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Performance optimization of reconfigurable intelligent surfaces in multipath channels

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Abstract

We investigate the performance of reconfigurable intelligent surfaces (RIS) in improving the characteristics of the propagation channel regarding the radio link between the transmitter (Tx) and the receiver (Rx). It is commonly considered that the RIS should be in line of sight (LOS)of both Tx and Rx, which may not always be the case. Whether this is the case or not, propagation through other paths should also be evaluated. To that aim, we compare in this work the received power that can be achieved through an optimal phase law for the scattering elements on the RIS resulting in constructive multipaths interference at the receiver, to its value through only a LOS path. The evaluation makes use of a simplified model of the RIS and of the multipath propagation, providing highlights on theses comparisons. The achieved gain can be high, combining array gain on both sides of the RIS and benefiting from channel hardening for large RIS sizes.

1. Introduction

A reconfigurable intelligent surface is a controlled electromagnetic (EM) object acting as intermediate reflector or scatterer between a transmitter and a receiver and able to adapt the characteristics of the propagation channel to improve the link quality. While this idea has been the subject of an enormous literature in the recent years (see, e.g. [1]-[6]), the interplay between the physics of propagation and of EM, the technology and architecture of such devices and the algorithms to estimate and optimize the performance still motivates interactive works between the various scientific communities involved. In particular, the impact of the complex features of the radio channel propagation between Tx and RIS or RIS and Rx is not so much considered (see, e.g. [4]-[6]). Most often, the RIS is seen as an intermediate between Tx and Rx to improve the link budget, especially in non-line of sight (NLOS) and at high frequencies where obstructions cannot efficiently be turned around by waves owing to reduced diffraction.
Furthermore, noteworthy is the difference between the RIS acting as a mirror or as a scatterer, which is often unclear and confused in the literature. The inherent physical phenomena between these two regimes have been discussed in [3] (Fig. 1), where it was shown that the scatterer regime operates when the Tx/Rx distance to the RIS is such that less than the 1st Fresnel zone is contained within the RIS, which is equivalently to say that the Tx/Rx is in the far field of the RIS. In that case, the received power decays with the 4th power of the distance, in accordance to the well-known radar equation.
Conversely, when more than a single Fresnel zone is contained within the RIS, the latter acts as a mirror and the received power is proportional to the 2nd power of the inverse of the distance. In case the RIS is a line (1D object) and not a (square) surface, the mirror behavior results in a 3rd power of the inverse distance.

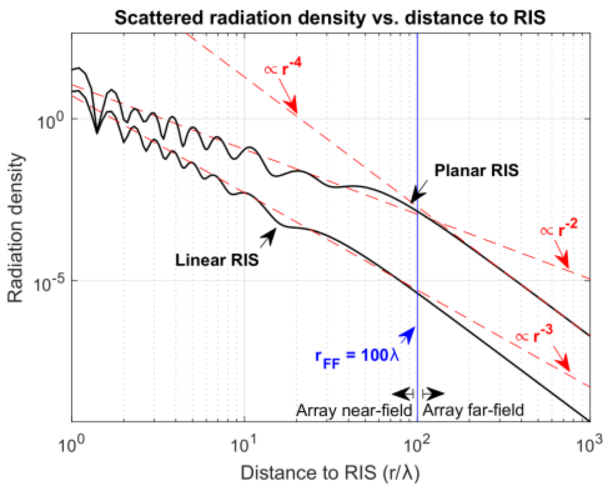

Figure 1. Dependence of the received power to the Tx(Rx)-RIS distance (extracted from [3]).

The 4th power incurred by the scattering behavior is a curse, meaning that the received power very quickly decreases with distance, making the RIS very inefficient. For that reason, among the design rules for a RIS, that of its size is essential. Indeed, the larger the RIS, the farther is the distance beyond which Tx/Rx can stay within the mirror regime. Unfortunately, large RIS incur large costs, especially at high frequencies where the size of the elemental devices composing the RIS is small and many are needed. It might be that in the mm wave range, thousands of devices should be necessary to enable proper RIS operation, within an adequate range of distances. Hence, the more we can make of the propagation channel to improve the link budget, the better it is.
In this context, the present work addresses the impact of propagation paths outside the main LOS on the performance of a radio link mediated by a RIS, evaluated as the received power. We do this through a simplified model of both the RIS and the radio channel, essentially in

order to appreciate how much we can get from NLOS multipaths. Furthermore, since the focus is on distances where the RIS performance is expected to be low, we restrict the work to the scattering regime, as explained above.

2. System, RIS and propagation models

2.1 RIS model

The model used for the RIS is depicted in Fig. 2. It is composed of a regular array of $N_{dip} = N_v \times N_h$ horizontal x vertical scattering elements. In the examples below, the spacing between adjacent elements in the x and y directions is chosen to be λ/2, where λ is the wavelength. We assume elements to be isotropic scatterers, in the sense that their bistatic scattering cross section is independent of any angle. Furthermore, the phase of the outgoing scattered wave is assumed to be possibly controlled over 2π radians by the embedded electronics. This is, e.g., what can be done through reactive loading of an antenna device [7]. Here, this is coined as "reactive scattering". Furthermore, we assume the elements to be uncoupled, i.e. the electromagnetic status of one element does not impact the status of another.
For simplicity, both Tx and Rx are assumed to be placed in the horizontal plane intersecting the RIS in its center.

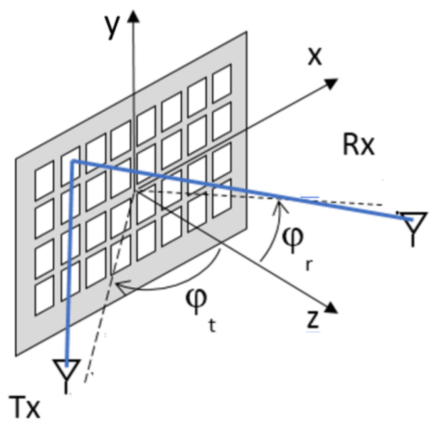

Figure 2. Schematic view of the system model; The blue line depicts one Tx/Rx antenna element pair propagation path through one RIS device.

2.2 Propagation model

We consider a discrete propagation model, expressed in terms of an integer number of incoming and outgoing waves. Furthermore, given that we restrict to the scattering regime for the RIS, all these waves can be approximated as plane waves. A second assumption is that there is no strong relation between the Tx→RIS propagation and the RIS→Rx propagation. In other words, the number of incoming and outgoing propagation paths are uncorrelated, as well as their directions. This is justified by the fact that, given the motivation to make use of a RIS, there is no reason that the Tx-RIS environments and the RIS-Rx environment were similar to the point of having strongly related propagation channels.
Since the goal is to address the impact of multipath propagation in its essential features, several more assumptions are made:

- The incoming and outgoing angles φ_t and φ_r of the wavevectors (see Fig. 1) are uniformly distributed over [-60° +60°], and the elevation angles θ_t and θ_r (not shown in Fig. 1) are uniformly distributed over [-30° +30°]
- The path amplitudes are Rice distributed, defined through the K factor
- The path carrying the highest power (both for the Tx→RIS and RIS→Rx propagations) is assumed to be in LOS while the others are NLOS
- The phases of all path amplitudes are independent and uniformly distributed over 2π radians
- Finally, the polarization is ignored.

From the well-known radar equation, we have for the received power, in the case of a single path:

$$P_{rec} = P_t \frac{\lambda^2 G_t G_r \sigma_{RCS}(\varphi_t, \varphi_r, \theta_t, \theta_r)}{(4\pi)^3 d_t^2 d_r^2} \quad (1)$$

Where P_t is the transmitted power $G_t G_r$ is the product of the antenna gains at Tx and Rx, d_t and d_r are the distances between the RIS and the transmitter or the receiver, respectively, and σ_{RCS} of dimension an area is the bistatic scattering cross section, expressing the power magnitude of the scattered spherical waveform from the incident plane wave.
In the case of a multipath structure before and after scattering by the RIS, the phases must be taken into account and the constructive/destructive interference of waves at the receiver must be accounted for. Under all assumptions, the received power can, hence, be written under the form:

$$P_{rec} = K \left| \sum_{m,n} A_{tm} B_{rn} \Delta_{RCS}(\varphi_{tm}, \varphi_{rn}, \theta_t, \theta_r) \right|^2 \quad (2)$$

Where A_{tm} and B_{rn} stand for the complex amplitudes of incoming and outgoing waves, indexed by m and n respectively, and where Δ_{RCS}, being complex valued, embeds the phase dependence of the scattering with $\sigma_{RCS} = |\Delta_{RCS}|^2$. Other terms are included in the constant K, taking into account the normalization

$$\sum_m |A_{tm}|^2 = \sum_n |B_{rn}|^2 = 1 \quad (3)$$

Furthermore, given that each elemental scatterer in the RIS is isotropic, we may further express Δ_{RCS} as follows:

$$\Delta_{RCS}(\varphi_{tm}, \varphi_{rn}, \theta_{tm}, \theta_{rn}) = exp(j\Phi_{k,l}) \sum_{k,l} exp\left[j(\boldsymbol{k}_{tm} - \boldsymbol{k}_{rn}).\boldsymbol{u}_{k,l}\right] \quad (4)$$

Where the sum is operated on any pair of scattering element and any coefficient specific of the (isotropic) elemental bistatic scattering is included in the constant K. The

directions of wavevectors $\boldsymbol{k}_{tm}$ and $\boldsymbol{k}_{rn}$ are defined by the angles $\varphi_{tm}, \varphi_{rn}, \theta_{tm}$ *and* θ_{rn} .
In other words, each incoming wave is equally scattered into each outgoing wave, however phase terms are utterly important through interferences at the receiver, coming either from the wave inherent phases, dephasing by the array factor or dephasing by the reactive load enforced on a scatterer, contained in $\Phi_{k,l}$.

2.2 Link optimization

The optimization goal is here simply taken to maximize the received power. To that aim, the RIS is assumed to be able to adjust the phases of each of the reactive scattering elements.

$$P_{rec} = K\left|\sum\nolimits_{k,l} exp(j\Phi_{k,l})\, C_{k,l}\right|^2 \qquad (5)$$

with

$$C_{k,l} = \sum\nolimits_{m,n} A_{tm}B_{rn}exp[j(\boldsymbol{k}_{tm} - \boldsymbol{k}_{rn}).\boldsymbol{u}_{k,l}] \qquad (6)$$

The maximization of P_{rec} is, hence, straightforward through $\Phi_{k,l} = -Arg(C_{k,l})$ (equal gain combining) and

$$P_{rec\,max} = K\left|\sum\nolimits_{k,l}|C_{k,l}|\right|^2 \qquad (7)$$

In the present scheme, the physical mechanism allowing to improve the Rx-Tx link budget is only through the control of interferences at the receiver, in a "holographic beamforming" spirit [8]. Indeed, in the present model the scattered wave is only phase adjusted, which means that the received power at Rx results from the constructive/destructive interference of N_r outgoing paths, themselves resulting from combining M_t incoming ones.
It is especially interesting to compare $P_{rec\,max}$ to its value for a single (LOS) path on both RIS sides, which according to the normalization rules brings:

$$P_{Single\ LOS} = K|N_{dip}|^2 \qquad (8)$$

The square dependence on N_{dip} is not surprising in comparison to a conventional beam steering antenna (linear dependence of the gain on the number of antenna elements), since here, in addition, the total scattered power is proportional to the RIS area, i.e. to N_{dip}.
The analysis below intends to address the impact of multipaths on the maximum received power, hence the comparison will also be made of $P_{rec\,max}$ to P_{LOS}, where the LOS path is assumed to be the strongest one (indexed as $n = m = 1$ in eq. (9) below). P_{LOS} is obtained by enforcing the following phase law on the RIS elements:

$$\Phi_{k,l} = -(\boldsymbol{k}_{t1} - \boldsymbol{k}_{r1}).\boldsymbol{u}_{k,l} \qquad (9)$$

Accordingly, the plots below show for the two quantities $P_{rec\,max}/K|N_{dip}|^2$ and $P_{rec\,max}/P_{LOS}$ the probability distribution function (PDF).

2. Results

The results presented here are shown using the coding convention (N_v x N_h RIS – M_t x N_r paths – K_t - K_r Kfact), where K_t - K_r are the Rice K factors (in dB) on the incoming and outgoing paths, respectively. For simplicity, the two K factors are taken identical in all results shown below.
The statistical distributions have been computed with 5000 realizations of the channel statistics mediated by the RIS. A fit of the PDF has been obtained with the generalized normal distribution (GND), version 1 [9], which has the capability to contain both the normal distribution and the Laplace distribution, in particular.
We can see on Fig. 3, for a 20 elements linear horizontal RIS and 20 paths on both sides, that the maximum received power for the optimal phase law very much exceeds the best path beam steering law (i.e. *the one involved in* P_{LOS}), by about 10 dB on average for K_t= K_r,=-10 dB, i.e. close to a pure Rayleigh channel. The gain vs. LOS is logically reduced with a higher K factor, down to less than 1 dB for K_t= K_r,=+10 dB. We also see that, generally speaking, the ratio $P_{rec\,max}/K|N_{dip}|^2$ stays a few dB below 0, although in some cases it can exceed the single path case by up to 1-2 dB.
A square RIS array of 20x20 elements results in narrower distributions (Fig. 4), which is certainly a consequence of the so called "channel hardening", well known for massive MIMO systems [10]. This is further observed for a 50x50 RIS array in Fig. 5.

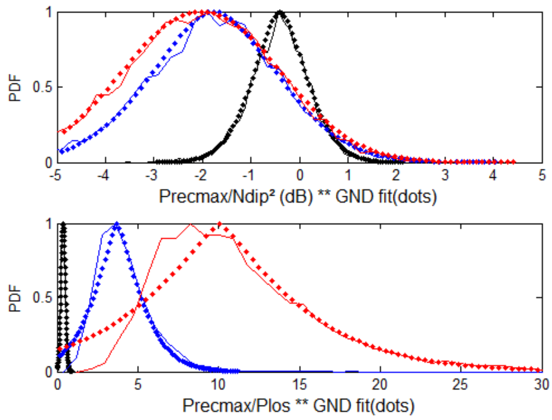

Figure 3. (1x20 RIS – 20x20 paths) case ; black: (10 – 10 Kfact) ; blue: (0 – 0 Kfact) ; red: (-10 – -10 Kfact) ;

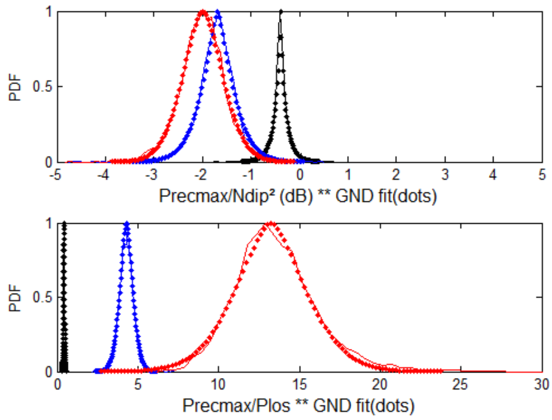

Figure 4. (20x20 RIS – 20x20 paths) case ; black: (10 – 10 Kfact) ; blue: (0 – 0 Kfact) ; red: (-10 – -10 Kfact) ;

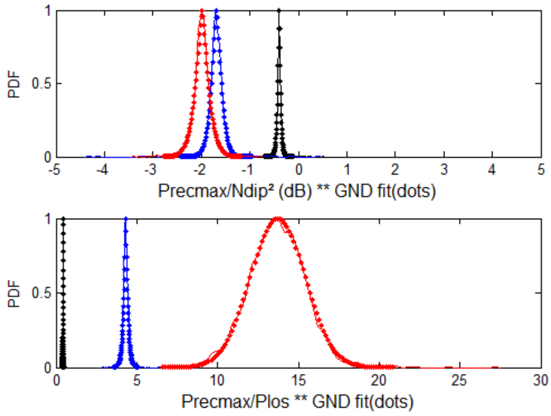

Figure 5. (50x50 RIS – 20x20 paths) case ; black: (10 – 10 Kfact) ; blue: (0 – 0 Kfact) ; red: (-10 – -10 Kfact) ;

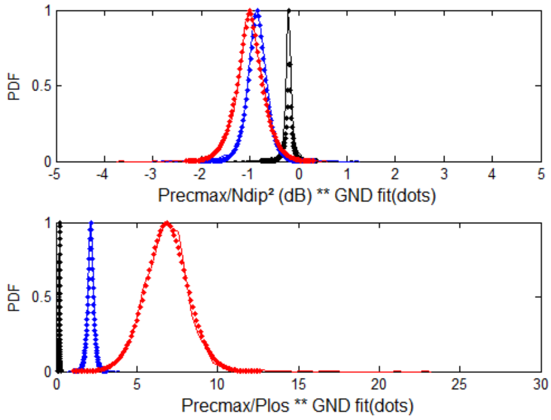

Figure 6. (20x20 RIS – 1x20 paths) case ; black: (10 – 10 Kfact) ; blue: (0 – 0 Kfact) ; red: (-10 – -10 Kfact) ;

Finally, the case of an asymmetric channel configuration, i.e. pure single LOS on the Tx side and fully multipath on the Rx side (Fig. 6), brings intermediate performance gain vs. the fully multipath channel on both sides, with mean values for $P_{rec\,max}/P_{LOS}$ of ~7 dB and 13 dB, respectively. This just confirms that the RIS optimal phase law allows to compensate for multipath dispersion on both sides of the RIS equally and, roughly speaking, the gains add.

6. Conclusion

In this work we have recalled the poor performance of RIS to mitigate heavy path losses when the RIS size is too small or the distance too large to be in the mirror regime, since the scatterer regime for a RIS results in the received power to decay as the 4th power of the distance. This has motivated us to look into a way to gather more received power than the usual single reflection mode. This can be achieved by enforcing an optimal phase law on the scattering elements constituting the RIS, for which the multipaths interfere constructively at the receiver, bringing a large array gain on both sides of the RIS.

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