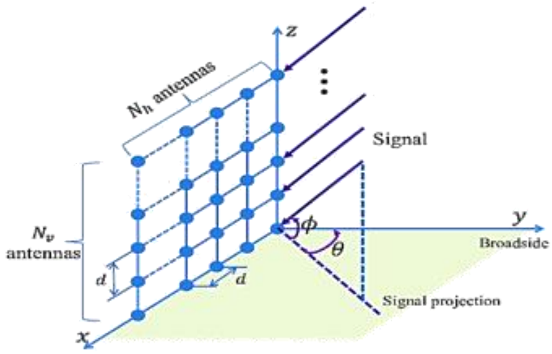

Figure 3: Structure of the uniform antennas (square planar) [25].

The task of maximizing the spectral efficiency can be expressed in terms of maximizing the mutual information attained by the Gaussian signal passing through the mmWave channel with respect to both the digital and analog beamforming,

$$I(\ V_{BB}, V_{PB}) = \ln\left(\left|I_{N_{St}} + \frac{P_t}{\sigma_z^2 . N_{st}}.H\ V_{BB}\,V_{PB}\ V_{PB}^H\,V_{BB}^H\ H^H\right|\right) \quad \dots.(8)$$

Basis of the system efficiency problem; Through this work, our primary focus is on the design of the analog beamforming via the spectral efficiency optimization which can be donated by the following task of eq. (10). Besides, to reduce the algorithm's complexity as much as possible, we employ standard formulas for each of the digital beamforming and the RIS- coefficients of the reflection. To this end, the proposed algorithm, namely MMSE-MP, uses a minimum mean squared error precoder (MMSE) approach for the Digital precoding, i.e., $\boldsymbol{V_{BB}} = [({V_{PB}}^H V_{PB} + \sigma_z^2.I)^{-1}\, {V_{PB}}^H]\,.V_{opt}$, and the Matching Pursuit method for the Analog precoding while for the reflecting element phase shift matrix the algorithm uses the angles of arrival/departure of the LoS rays at the RIS array, i.e., $\boldsymbol{\varphi} = \{\mathbf{g}_t\, {\mathbf{g}_r}^H\}_{LoS}^{RIS}$;

$$Problem: \quad (V_{BB}^*, V_{PB}^*) = arg \max_{V_{PB},V_{BB}} \ln\left(\left|I_{N_{St}} + \frac{P_t}{\sigma_z^2\, N_{st}}.H\ V_{BB}\,V_{PB}\ V_{PB}^H\,V_{BB}^H\ H^H\right|\right)$$

$$\boldsymbol{C^1}; \quad V_{PB}(i,j) \in \mathcal{V} \quad \forall i,j$$

$$\boldsymbol{C^2}; \quad \|V_{PB}V_{BB}\|_F^2 \ = N_{st} \qquad \dots(9)$$

This hardware constraint seems to be the same as the unit-modulus requirement for an infinite-determination phase shift network, where $\mathcal{V}$ characterizes the feasible set of passband precoder, $|V_{PB}(i,j)|^2 = 1$. The second constraint in eq. (7), i.e., $\boldsymbol{C^2}$ denotes agreement with the restriction on total power. By using same strategy as in reference [24], it is possible to reduce the Euclidean distance between the ideal full-digital-beamforming and the hybrid-precoding design problem. Tracking the same approach employed in [25], one can rewrite eq.(8) in terms of the distance between the analog/digital-BF and the optimum unconstrained precoder for the channel V_{opt}. To accomplish this, we express the channel matrix in terms of the singular value decomposition for the channel (SVD) i.e., product of three-matrices; $H = U\Sigma V^H$, where V is an $N_t \times rank(H)$ unitary-matrix (orthonormal), Σ is a $rank(H) \times rank(H)$ diagonal-matrix of positive real entries (decreasing order singular values), and U is an $N_r \times rank(H)$ unitary-matrix (orthonormal). Therefore, the objective of eq. (8) can be stated as follows,

$$(V_{BB}^*, V_{PB}^*) = arg \max_{V_{PB},V_{BB}} \ln\left(\left|I_{rank(H)} + \frac{P_t}{\sigma_z^2 . N_{st}}.\Sigma^2 V\ V_{BB}\,V_{PB}\ V_{PB}^H\,V_{BB}^H\ V\right|\right)$$

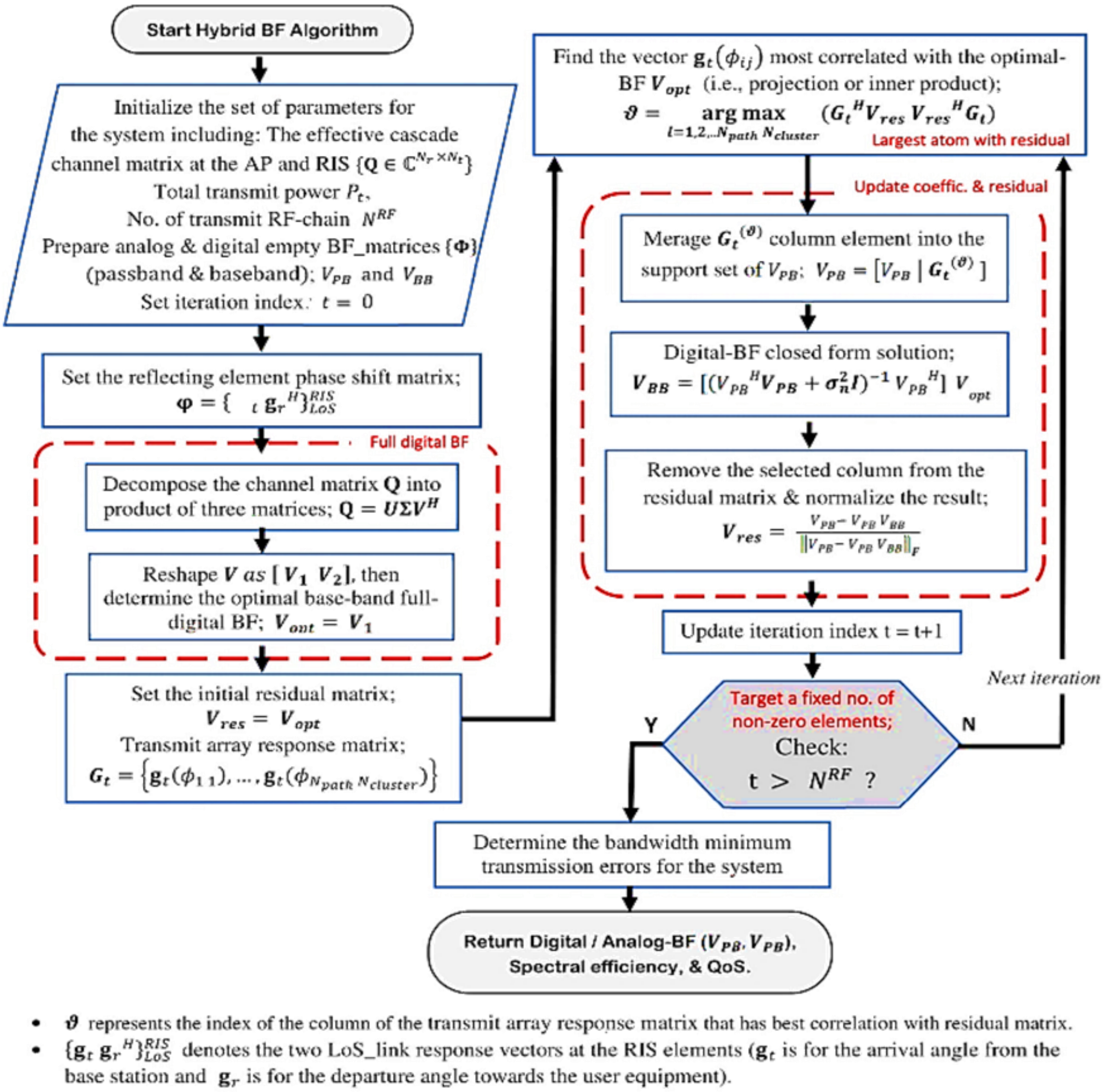

Figure 4: The proposed hybrid-BF method's flowchart.

Also, Σ *and* V can be expressed as, $\Sigma = \begin{bmatrix} \Sigma_1 & 0 \\ 0 & \Sigma_2 \end{bmatrix}$ and $V = [\,V_1 \;\; V_2]$, respectively, where the columns of V_1 *and* V_2, respectively, hold the eigenvectors consistent to non-zero and zero eigenvalues. The unitary-precoder (optimal) can be merely expressed as, $V_{opt} = V_1$. Next, since the columns of V_{opt} are associated with the response vectors of the transmit antennas the $\mathbf{g}_t(\phi_{ij})$ through a linear transformation [25], consequently, the optimization problem of eq.(8) becomes,

$$Problem: \quad \tilde{V}_{BB}^{*} = arg \min_{\tilde{V}_{BB}} \left\| V_{opt} - G_t \tilde{V}_{BB} \right\|_F$$

$$\boldsymbol{C^1}; \quad \left\| \mathrm{dig}(\tilde{V}_{BB} \tilde{V}_{BB}^{H}) \right\|_o = N_t^{RF}$$

$$\boldsymbol{C^2}; \quad \left\| G_t \tilde{V}_{BB} \right\|_F^2 = N_{st} \qquad \ldots(10)$$

Where, $\|\cdot\|_o$ is the zero-norm (number of the non-zero elements), $\|\cdot\|_F$ is the Frobenius norm (length), and V_{opt} the optimum full-digital beamforming matrix which is capable of supporting the channel matrix's unique vectors. The matrices G_t *and* $\tilde{V}_{BB}$ can be thought as auxiliary variables that help to determine, respectively, V_{PB}^{*} *and* V_{BB}^{*}. The sparsity con-straint (zero-Norm) $\left\|\text{dig}(\tilde{V}_{BB}\ \tilde{V}_{BB}^{H})\right\|_o = N_t^{RF}$ conditions that $\tilde{V}_{BB}$ can have only N_t^{RF} non-zero rows and in this case the columns of the G_t matrix are successfully nominated. Consequently, the N_t^{RF} non-zero rows of $\tilde{V}_{BB}^{*}$ will represent V_{BB}^{*}, and the corresponding N_t^{RF}columns of G_t will represent V_{PB}^{*}. Basically, the joint problem of optimizing V_{BB} and V_{PB} is converted into a one variable matrix reconstruction, i.e., sparsity-constrained signal-recovery optimization.

The proposed precoding method is reviewed in the flowchart of figure 4, which begins by determining the vector $\mathbf{g}_t(\phi_{ij})$ along which, V_{opt} has the greatest correlation. It then attaches this nominated column vector to V_{PB}. After the determination of the best vector, and the solution finding V_{BB} least-squares, the influence of the best vector is detached and the procedure endures to determine the column along which V_{res} , i.e., residual matrix of precoding has the greatest correlation. The algorithm endures N_t^{RF} iterations, i.e., till all the N_t^{RF} precoding vectors have been nominated. Lastly, the RIS-Reflection precoding updating can be done using any Convex optimization software program [26] due to the semidefinite programming (SDP) restrictions in eq. (10).

3. RESULTS OF THE SIMULATION

The proposed RIS-assisted multiuser MIMO communication system's numerical results are now presented. Table 1 lists the system parameters, unless specifically noted. As per Table 1, various scenarios are considered with the use of large-scale path-loss. It is supposed that the link between the RIS unit and AP, as well as the link between the RIS and user's equipment, both experience Rayleigh fade for small-scale fade, whereas the link between the AP and users' equipment experiences Rician fading. Additionally, the angles of arrival and departure are considered to be distributed at random between [0, 2]. For the RIS technique to be implemented effectively, it is important to note that phase shifters may only be able to take on a specific set of discrete values. where b stands for the bits number required to attain some levels of resolution. For demonstrating performance rise brought about by the engagement of RIS technique, we deliver the following baseline schemes to be compared with our proposed algorithm;

1) Optimal precoder (Base-band only),
2) Traditional precoder without RIS technique (w/o RIS), and,
3) the Duality Theory and Quadratic Transformation Beamforming DQBF [1].

Firstly, to show the impact of utilizing RIS technology, figure 5 compares bandwidth efficiency with the transmit power,

Table 1. System parameters for simulation

Parameter	setting
The carrier frequency for the modulation of input- data signal	28.0 GHz (Ka band)
The BS array configuration	The uniform Squared planner antenna with λ/2 elements' spacing i.e., 10.7/2 mm. with λ/2 elements' spacing i.e., 10.7/2 mm.
Number of RIS elements	$N_r = 256$ elements
Access point antenna's number	$N_{at} = 64$ elements
Antenna's number of user	N_{ar} = 32 elements
Transceivers' chain number	N_{ar} = 3 RF-chains
Number of Data-Stream	N_{st} = 3 Streams
Transmit power budget	P_t = 3 [-15;35] dB
Noise power	n^2= -100 dBm
Channel model	Saleh Valenzuela clustered channel model with LoS/NLoS = 20 dB (Gaussian distribution), i.e., LoS channel path variance $\sigma_{11}^2 = 1,$ and NLoS variance $\sigma_{ij}^2 = 10^{-2.0}$
Clusters number	$N_{cluster} = 6$ clusters
Paths number	$N_{path} = 10$ rays
The distribution of the Arrival and Departure angles	Uniform-distribution $\{\frac{-\pi}{2}, \frac{\pi}{2}\}$, with 10 degrees cluster azimuths' spread angles.

Baseline algorithms for comparison	Optimal precoder (Base-band only), Traditional precoder (w/o RIS), and the Duality Theory and Quadratic Transformation Beamforming DQBF [1].

using the traditional scheme without employment of the RIS technique as a baseline1. Since each of direct AP-user path and RIS-aided path receives support as the access point transmitted power increases, it is obvious that the bandwidth efficiency of the RIS-assisted link grows exponentially. This figure reveals that when the RIS technique is employed, the contribution of the line of sight can be efficiently used where an indirect LoS path from the AP to the user (through the intelligent surface) can be initiated for enhancing the quality of the channel. Nonetheless, when the RIS technique is not employed, only NLoS rays can be initiated from the AP to the user, and consequently declines the quality of the channel. Therefore, for a specific transmit power scenario (10 dB) of the system, the proposed RIS-aided MIMO communication system shows a significant improvement of 66.5% in terms of spectral enhancement (SE) from 17 nats/s/Hz ($Maximum\ value$) to 3 nats/s/Hz ($Minimum\ value$) in comparison to a traditional network without the use of RIS technique where,

$$SE - Persentag\ gain = \frac{Maximum\ value - minimum\ value}{Maximum\ value}\ X\ 100\ \% = \frac{17-3}{3}\ X\ 100\ \% = 66.5\%.$$

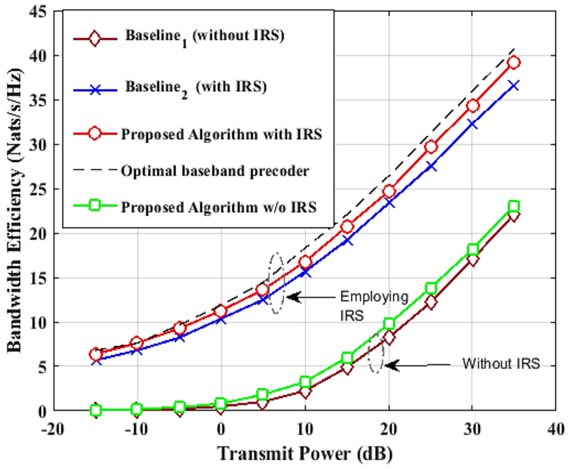

Figure 5: Efficiency of the bandwidth vs transmission power.

Next, regarding the probability of error, figures 6 considers the case when a line of sight (LoS) is founded directly from the AP to the user. This figure shows the spectral efficiency benefits of the proposed RIS-based system for this scenario. For example, for nats probability of 10^(-3), the transmit power gain is about 9 dB if compared with the firstt baseline.

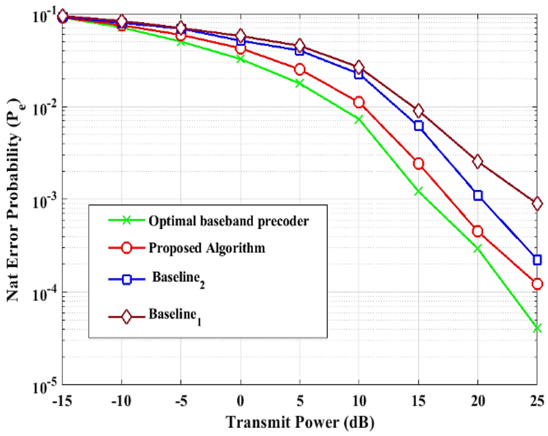

Figure 6: Error probability performance (with LoS component).

Figure 7 considers the case when the line of sight is obstructed and the multipath channel (NLoS) paths are founded directly from the AP to the user (without the aid of the RIS).

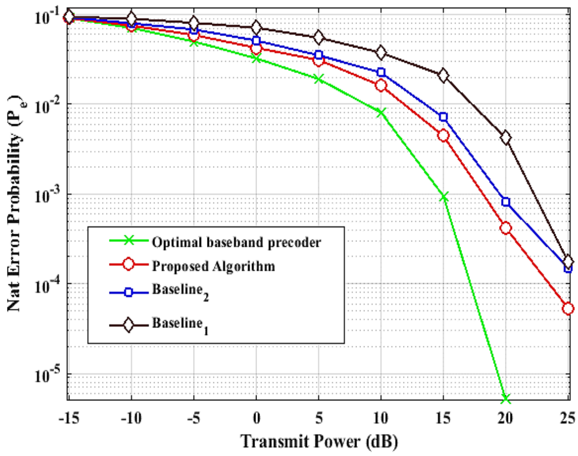

Figure 7: Error probability performance (no LoS component).

It can be seen from this figure that the proposed technique exceeds both the baselines in terms of the BER performance and there is a small performance gap between the optimal system and the proposed one at a low SNR region. Finally, it is depicted in figure 8 that the proposed technique is more robust against channel estimation error. For instance, with the transmit power assigned to 15 dB (when the channel estimation error is below 0 dB), the bandwidth efficiency of the proposed technique with RIS almost remains unchanged.

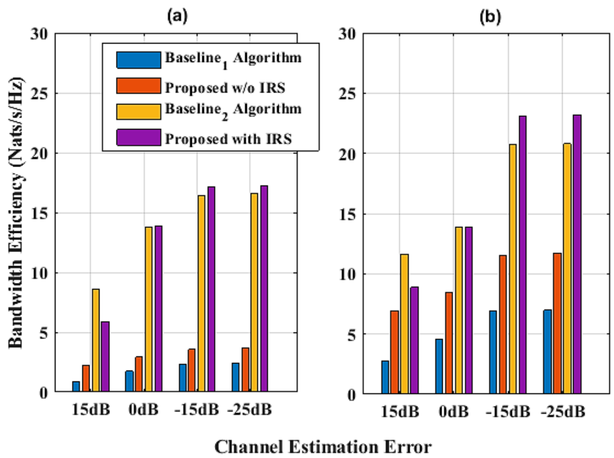

Figure 8: Robustness of the proposed algorithm against channel estimation error;

a) SNR= 10 dB, and b) SNR= 20 dB.

3. CONCLUSIONS

In this work, it had been employed the sparse precoding approach for the BS-MIMO system to attain the minimum QoS for all the uses at the least amount of total power, where the sparse approximation problem has been solved via the building of the basis and Matching pursuit. For the passive-BF (RIS- reflection) phase a shifter of discrete degree is employed. The simulation result demonstrates that, for the particular distance scenario of the scheme, we have achieved about 66 % spectral enhancement and 9 dB power gain in comparison to the conventional MIMO system (without RIS) for certain system parameters.

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