SNR-based Configuration for RIS-Integrated NR

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***Abstract*—Configuration of a reconfigurable intelligent surface (RIS) as a solution to an optimization problem for spectral or energy efficiency requires the estimation of the channels between the transmitter and the RIS and between the RIS and the receiver. The channel estimation and the RIS configuration by optimization are computationally intensive processes in RIS assisted wireless links. The approach proposed in this paper simplifies and speeds up the RIS configuration process by relaxing the demand to find the optimal solution but instead aims to reach a predetermined channel quality measured with the signal-to-noise ratio. It is also shown that when a single dominant path exists between a mobile user and the RIS and also between the RIS and a base station, the RIS configuration calculated as a solution to a spectral efficiency maximization problem and configuration based on conventional antenna array beam steering give the same result.**

***Index Terms*—Intelligent reconfigurable surface (RIS), RIS configuration, coverage enhancement, 5G.**

I. INTRODUCTION

Reconfigurable intelligent surface (RIS) is a programmable structure that can be used for controlling the propagation of electromagnetic (EM) waves by changing the electric and magnetic properties of the surface [1]. By placing RIS units into the environment where wireless systems are operating, the properties of the radio channels can be partially controlled [2]. One application of the RIS is the coverage enhancement of wireless links. In this application, a RIS is used to enhance the signal-to-noise ratio (SNR) at the receiver.

The basic version of a RIS is a passive device in the sense that it does not amplify the signal. It merely collects the (EM) wave impinging to it and reflects the impinging signal in the direction of the receiver. It is often used to enhance the coverage of a wireless communication system in a case where the direct link between a base station (BS) and a user equipment is severely shadowed or completely blocked. In such a setting, the RIS is deployed at a location, where a line-of-sight (LOS) channel exist between the RIS and both the UE and the BS.

To maximize the SNR at the receiver, the radiation pattern of the RIS must be accurately directed. In [3], the composite channel for the transmitter – RIS – receiver path is estimated with an atomic norm minimization technique. After the composite channel has been estimated, the RIS configuration is selected based on the largest singular value of the estimated channel matrix. The singular value decomposition (SVD) is also used in [4] for the RIS configuration after the composite channel is estimated with a channel-decomposition based sub-channel estimation method. In [5], the RIS configuration is calculated as a solution to the spectral and energy efficiency maximization problem assuming the composite channel is known.

The channel estimation for the RIS configuration is a computationally intensive process and requires the transmission of several training sequences. Further, the channel can be estimated only after all the transmitted sequences have been received as is seen in [3], [4] as well as in other methods such as in the orthogonal matching pursuit (OMP) based estimators developed, e.g., in [6] and in the iterative reweighted method in [7]. However, the RIS can be configured also without the need for the channel estimation as it has been shown in [8], where a majority voting algorithm is used.

In this paper, it is shown that the RIS configuration by solving the spectral efficiency optimization problem in [5] is equivalent with the RIS configuration based on the SNR maximization with beam steering approach. Hence, the proposed RIS configuration is based on measuring the SNR at the receiver. No explicit channel estimation is needed in the configuration process leading to a computationally simple procedure. To decrease the computational complexity and to speed up the the RIS configuration process, the method proposed in this paper can be stopped after a predetermined channel quality has been achieved. The system model in Section II assumes a single antenna user equipment (UE) and a single antenna base station (BS). However, the same principle can be applied with multi-antenna devices as described in Section V.

The rest of the paper is organized as follows: Section II introduces the system model, the SNR maximization and RIS configuration is considered in Section III. Numerical examples are given in Section IV and conclusions are drawn in Section V.

II. SYSTEM MODEL

The considered system consists of a BS, a UE and an N-element RIS as illustrated in Fig. 1. When a direct link exists between the UE and the BS, the role of the RIS is to enhance the link performance. If the direct link is blocked completely, the RIS is needed to enable transmissions between the UE

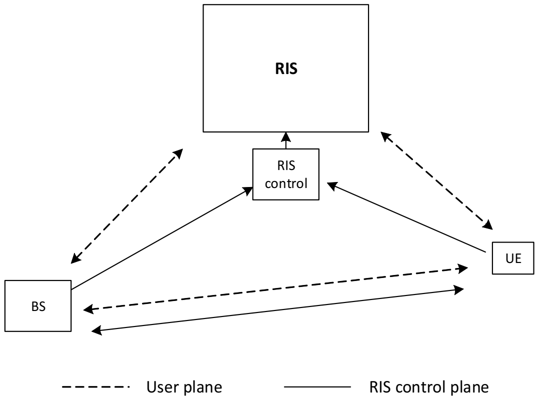

Fig. 1. RIS assisted wireless link.

and the BS. When the RIS control unit is located at the RIS location both the BS and the UE can control the RIS assuming that the RIS control unit is equipped with a transceiver. Since the data rate requirement for the control plane can be low, the transceiver in the RIS control unit can be a relatively simple low power unit. The control plane can be implemented, e.g., with a Bluetooth or WiFi connection or in a 5G NR network it could be based on the 5G sidelink. In Fig. 1, the RIS control unit is placed at the RIS location. In this way, both the UE and the BS can communicate with the RIS, even if the direct link between the UE and the BS was completely blocked.

III. SNR MAXIMIZATION AND RIS CONFIGURATION

The signal at the input of a single antenna receiver can be written as

$$y = (\mathbf{h}_1 + \mathbf{h}_3^{\mathrm{H}}\mathbf{\Phi}\mathbf{h}_2)x + n, \tag{1}$$

where $\mathbf{h}_1$, $\mathbf{h}_2$, $\mathbf{h}_3$, $\mathbf{\Phi}$, x and n are the direct channel between the UE and the BS, the channel between the transmitter and the RIS, the channel between the RIS and the receiver, the RIS configuration matrix, transmitted symbol and the noise term, respectively. When the direct channel $\mathbf{h}_1$ is completely blocked and since $\mathbf{\Phi}$ is a diagonal matrix, (1) can be written as

$$y = \mathbf{g}^{\mathbf{T}}\boldsymbol{\phi}x + n, \tag{2}$$

where $\mathbf{g}^{\mathrm{T}} = [h_3^{(1)}h_2^{(1)}\ h_3^{(2)}h_2^{(2)}\ \cdots\ h_3^{(N)}h_2^{(N)}]$, $h_3^{(n)}$ and $h_2^{(n)}$ are the n^{th} elements of the channel vectors $\mathbf{h}_2, \mathbf{h}_3$, respectively, and $\boldsymbol{\phi} = [e^{-j\phi_1}\ \cdots e^{-j\phi_N}]^{\mathrm{T}}$. Further, the vector multiplication in (2) can be written as a sum resulting in

$$y = \sum_{n=1}^{N} g^{(n)}e^{-j\phi_n}x + n. \tag{3}$$

A. SNR Maximization

The signal-to-noise ratio (SNR) of the received signal is

$$\gamma = \frac{|\sum_{n=1}^{N} g^{(n)}e^{-j\phi_n}x|^2}{\sigma^2}, \tag{4}$$

where $\sigma^2 = E(|n|^2)$ is the noise power.

When only one path exists between the transmitter and the RIS and between the RIS and the receiver, the SNR is maximized when the elements of the summation in the numerator of (4) add up coherently. Hence, the requirement for the SNR maximization is

$$\begin{aligned}\arg(g^{(n)}e^{-j\phi_n}) &= \arg(h_3^{(n)}h_2^{(n)}e^{-j\phi_n})\\ &= \arg(h_3^{(n)}h_2^{(n)}) - \phi_n = \Delta_\phi,\ \forall n \in [1, N].\end{aligned} \tag{5}$$

The requirement for the phase of the RIS element n is then

$$\phi_n = \arg(h_3^{(n)}h_2^{(n)}) + \Delta_\phi,\ \forall n \in [1, N], \tag{6}$$

where $\arg(\cdot)$ is the phase of complex number inside the parentheses and $\Delta_\phi \in \mathbb{R}$ is any constant.

The same result was derived as a solution to the lower bound maximization of the energy efficiency and rate in [9]. In the case of the uniform linear array (ULA) based RIS, the channel vectors are $\mathbf{h}_2 = \mathbf{a}_{\text{in}}h_2$ and $\mathbf{h}_3 = \mathbf{a}_{\text{out}}h_3$ where $\mathbf{a}_{\text{in}}$ and $\mathbf{a}_{\text{out}}$ are the array response vectors for the impinging and reflected waves and $h_2,\ h_3$ are the complex channel gains. This leads to

$$\begin{aligned}\arg(h_3^{(n)}h_2^{(n)}) &= \arg(h_2h_3e^{j2\pi/\lambda nd(\sin\theta_{\text{out}} - \sin\theta_{\text{in}})}\\ &= \frac{2\pi}{\lambda}nd(\sin\theta_{\text{out}} - \sin\theta_{\text{in}}) + \arg(h_3h_2).\end{aligned} \tag{7}$$

When there is only one path between the UE and the RIS and the RIS and the BS, the phase values to maximize the SNR can be found also by considering conventional antenna array steering. To maximize the power at the receiver, the RIS must form a narrow beam and direct it accurately towards the UE. When the RIS is implemented with a planar array, the RIS configuration depends on the angle-of-arrival (AoA), zenith-of-arrival (ZoA), angle-of-departure (AoD) and zenith-of-departure (ZoD) ($\theta_{\text{in}}, \phi_{\text{in}}, \theta_{\text{out}}$ and ϕ_{out} respectively in (8) below) at the RIS. For the beamforming, the RIS elements must perform phase shifts for the signals impinging to RIS element to steer the signal towards the BS. The required phase shift for an element at position (n, m) can be calculated as [10]

$$\begin{aligned}\psi(n, m) =& \frac{2\pi}{\lambda}dn[\sin\theta_{\text{out}}\cos\phi_{\text{out}} - \sin\theta_{\text{in}}\cos\phi_{\text{in}}]\\ &+ \frac{2\pi}{\lambda}dm[\sin\theta_{\text{out}}\sin\phi_{\text{out}} - \sin\theta_{\text{in}}\sin\phi_{\text{in}}],\end{aligned} \tag{8}$$

where d is the distance between the array elements and λ is the wavelength of the impinging wave. In the ULA case (8) reduces to (7).

The constant phase term Δ_ϕ in (6) can be used to further improve the SNR at the receiver when the direct channel $\mathbf{h}_1$ exists. By varying Δ_ϕ, the beam direction and shape at the RIS does not change, but the phase of the reflected signal can be controlled. The received signal at the receiver is the sum of the signals through the direct channel and reflected from the RIS. Due to the different path lengths, the summation can be destructive resulting in lowered gain unless the phases are further adjusted. The destructive summation can be turned into constructive by adjusting the phase responses of the RIS elements accordingly with Δ_ϕ in (6).

B. RIS Configuration

When the RIS configuration is set by (6), (7) or (8), the RIS forms narrow beams to the UE and BS. The maximization of the SNR at the receiver requires accurate alignment of the beams, which generally requires computationally complex algorithms or long search times. However, if the goal is not to find the highest possible SNR, but instead to find the RIS configuration that fulfills some minimum performance level, e.g., a predetermined SNR value, the search time can be reduced. The proposed RIS configuration method is described in Algorithm 1. The threshold for the SNR (γ_{target}) varies depending on the application. The search time can be limited with the parameter $i_{\max}$. The search time limitation can be useful in cases where the RIS fails to assist in the communication between a UE and a BS and can be freed to be used by some other UE. The codebook of the proposed search procedure consists of the rows of an $M \times M$ discrete Fourier transform matrix $\mathbf{F}$. The accuracy of the search can be improved with spatial oversampling by selecting $M > N$.

Algorithm 1 RIS configuration search

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Target: $i_{\max}$, $\gamma_{\text{target}}$
Initialize: $i = 0$, $\gamma_i = -\infty$ dB
  while $i < i_{\max}$ & $\gamma_i < \gamma_{\text{target}}$ do
    $i = i + 1$
    Set $\mathbf{\Phi}_i = \text{diag}(\mathbf{F}(i, 1 : N_{\text{RIS}}))$
    Receive $y = (\mathbf{h}_1 + \mathbf{h}_3^{\text{H}}\mathbf{\Phi}_i\mathbf{h}_2)x + n$
    Measure $\gamma_i$
  end while
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1) Application in 5G NR Networks : The proposed method can be applied in 5G NR networks with minor additions to the specifications. When a UE arrives to a cell equipped with a RIS, it needs to discover the presence of the RIS. The RIS discovery can be integrated into the initial access procedure. For the initial access, a 5G NR base station (gNB) transmits SS blocks periodically. The periodicity can vary between 10 ms and 160 ms. The SS block consists of the primary synchronization (PSS) and the secondary synchronization signals (SSS) together with the physical broadcast channel (PBCH). When a UE is searching for a new cell, it waits to receive the SS. After the SS is detected, the device can synchronize to the network and acquires system information of the network. If a RIS is present in the cell, the information about its presence is added in the data transmitted in the PBCH. If the RIS has not been reserved for any link between the gNB and some UE, the network varies the RIS configuration in sync with the SS block transmission. The information about the periodicity of the RIS configuration can also be added to the PBCH content. The required additions to the 5G NR specifications are 1) RIS and RIS control unit deployment, 2) addition of the RIS information field to the PBCH containing the information about the presence of the RIS and the timing related to the RIS configuration, and 3) the control link between the UE and the RIS control unit.

When a UE initiates the data transfer, it measures the power of the received SS block and calculates the SNR. If the SNR is below a required threshold value, the UE sends a request for the RIS control unit to reserve the RIS. If the RIS is available, the UE is granted the control of the RIS. The two options for the RIS configuration are:
Option 1: UE keeps monitoring the SNR calculated from the SS block while the RIS configuration is varied. When the SNR reaches or exceeds the required threshold value, the UE reserves the RIS and informs the RIS controller to use the corresponding RIS configuration and starts the data transmission with the gNB.
Option 2: The link between the UE and the gNB is established even when the SNR level is lower than requested. The UE reserves the RIS. The gNB then transmits the CSI-RS with minimum periodicity (5 ms). When the SNR reaches or exceeds the required threshold value, the UE instructs the RIS controller to use the corresponding RIS configuration, and the actual data transmission is started. If the SNR target is not reached after a predetermined time, the RIS is released.

If no direct link between a UE and gNB exist, the RIS must be configured before the connection can be established. In this case, the RIS configuration is varied in sync with the SS block transmission. When a UE receives the SS block, it can synchronize with the network and receive system information from the PBCH. The PBCH includes the information about the periodicity of the RIS configuration, hence, after PBCH reception the UE knowns the network and RIS control timing. When the UE needs to establish the connection for the data transmission it reserves the RIS and informs the RIS controller that it was able to receive signals from the gNB with the corresponding RIS configuration. The RIS configuration is initially set to this configuration. If the SNR threshold requirement is not met, the set RIS configuration is used as the starting point for the search process. When the target SNR is reached, the RIS configuration process is stopped, and data transmission starts. If the SNR target is not reached after a predetermined time, the RIS is released. An example for the RIS configuration signal timing is sketched in Fig. 2.

IV. NUMERICAL EXAMPLES

A. Constructive vs. Destructive Summing of the Signals

The use of Δ_ϕ in (6) to increase the SNR at the receiver in a case when the direct channel between the UE and the BS exists is illustrated in Fig. 3. The direct channel in this example has been modelled with the 5G NR CDL-A delay profile and its path-loss is according to non-line-of-sight (NLoS) urban micro – street canyon model [11] (UE antenna height 1.5 m, BS antenna height 10 m, RIS height 5 m, RIS size 16×16 elements, distance between the UE and BS 180 m). The UE – RIS and RIS – BS channels are modelled as one-tap channels, the UE – RIS and the RIS – BS distances have been 5 m and 180 m, and the path losses have been calculated with the line-of-sight (LoS) indoor – office and LoS urban micro – street canyon loss models defined in [11], respectively. The RIS is first configured based on the AoA, ZoA, AoD and DoA

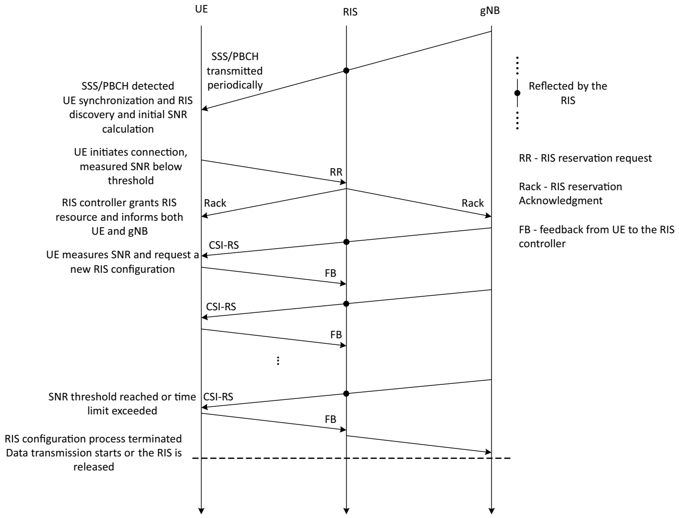

Fig. 2. Control siganling for RIS configuration when no link between a UE and gNB exist.

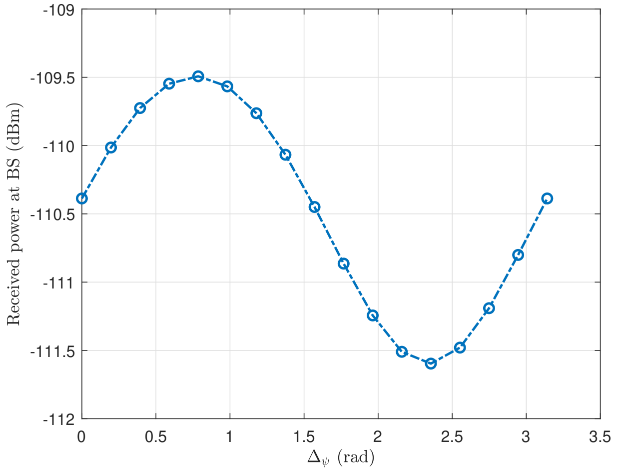

Fig. 3. SNR improvement by Δ_{ϕ}.

angles at the RIS. The phase shift Δ_{Φ} is then swept from 0 to π radians with the sweep step size $\pi/16$. In this example case the received power variation is 2.1 dB.

B. RIS Configuration

The search for the RIS configuration was tested with simulations in a case where a 64-element uniform-linear array type RIS is used to form a link between a single antenna UE and a single antenna BS when there is no direct link between the UE and the BS. The SNR threshold (γ_{target}) is set to 10 dB and the search time is limited based on the RIS size and the oversampling factor (SP), i.e., $i_{\text{max}} = SP \cdot N$. The signal bandwidth is 20 MHz, the center frequency is 10 GHz, the transmit power is 20 dBm and the noise figure of the receiver is assumed to be 5 dB. The link distances, the UE and BS antenna heights as well as the RIS height are the same as in Section IV-A. The recorded SNR values for 10^5 channel realizations are shown in Fig. 4. The ideal SNR value marked with the dashed line is calculated with the perfect channel information. The averaged SNR line is calculated over all iterations and includes also the data points where the search has failed.

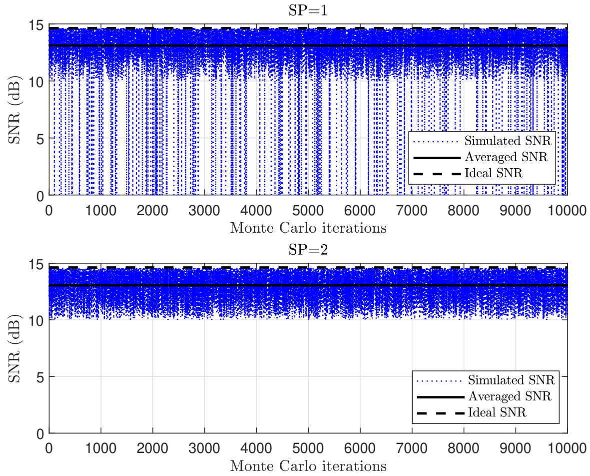

Fig. 4. The effect of spatial oversampling in outdoor environment.

With $SP = 1$ the fail rate, i.e., the fraction of cases when the target SNR value has not been reached, is 0.017. When the spatial oversampling is increased to $SP = 2$, the fail rate drops to 0. The average numbers of required iterations (i in Algorithm 1) with $SP = 1$ and $SP = 2$ are 33 and 63, respectively. If the goal would be to find the RIS configuration providing the maximum SNR in the $SP = 1$ and $SP = 2$ cases, the number of transmissions would be 64 and 128, respectively.

Simulations have also been run for an indoor scenario where the SNR target value has been set to 8 dB. The path losses for the channels from the UE to the RIS and from the RIS to the BS are calculated according the indoor – office model in [11], and distances are 5 and 15 meters, respectively. The RIS, the transmit antenna and the receive antenna heights are 2 m, 1.5 m and 2.5 m, respectively. Results presented in Fig. 5 show the SNR performance with spatial oversampling ratios 1 and 2. With no oversampling ($SP = 1$), the fail rate is 0.030. When the oversampling is increased to 2, the fail rate has dropped to zero. The mean numbers of required iterations with $SP = 1$ and $SP = 2$ are 33 and 63, respectively. The required number of iterations to find the RIS configuration providing the maximum SNR would be the same as in the outdoor scenario above.

V. CONCLUSION

It was shown that when a single dominant path exists between the UE and the RIS and also between the RIS and the BS, the RIS configuration calculated as a solution to a spectral efficiency maximization problem and conventional antenna array beam steering at the RIS give the same result. Hence, in this use case, the RIS configuration can be found

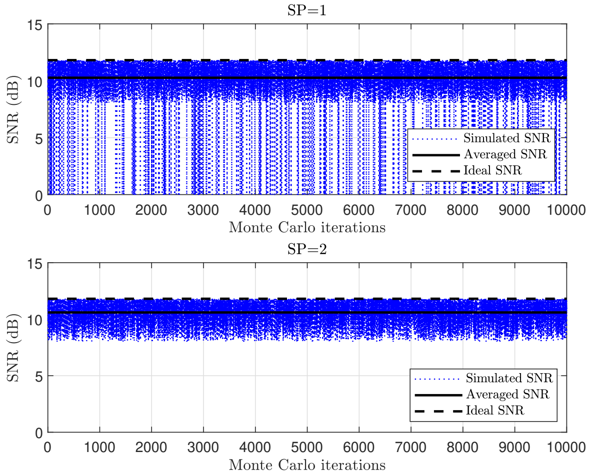

Fig. 5. The effect of spatial oversampling in indoor environment.

without explicit channel estimation. However, it is computationally complex to find a RIS configuration resulting in SNR maximization without the channel estimation. When the requirement to find the maximum SNR is relaxed, the search time can be reduced significantly. Thereby, a RIS configuration method to achieve a target SNR instead of the theoretical maximum has been proposed. The proposed method does not require channel estimation, instead only the measurement of the received SNR is needed. When the target SNR value is reached, the configuration process can be stopped. This has the potential to shorten the time needed to find the RIS configuration. The search time and the probability to find the correct RIS configuration can be adjusted by the spatial oversampling factor. It is also shown that when the direct channel between the UE and the BS exists, the gain provided by the RIS can be further enhanced by adding a constant phase shift to all RIS elements after the RIS has been configured based on the AoA and AoD at the RIS.

Only a single antenna BS and UE have been considered. However, the proposed RIS configuration search can be used also with multi-antenna devices. For example, in a 5G NR multi-antenna UE the sounding reference sequences (SRSs) transmitted from each antenna port are orthogonal. If the number of physical antennas in the UE equals the number of antenna ports, each SRS is transmitted omnidirectionally. When the RIS is in the far-field of the UE, the transmitted SRSs arrive at the RIS from the same direction and are then reflected to the BS. The BS can detect the orthogonal SRSs and measure the received power.

An efficient RIS configuration process is one of the key elements in the utilization of RIS units in wireless networks. However, before large scale deployment of RIS units can be started, there are still open questions to be answered. These include, but are not limited to the sharing of RIS resources between several users and coordination of multiple RIS units in a network.

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