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RIS-ENHANCED 6G MMWAVE COMMUNICATIONS: CAPACITY ANALYSIS AND OPTIMIZATION

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Abstract:
The advent of 6G mobile networks promises unprecedented data rates, ultra-low latency, and massive connectivity. However, the utilization of millimeter-wave (mmWave) frequencies, such as 28 GHz, introduces significant challenges regarding path loss and signal blockage. Reconfigurable Intelligent Surfaces (RIS) have emerged as a key enabling technology to overcome these propagation limitations by intelligently reflecting signals. This paper presents a performance analysis of an RIS-assisted Orthogonal Frequency Division Multiplexing (OFDM) system tailored for 6G mmWave networks. We derive the transmission capacity relations based on the impulse response method in the complex baseband, and describe an optimization algorithm based on the power iteration method to maximize the system capacity by configuring RIS phase shifts. Simulation results for the 28 GHz band demonstrate significant gains in transmission capacity and Bit Error Rate (BER) performance compared to systems without RIS or with random configurations.

Keywords: *6G, Reconfigurable Intelligent Surfaces (RIS), OFDM, mmWave, Capacity Optimization, Impulse Response.*

Introduction

The evolution towards 6G mobile networks aims to support advanced applications such as holographic communications, autonomous systems, and the Internet of Everything (IoE). To achieve terabit-per-second data rates, 6G networks will extensively utilize higher frequency bands, including the *mmWave* spectrum (e.g., 28 GHz) and terahertz frequencies. However, signals in these bands suffer from severe path loss and are highly susceptible to blockage, limiting coverage and reliability. Reconfigurable Intelligent Surfaces (RIS) offer a transformative solution by creating smart radio environments. An RIS consists of a large number of passive meta-atoms that can independently manipulate the phase and amplitude of incident electromagnetic waves. By dynamically configuring these elements, an RIS can establish virtual Line-of-Sight (LoS) links, enhance signal strength, and mitigate interference.

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This paper focuses on modeling and optimizing an RIS-assisted OFDM system for 6G *mmWave* communications. Here we present:

- A mathematical model of the wideband OFDM channel with RIS based on the impulse response method.
- Derivation of the transmission capacity and a suboptimal algorithm for RIS configuration optimization.
- Performance evaluation at 28 GHz, analyzing transmission capacity versus bandwidth and Bit Error Rate (BER).

1. System Model

Orthogonal Frequency Division Multiplexing (OFDM) is a modulation technique that divides the available frequency spectrum into a large number of narrowly spaced orthogonal subcarriers. This orthogonality ensures that the integral of the product of any two different subcarriers over one period is zero, significantly reducing Inter-Carrier Interference (ICI) and improving spectral efficiency. In the transmitted baseband, a block of K complex symbols $X[\nu]$ (where ν ν=0, …, K−1) is mapped onto the subcarriers. These frequency-domain symbols are converted into a time-domain signal $x[k]$ using the Inverse Discrete Fourier Transform (IDFT), typically implemented via the Inverse Fast Fourier Transform (IFFT):

$$x[k] = \frac{1}{\sqrt{K}} \sum_{k=0}^{K-1} X[\nu] e^{j\frac{2\pi}{K}\nu k} . \quad (1)$$

To mitigate Inter-Symbol Interference (ISI) caused by multipath propagation, a Cyclic Prefix (CP) of length M is appended to the beginning of each OFDM symbol. The CP is a copy of the last M samples of the symbol. The length of the CP is chosen to be larger than the maximum delay spread of the channel (τ_{max}), ensuring that linear convolution with the channel impulse response appears as circular convolution.

At the receiver, after removing the CP, the received time-domain signal $y[k]$ is transformed back to the frequency domain $Y[\nu]$ using the Discrete Fourier Transform (DFT):

$$Y[\nu] = \frac{1}{\sqrt{K}} \sum_{k=0}^{K-1} y[k] e^{-j\frac{2\pi}{K}\nu k} . \quad (2)$$

This process effectively decomposes the frequency-selective wideband channel into K parallel flat-fading narrowband subchannels, simplifying equalization and capacity analysis.

We consider a Single-Input Single-Output (SISO) OFDM system assisted by an RIS comprising N meta-atoms[1], [4]. The signal propagation occurs via two paths: a direct path from the Base Station (BS) to the User Equipment (UE), and a reflected path via the RIS. Using the impulse response method in the complex baseband, the total continuous-time impulse response $h(t)$ is the superposition of the direct channel $h_d(t)$ and the cascaded RIS channel. The signal $v(t)$ at the receiver input is given by the convolution (denoted with $\otimes$) of the transmitted signal $z(t)$ and the channel impulse response $h(t)$:

$$v(t) = h(t) \otimes z(t) = \left(h_d(t) + \sum_{n=1}^{N} h_{\mathrm{r},n}(t) \otimes \Phi_n(t) \otimes h_{\mathrm{t},n}(t) \right) \otimes z(t), \quad (3)$$

where $h_{t,n}$ and $h_{r,n}$ represent the channels from BS-to-RIS and RIS-to-UE respectively, and $\Phi_n(t)$ represents the transformation by the n-th meta-atom introducing a phase shift ϕ_n. After sampling and filtering with a pulse shaping function $p(t)$ (e.g., sinc function), the discrete impulse response $h[k]$ is derived as:

$$h[k] = h_d[k] + \sum_{n=1}^{N} h_{r,n}[k] \otimes \mathbf{\Phi}_n[k] \otimes h_{t,n}[k]. \quad (4)$$

Considering the multipath components with attenuations α and delays τ, the discrete impulse response coefficient $h[k]$ can be explicitly expressed as:

$$h[k] = \sum_{i=1}^{L_d} \alpha_{d,i} e^{-j2\pi f_c(\tau_{d,i}-\eta)} \operatorname{sinc}\left(k + B(\eta - \tau_{d,i})\right) + \sum_{n=1}^{N} \sum_{j=1}^{L_r} \sum_{i=1}^{L_t} \alpha_{\mathrm{r},n,j} \alpha_{\mathrm{t},n,i} e^{-j2\pi f_c(\tau_{\mathrm{r},n,j}+\tau_{\mathrm{t},n,i}+\tau_{\phi_n}-\eta)} \operatorname{sinc}\left(k + B(\eta - \tau_{\mathrm{r},n,j} - \tau_{\mathrm{t},n,i} - \tau_{\phi_n})\right), \quad (5)$$

where B is the bandwidth, η is sampling delay of UE, L_d, L_r and L_t are numbers of direct, RIS-UE and BS-RIS paths respectively, and f_c is carrier frequency. In the frequency domain, for the ν-th OFDM subcarrier, the channel coefficient $H[\nu]$ is obtained by taking the DFT of $h[k]$:

$$H[\nu] = H_d[\nu] + \mathbf{h}_{BS-RIS}^{T}[\nu] \mathbf{\Phi} \mathbf{h}_{RIS-UE}[\nu], \quad (6)$$

where $\mathbf{\Phi}$=diag($e^{j\phi_1}$,...,$e^{j\phi_N}$) is the diagonal matrix of RIS phase shifts. Explicit forms of channel vectors $\mathbf{h}_{BS\text{-}RIS}$ and $\mathbf{h}_{RIS\text{-}UE}$ can be obtained from the previous relation [1],[2]. This formulation allows us to analyze the impact of RIS configuration on each subcarrier independently.

2. Capacity Analysis and RIS Optimization

According to the Shannon-Hartley theorem, the transmission capacity C depends on the bandwidth and the Signal-to-Noise Ratio (SNR). For a wideband OFDM system with K subcarriers, the total capacity in bits per second is derived as [1]:

$$C = \frac{B}{K+M}\sum_{\nu=0}^{K-1}\log_2\left(1+\frac{q_\nu^{opt}\left|H[\nu]\right|^2}{N_0}\right)\ \left[\text{bit/sec}\right], \tag{7}$$

where B is the total bandwidth, M is the cyclic prefix length, N_0 is the noise power spectral density, and $q^{opt}[\nu]$ is the optimal power allocated to subcarrier ν (obtained via water-filling). The term $|H[\nu]|^2$ represents the channel gain, which is directly influenced by the RIS configuration $\mathbf{\Phi}$. The SNR for subcarrier ν is given by:

$$SNR[\nu] = \frac{P\left|H[\nu]\right|^2}{BN_0}, \tag{8}$$

Where P is the transmit power. The objective is to determine the phase shifts ϕ_n that maximize the system capacity. Since capacity is monotonically increasing with SNR, a practical approach is to maximize the total channel gain across all subcarriers. The optimization problem is formulated as maximizing the quadratic form:

$$\max_{\mathbf{\Phi}}\sum_{\nu=0}^{K-1}\left|H_d[\nu]+\mathbf{h}_{BS-RIS}^T[\nu]\mathbf{\Phi}\mathbf{h}_{RIS-UE}[\nu]\right|^2, \tag{9}$$

subject to $|\phi_n|=1$ (unit modulus constraint for passive RIS). This is a non-convex problem. We employ a suboptimal iterative algorithm based on the Power Iteration Method [5]. The algorithm initializes the configuration vector $\mathbf{w}_0$ (e.g., all ones) and iteratively updates it:

$$\mathbf{w}_{i+1} = \frac{\mathbf{A}\mathbf{w}_i}{\left\|\mathbf{A}\mathbf{w}_i\right\|}, \tag{10}$$

where $\mathbf{A}$ is a matrix constructed from the channel correlations

$$\mathbf{A} = \sum_{\nu=0}^{K-1}\mathbf{h}_{BS-RIS}^T[\nu]\mathbf{h}_{RIS-UE}[\nu]. \tag{11}$$

In each iteration, the phase of the resulting vector is extracted to update the RIS configuration $\mathbf{\Phi}$, while maintaining the unit modulus constraint.

This method converges to a configuration that aligns the reflected signals constructively with the direct path.

In addition to capacity, the reliability of the link is assessed via the Bit Error Rate (BER). For a given modulation scheme, the BER is a function of the SNR. For square M-QAM modulation in an AWGN channel, the approximate BER is given by [6]:

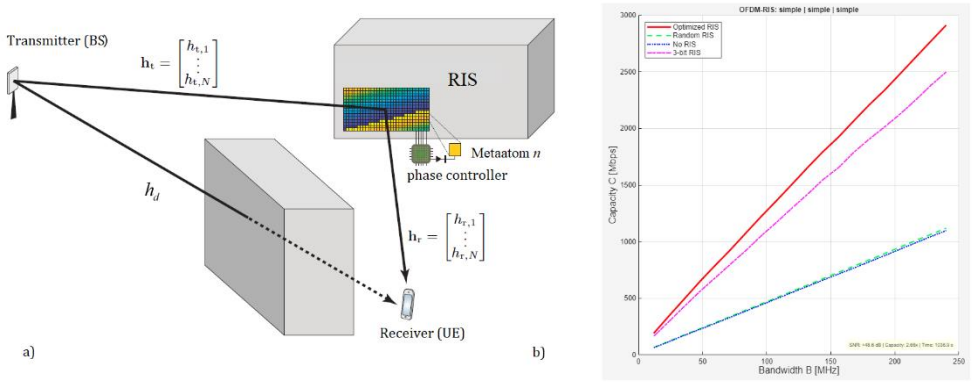
$$\mathrm{BER} \approx \frac{4}{\log_2 \mathrm{M}}\left(1-\frac{1}{\sqrt{\mathrm{M}}}\right) Q\left(\sqrt{\frac{3SNR}{\mathrm{M}-1}}\right), \tag{12}$$

where $Q(\cdot)$denotes the Gaussian Q-function, defined as the tail probability of the standard normal distribution. The optimized RIS configuration increases the received SNR, thereby exponentially reducing the BER according to the above relation.

3. Simulation Results

Simulations were conducted using a devoloped MATLAB code consistent with the methodology outlined in 3GPP TS 38.901 [3], which provides spatial channel models for frequencies up to 100 GHz, making it suitable for *mmWave* and future 6G scenarios. The code is primarily based on the book [1] and the 3GPP TS 25.996 standardization document [7], which provides detailed recommendations for MIMO channel modeling. The carrier frequency was set to 28 GHz (mmWave) to reflect 6G use cases. Schematic diagram of the system is shown in Picture 1.a). Some of simulation parameters are:

- BS position (20, 0, 15) [m]
- UE position (100, 100, 0) [m]
- RIS position (0, 0, 5) [m]
- RIS Size: $N=N_V \times N_H$ (40×40)
- Bandwidth B: Variable (subcarrier spacing × number of subcarriers)
- Noise Density N_0: -174 dBm/Hz
- Path Loss Model: 3GPP Urban Macro (LoS and NLOS components)
- Modulation: 16-QAM and 64-QAM (for BER estimation)

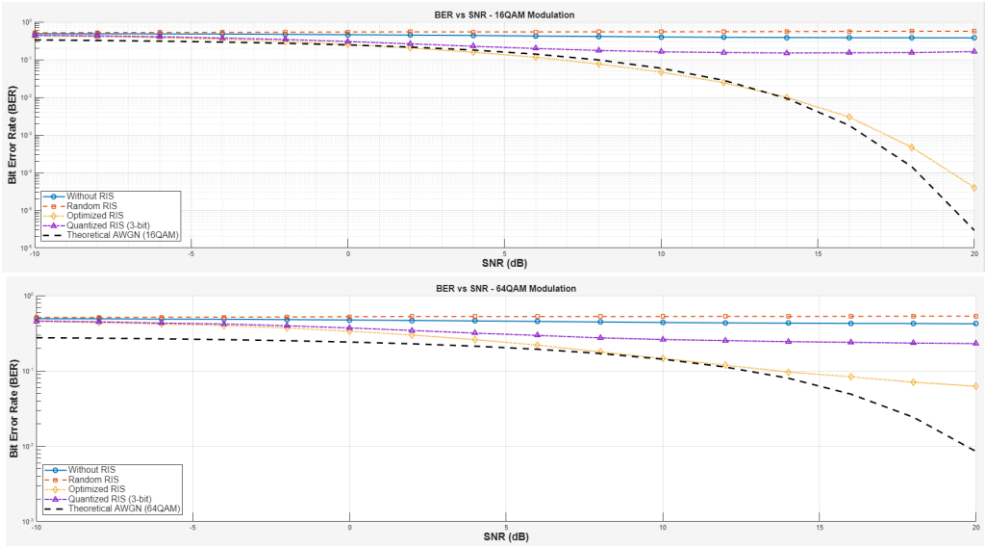


Picture 1. *a) Schematic diagram of OFDM-RIS system b) Total transmission capacity for different RIS configurations*

The position of the RIS- was chosen to be close to the transmitter, since it is known that the effects are significantly better then. Picture 1.b) illustrates the transmission capacity as a function of bandwidth for four scenarios:

1. No RIS**:** Direct link only (often NLOS in *mmWave*).
2. Random RIS**:** RIS phase shifts are randomly conPictured.
3. Optimized 3-bit quantized phase shifts
4. Optimized RIS**:** Phase shifts conPictured exactly using the proposed power iteration algorithm.

The presented results were obtained by averaging over 500 realizations of the system. They indicate that capacity increases logarithmically with bandwidth. However, the absolute values differ significantly. The Optimized RIS scenario achieves the highest capacity, outperforming the "No RIS" case by a substantial margin. Also, 3-bit quantized phase shifts (8 discrete values) give significantly weaker results, which is somewhat unexpected given that some research shows that even 2-bit quantization can give satisfactory results. The "Random RIS" case performs similarly to "No RIS," highlighting the necessity of intelligent configuration. At 28 GHz, the high path loss makes the RIS gain critical; the optimized surface effectively creates a virtual LoS path, recovering the link budget. The capacity gain is proportional to the number of meta-atoms *N*, confirming the beamforming gain of large RIS arrays.



Picture 2. *BER versus SNR for 16-QAM (upper) and 64-QAM(lower) modulations for diferrent RIS configurations*

The BER was evaluated based on the SNR obtained from the channel model. Picture 2. shows the BER versus SNR for different RIS configurations for 16-QAM and 64-QAM modulations. Also, the theoretical values obtained by using relation (12) are shown on diagrams. The Optimized RIS configuration yields a significantly higher SNR compared to the other scenarios. Consequently, the BER curve for the optimized case drops sharply as SNR increases. This confirms that RIS optimization not only improves capacity but also enhances link reliability, which is crucial for 6G ultra-reliable low-latency communication (URLLC) services.

5. Conclusion

This paper analyzed the performance of RIS-assisted OFDM systems in the context of 6G *mmWave* networks. By detailing the OFDM signal structure and utilizing the impulse response method, we presented the capacity relations and implemented a power iteration-based algorithm to optimize RIS phase shifts. Simulation results at 28 GHz demonstrate that an optimally conPictured RIS significantly enhances transmission capacity and reduces BER compared to conventional systems. These findings validate RIS as a pivotal technology for overcoming *mmWave* propagation challenges in future 6G networks. Future work will focus on

dynamic RIS configuration in mobile scenarios and integration with machine learning techniques.

REFERENCES

[1] Bjornson E. and Demir O. T. (2024). Introduction to Multiple Antenna Communications and Reconfigurable Surfaces, Boston-Delft: Now Publishers

[2] Rađenović F. (2024). Modelovanje rekonfigurabilnih inteligentnih površina u kanalima sa ortogonalnim frekvencijskim multipleksiranjem u 5G i B5G mobilnim mrežama primenom metode impulsnog odziva, Master Thesis, ALFA BK Univerzitet, Beograd

[3] 3GPP Technical Specification 38.901 (2022). Study on channel model for frequencies from 0.5 to 100 GHz, 3rd Generation Partnership Project

[4] Wu Q. and Zhang R. (2020). Towards smart and reconfigurable environment: Intelligent reflecting surface aided wireless network, *IEEE Commun. Mag.*, *vol. 58, no. 1*, 106–112

[5] E. Björnson (2021). Optimizing a binary intelligent reflecting surface for OFDM Communications under mutual coupling, in *International ITG Workshop on Smart Antennas(WSA)*, 1–6

[6] J. Proakis G. and Salehi M. (2008). Digital Communications, 5th ed. New York, NY, USA: McGraw-Hill

[7] 3GPP Technical Specification 25.996(2020). Spatial channel model for Multiple Input Multiple Output (MIMO) simulations, 3rd Generation Partnership Project