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Beam Split Mitigation in RIS-Aided Wideband THz Communications using parallel SPDP architecture

***Heba Medhat zegallai[1] and Reem Ibraheem Hussein [2]**

1,2- Faculty of Engineering, University of Tripoli, Libya

*h.zegallai@uot.edu.ly

Abstract

Terahertz (THz) communication systems are considered a promising technology for achieving high data rates in next-generation wireless networks. However, these systems face several challenges, including severe signal attenuation and the beam split effect in wideband scenarios, which is caused by frequency-dependent phase variations. Reconfigurable Intelligent Surfaces (RIS) have been introduced as an effective solution to enhance signal quality by intelligently controlling wave reflections. Nevertheless, conventional phase-only RIS designs still suffer from performance degradation in wideband environments.

This paper aims to enhance the performance of RIS-assisted communication systems by mitigating the beam-split effect and improving beam alignment across different frequencies. Phase Delay Phase (SPDP) architecture is employed to compensate for frequency-dependent effects. In addition, a dual-RIS configuration is proposed to exploit multiple propagation paths, improving the received signal strength, communication reliability, and overall system performance in terms of achievable rate, coverage probability, outage probability, and energy efficiency. Simulation results demonstrate that the proposed SPDP architecture effectively mitigates the beam split effect and achieves accurate beam alignment across all subcarriers, leading to a significant improvement in the achievable rate. Moreover, the proposed

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parallel two-RIS configuration outperforms the conventional single-RIS system by providing higher achievable rates, improved coverage probability, lower outage probability, enhanced energy efficiency, and extended communication coverage, making it a promising solution for future wideband THz communication systems.

Keywords: Terahertz (THz), Reconfigurable Intelligent Surfaces (RIS), Beam Split Effect, Sub-Connected Phase–Delay–Phase (SPDP), Wideband Precoding, Parallel RIS.

التخفيف من ظاهرة انقسام الحزمة في اتصالات التيراهرتز عريضة النطاق المدعومة بالأسطح الذكية القابلة لإعادة التشكيل (RIS) باستخدام الترميز المسبقPSPD

*هبة مدحت الزقلعي، ريم إبراهيم حسين
كلية الهندسة، جامعة طرابلس، ليبيا
*h.zegallai@uot.edu.ly

الملخص:

تعد أنظمة الاتصالات في نطاق التيراهيرتز (THz) من التقنيات الواعدة التي تتيح تحقيق معدلات نقل بيانات عالية في شبكات الجيل القادم. ومع ذلك، تواجه هذه الأنظمة تحديات كبيرة، من أبرزها الفقد العالي في الإشارة وتأثير انقسام الحزمة في الأنظمة واسعة النطاق، والذي ينتج عن التغير في الطور مع التردد. وقد تم اقتراح استخدام الأسطح الذكية القابلة لإعادة التشكيل (RIS) كحل فعال لتحسين جودة الإشارة من خلال التحكم في انعكاس الموجات، إلا أن الأنظمة التقليدية المعتمدة على إزاحة الطور فقط لا تزال تعاني من ضعف الأداء في البيئات واسعة النطاق. تهدف هذه الورقة البحثية إلى تحسين أداء أنظمة الاتصالات المدعومة ب RIS من خلال تقليل تأثير انقسام الحزمة وتحقيق محاذاة دقيقة للإشارة عبر مختلف الترددات. كما يسعى إلى تقييم أداء النظام باستخدام عدة مؤشرات، مثل معدل الإرسال، واحتمالية التغطية، واحتمالية

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الانقطاع، وكفاءة الطاقة، تحت ظروف تشغيل مختلفة. ولتحقيق ذلك، تم اعتماد بنية الطور –التأخير الطور(PSPD) التي تجمع بين إزاحة الطور ووحدات التأخير الزمني لتعويض التغيرات المعتمدة على التردد. بالإضافة إلى ذلك، تم اقتراح نظام مطور يعتمد على استخدام سطحين RIS بشكل متوازي، بهدف الاستفادة من تعدد مسارات الانتشار، مما يساهم في تعزيز قوة الإشارة المستقبلة وتحسين موثوقية الاتصال. أظهرت نتائج المحاكاة أن البنية المقترحة (SPDP) تُخفف بفعالية من تأثير انقسام الحزمة وتحقق محاذاة دقيقة للحزمة عبر جميع الحوامل الفرعية، مما يؤدي إلى تحسين ملحوظ في معدل الإرسال القابل للتحقيق. علاوةً على ذلك، يتفوق التكوين المقترح الذي يعتمد على سطحين ذكيين قابلين لإعادة التشكيل (RISs) موصولين على التوازي على النظام التقليدي المعتمد على سطح ذكي واحد، وذلك من خلال تحقيق معدلات إرسال أعلى، وتحسين احتمالية التغطية، وخفض احتمالية الانقطاع، وتعزيز كفاءة الطاقة، وتوسيع نطاق التغطية الاتصالية، مما يجعله حلاً واعدًا لأنظمة الاتصالات المستقبلية عريضة النطاق العاملة في نطاق التيراهيرتز.

الكلمات المفتاحية: ترددات التيراهرتز (THz) ، الأسطح الذكية القابلة لإعادة التشكيل (RIS)، ظاهرة انقسام الحزمة، بنية الطور–التأخير–الطور ذات الاتصال الجزئي (SPDP)، الترميز المسبق عريض النطاق، الأسطح الذكية المتوازية.

1- Introduction

The rapid evolution of wireless communication systems and the emergence of sixth generation (6G) networks have increased the demand for high data rates and large bandwidths. Consequently, millimeter-wave (mmWave) and terahertz (THz) frequency bands have attracted significant attention due to their abundant spectrum resources, however, communications at these frequencies suffer from severe path loss, high attenuation, and blockage sensitivity, which limit system reliability and coverage [1]. Reconfigurable Intelligent Surfaces (RIS) is an effective solution to improve signal propagation by intelligently controlling the phase of reflected waves without increasing transmit power. Nevertheless, in

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wideband THz systems, conventional phase-only RIS architectures suffer from the beam split effect caused by frequency-dependent phase shifts, resulting in beam misalignment across subcarriers and degraded system performance [2]. To address this issue, true time delay (TTD)-based and SPDP (Phase–Delay–Phase) architectures have been introduced, where time-delay elements compensate for frequency-dependent effects and significantly improve beam alignment and achievable rate [1]. However, most existing studies focus on single-RIS deployments, while the combination of SPDP precoding with parallel multi-RIS architectures has received limited attention. Its impact on achievable rate, coverage probability, outage probability, and energy efficiency has not been comprehensively investigated.
Motivated by this research gap, this paper proposes a parallel Multi-RIS-SPDP architecture that employs two RISs simultaneously to exploit multiple reflected propagation paths, providing additional spatial diversity and enhanced received signal power. The proposed framework effectively mitigates the beam split effect while improving beam alignment, achievable rate, coverage probability, outage performance, and energy efficiency, making it a promising solution for future wideband THz communication systems. The performance of the proposed framework was evaluated through MATLAB simulations under various operating condition.

2- Literature Review

(THz) communication is considered one of the key technologies for future 6G networks due to its ability to provide ultra-high data rates. However, THz systems suffer from severe path loss, molecular absorption, and high sensitivity to blockage, which significantly degrade communication performance [2], [3].
Reconfigurable Intelligent Surfaces (RIS) have been introduced to enhance signal propagation by intelligently controlling electromagnetic wave reflections. Although conventional phase-only RIS architectures improve coverage and signal quality, they suffer from the beam split effect in wideband THz systems because

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the phase shifts are optimized only for the carrier frequency [4], [5].

Several studies have proposed beam split mitigation techniques based on TTD and SPDP architecture that demonstrated that the SPDP architecture effectively compensates for frequency-dependent phase variations while maintaining lower hardware complexity than fully connected TTD-based designs.

Recently, multi-RIS systems have been investigated to improve coverage, reliability, and received signal strength by exploiting multiple propagation paths [6], [7]. However, most existing studies focus on communication reliability and coverage enhancement without jointly addressing the beam split effect in wideband THz communications.

Therefore, this work combines the SPDP architecture with a parallel two-RIS deployment to mitigate the beam split effect while improving achievable rate, coverage probability, outage probability, and energy efficiency in wideband THz communication systems

3- System model and problem formulation

A wideband RIS assisted communication system is considered. Since the system operates over a wide bandwidth, the transmitted signal is divided into multiple subcarriers, each with a different operating frequency [3].

The frequency of the m-th subcarrier is given by: [3]

$$f_m = f_c + \frac{B}{M}\left(m - 1 - \frac{M-1}{2}\right) \quad (1)$$

where:

f_m is the frequency of the m-th subcarrier, measured in Hz, f_c is the center or carrier frequency of the whole wideband system, measured in Hz, B is the total transmission bandwidth, measured in Hz, M is the total number of subcarriers, m is the subcarrier index, where m = $1,2, \dots, M$, $\frac{B}{M}$ represents the subcarrier spacing.

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To ensure proper array sampling and to avoid spatial aliasing, the antenna spacing is chosen as half the carrier wavelength, which is expressed as:

$$d = \frac{c}{2f_c} \quad (2)$$

where:

d is the spacing between adjacent antennas or reflecting elements, c is the speed of light in free space, approximately $3 \times 10^8 m/s$, f_c is the carrier frequency.

The received signal at the user is expressed as [3]:

$$y_m = h_m^T \Theta G_m x_m + n_m \quad (3)$$

Where:

y_m is the received signal at the m^{th} subcarrier, h_m is the RIS-to-user channel vector at the m-th subcarrier, Θ is the RIS reflection or phase-shift matrix $\Theta = diag\left(e^{j\theta_1}, e^{j\theta_2}, \dots, e^{j\theta_N}\right)$, G_m is the Base Station-to-RIS channel matrix at the m-th subcarrier, x_m is the transmitted signal vector at the m-th subcarrier, n_m is the additive white Gaussian noise at the receiver.

3-1. Channel Model

The THz channel incorporates free-space path loss and molecular absorption. [3],[4].

The BS to RIS channel matrix is modeled as: [3]

$$G_m = g_1(f_m, d_1)e^{-j2\pi\tau_1 f_m}\boldsymbol{a}(f_m, \vartheta_1^r, \zeta_1^r)\boldsymbol{b}^H(f_m, \phi) \quad (4)$$

Where $g_1(f_m, d_1)$ is the path gain including molecular absorption, $\tau_1$is the propagation delay, **a(.)** is the RIS steering vector (with elevation ϑ_1^r,and azimuth ζ_1^r), and **b(.)** is the BS steering vector with angle of departure ϕ. Similarly, the RIS to UE channel vector is [2]:

$$h_m = g_2(f_m, d_2)e^{-j2\pi\tau_2 f_m}a(f_m, \vartheta_2^t, \zeta_2^t) \quad (5)$$

2.1. The Beam Split Effect

In conventional RIS designs, the phase shift $\theta_k$for the k^{th}element is designed based solely on the center frequency f_c [6]. The

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normalized RIS array gain for the m^{th} subcarrier can be expressed using the Dirichlet sinc function $\Xi_N(x) = \frac{\sin(Nx/2)}{N\sin(x/2)}$ as:

$$\eta_{RIS}(f_m) = \left|\Xi_{N_1}\big((\xi_m - 1)(\alpha_1 + \alpha_2)\big)\Xi_{N_2}\big((-1)(\beta_1 + \beta_2)\big)\right| \quad (6)$$

Where: $\xi_m = \frac{f_m}{f_c}$ is the normalized frequency of the m-th subcarrier, $(\xi_m - 1)$ represents the deviation of the subcarrier frequency from the carrier frequency, $\xi_m$deviates significantly from 1 for edge subcarriers, causing the beam to split and the array gain to plummet.

3-2. Double Beam Split Effect

When the BS is equipped with a massive antenna array ($N_t \gg$1), the beamforming vector **w** at the BS also suffers from frequency dependent misalignment. The total array gain becomes a product of both the RIS and BS gains: [3]

$$\eta(f_m) = |g_1 g_2| \cdot \eta_{RIS}(f_m) \cdot \eta_{BS}(f_m) \quad (7)$$

Where g_1 is the BS-to-RIS path gain, $g_2$is the RIS-to-user path gain.

This double beam split effect severe spatial dispersion of the signal energy, as the beam is misaligned twice: once during transmission from the BS and again during reflection at the RIS.

Figure (1) illustrated Beam split and Double beam split effect at the BS and the RIS.

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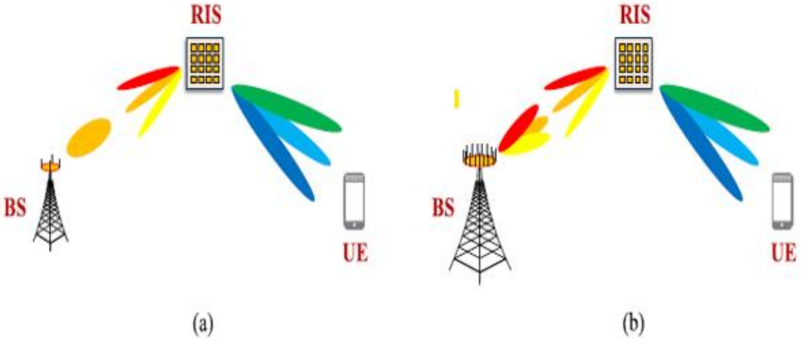

Figure (1): RIS-aided THz communications: (a) Beam split effect at the RIS; (b) Double beam split effect at the BS and the RIS [3].

4- Proposed SPDP with Parallel RIS Architecture

Following the SPDP architecture proposed in [6], the RIS is partitioned into $Q1 \times Q2$ subarrays. Each subarray consists of two-phase shifting layers sandwiching a central time delay (TD) layer.

The proposed Parallel RIS architecture was implemented and evaluated using MATLAB.

Figure 2 illustrates Parallel RIS system model with two RIS surfaces

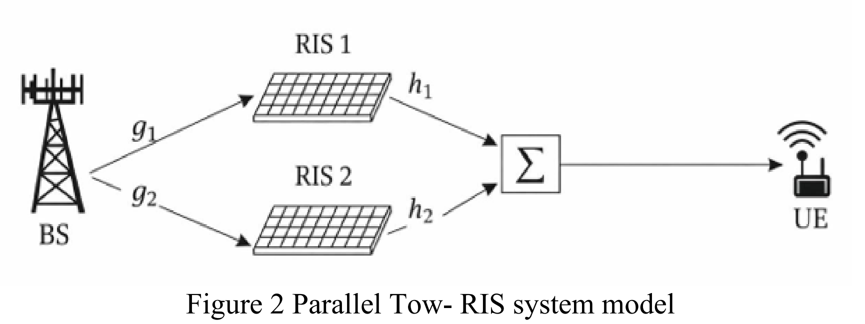

Figure 2 Parallel Tow- RIS system model

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The TD module applies a frequency independent true time delay, represented by the vector $\mathbf{P}_m = e^{-j2\pi f_m t}$, where $\mathbf{t}$ contains the delay values for each subarray. The signal processing occurs in three stages:

a. First Phase Layer: Provides coarse spatial beam steering.

b. Time Delay Layer: Compensates for the frequency dependent phase variations across the subarray.

c. Second Phase Layer: Refines the beam direction for precise alignment.

The optimal time delay t_q assigned to the q^{th} subarray to perfectly align the beam across all frequencies in analytically derived as: [3]

$$t_q = \frac{1}{2f_c}\left[\left(q_1 K_1 - \frac{K_1 - 1}{2}\right)(\alpha_1 + \alpha_2) + \left(q_2 K_2 - \frac{K_2 - 1}{2}\right)(\beta_1 + \beta_2)\right] \quad (8)$$

Where: $K_1 and K_2$ are the subarray dimensions.

By applying this optimal delay, the SPDP array gain becomes: [3]

$$\eta(p_m, f_m) = \frac{Q_1 Q_2 K_1^2 K_2^2}{N_1 N_2}\left|\Xi_{K_1}\left((\xi_m - 1)\alpha_1\right)\Xi_{K_1}\left((\xi_m - 1)\alpha_2\right)\Xi_{K_2}\left((\xi_m - 1)\beta_1\right)\Xi_{K_2}\left((\xi_m - 1)\beta_2\right)\right| \quad (9)$$

This formulation proves that the beam split effect is confined within the much smaller subarrays (dimensions K_1, K_2) rather than the entire RIS (N_1, N_2), drastically reducing the energy dispersion.

4-1. Parallel Two-RIS system model

To further enhance reliability and overcome deep fades or blockage, we extend the system to a parallel 2-RIS configuration. The transmitted signal is reflected by two independent RIS panels. The received signal at the UE is a superposition of both paths:[8]

$$y_m = h_{1,m}^T \Theta_1 G_{1,m} x_m + h_{2,m}^T \Theta_2 G_{2,m} x_m + n_m \quad (10)$$

The total equivalent cascaded channel is $h_{eq,m} = h_{eq,1,m} + h_{eq,2,m}$

Where $h_{eq,i,m} = h_{i,m}^T \Theta_i \, G_{i,m}$

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By jointly optimizing the phase shifts of both RIS panels, the signals combine constructively at the UE, maximizing the received power.

4-2. Performance Metrics

a. Achievable rate: the average achievable rate across all subcarriers is:

$$R_{\mathrm{SPDP}} = \frac{1}{M}\sum_{m=1}^{M} \log_2 .\left(1 + \mathrm{SNR} \cdot \left|h_{eq,1,m}^{\mathrm{SPDP}} + h_{eq,2,m}^{\mathrm{SPDP}}\right|^2\right) \quad (11)$$

b. Coverage and outage probability:

Coverage probability $P_{\mathrm{cov}} = \Pr(R \geq R_{\mathrm{th}})$ and outage probability $P_{\mathrm{out}} = \Pr(R < R_{\mathrm{th}})$, where $R_{\mathrm{th}}$is the target rate threshold.

c. Energy Efficiency (EE): Defined as $\eta_{\mathrm{EE}} = \frac{\bar{R}}{P_{\mathrm{total}}}$, measuring the bits transmitted per Joule of energy consumed.

5- Simulation Results and Discussion

This section presents numerical simulation results to evaluate a wideband communication system, focusing on the effectiveness of the SPDP architecture in mitigating the beam split effect and enhancing system performance. The analysis includes both single-RIS and parallel dual-RIS configurations to assess performance improvements. Key metrics such as achievable rate, coverage probability, outage probability, and energy efficiency are examined under varying bandwidth, and distance conditions.

5-1. Simulation Setup

The system parameters used for the numerical evaluations are summarized in Table 1. Most simulation parameters are adopted from [3] to enable a fair comparison with the conventional SPDP architecture.

Table (1) Simulation parameters used in result parameters

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Parameter	Description	Value
Total RIS elements	Total number of RIS reflecting units	4096
Number of RIS subarrays	Number of SPDP subarrays	16
Subarray dimensions	Number of elements in each subarray	16 × 16
Carrier frequency	Center operating frequency	100 GHz
System bandwidth	Total transmission bandwidth	10 GHz
Number of subcarriers	Number of OFDM subcarriers	128
BS–RIS distance	Distance between BS and RIS	2 m
RIS–UE distance	Distance between RIS and UE	10 m
Transmit power	Transmission power at BS	30 dBm
Noise power	AWGN noise power at receiver	-120 dBm
Signal-to-noise ratio	Ratio between signal power and noise power	$Pt - \sigma^2$
Elevation angle	Vertical angle	$0 \rightarrow \pi/2$
Azimuth angle	Horizontal angle	$-\pi \rightarrow \pi$
Rician factor	Channel fading parameter	3dB

5-2. Beam Alignment Performance

Figure (3) illustrates the 3D and 2D beam patterns of the SPDP architecture across different subcarriers (center and edge frequencies). As reported in [3], unlike conventional RIS, where edge subcarriers point in diverging directions, due to the beam split effect, the SPDP architecture aligns all subcarriers toward the desired spatial direction. Figure 3 presents this beam alignment behavior as a baseline for comparison with the proposed parallel RIS architecture.

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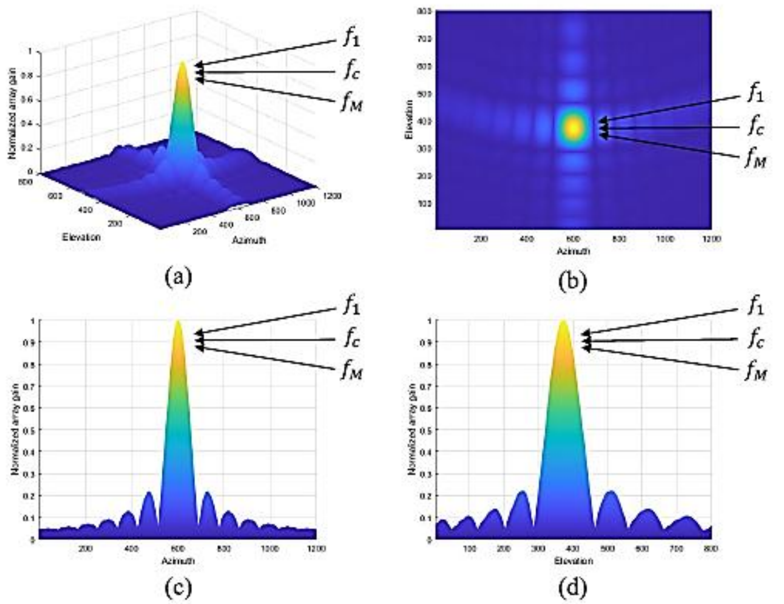

Figure (3) The generated beams based on the SPDP: (a) 3-dimensional view; (b) Bird-eye's view; (c) Side-view; (d) Front-view

5-3. Effect of Time-Delay Modules on Achievable Rate

Figure (4) shows that the parallel RIS configuration (2 RIS) achieves higher performance compared to the single RIS case (1 RIS) as the number of time-delay (TD) modules increases.

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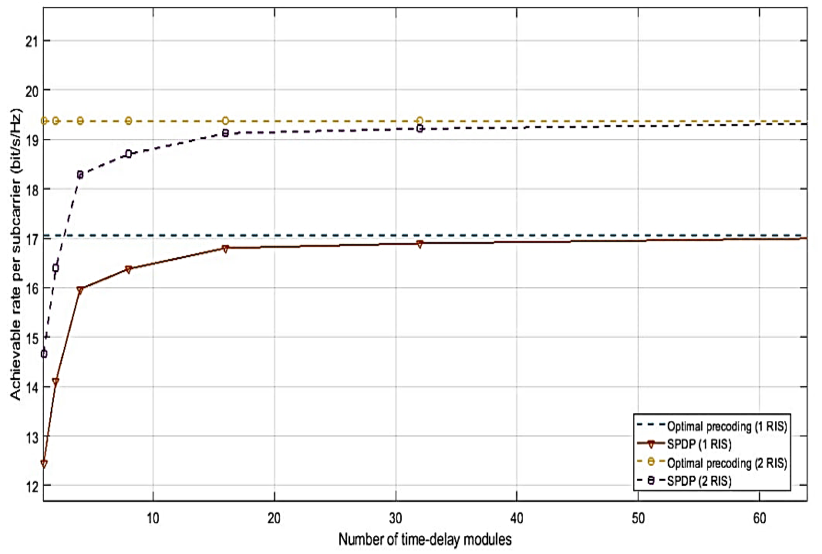

Figure (4) achievable rate versus the number of time-delay modules for 1- RIS and 2 -RIS

By comparing the two configurations, it is clear that the 2 RIS system achieves higher performance than the 1 RIS system across all values of TD modules. The achievable rate of the 2 RIS configuration remains consistently higher under the same conditions. This improvement is mainly due to the presence of multiple propagation paths, which enhances the received signal strength and improves overall system reliability. In contrast, the single RIS configuration relies on only one reflection path, which limits its performance.

5-4. Effect of Bandwidth on Achievable Rate

Figure (5) shows that the parallel RIS configuration (2 RIS) maintains higher performance compared to the single RIS case (1 RIS) as the bandwidth increases.

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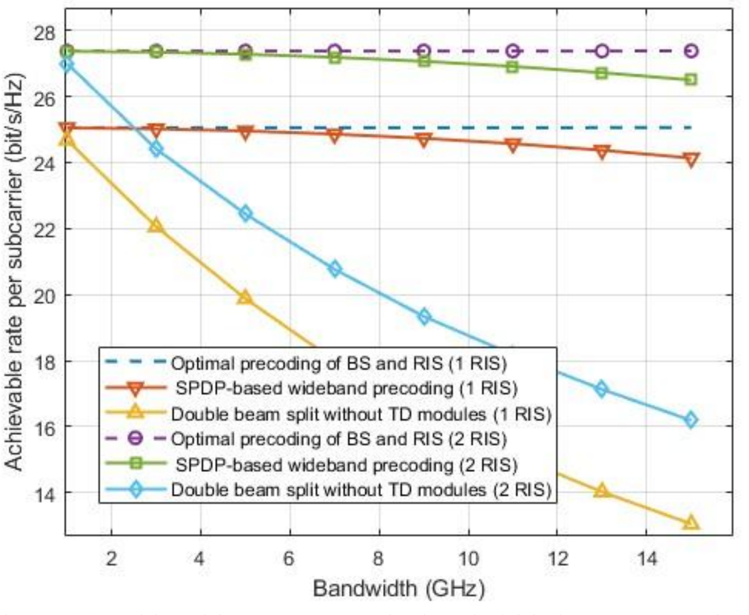

Figure (5) achievable rate versus the bandwidth for 1 -RIS and 2 -RIS with $N_t = 256$ and $Q = 16$.

5-5. Coverage and Outage Probability Analysis

Coverage probability and outage probability are important performance metrics used to evaluate the reliability of wireless communication systems. They reflect the ability of the system to achieve the required data rate.

Coverage probability represents the success of the system in providing reliable communication, while outage probability indicates the failure to achieve the required performance. These two metrics are inversely related, meaning that higher coverage leads to lower outage, and vice versa.

These metrics are affected by several factors such as distance and signal quality, and therefore they are widely used to assess system performance under different conditions. [8],[9]

Figure (6) illustrates the outage probability versus distance for both single RIS (1 RIS) and parallel RIS (2 RIS) configurations

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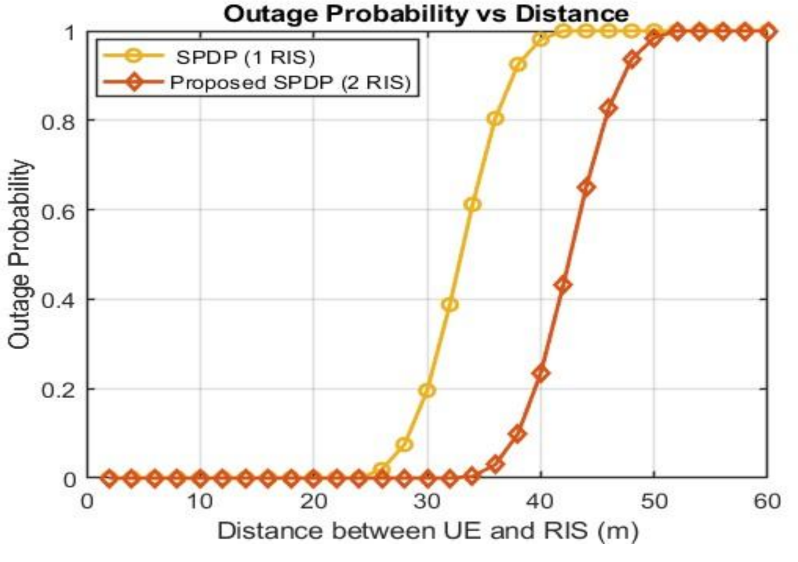

Figure (6) outage probability versus distance for 1- RIS and 2 -RIS

Figure (7) illustrates the coverage probability versus distance for both single RIS (1 RIS) and parallel RIS (2 RIS) configurations.

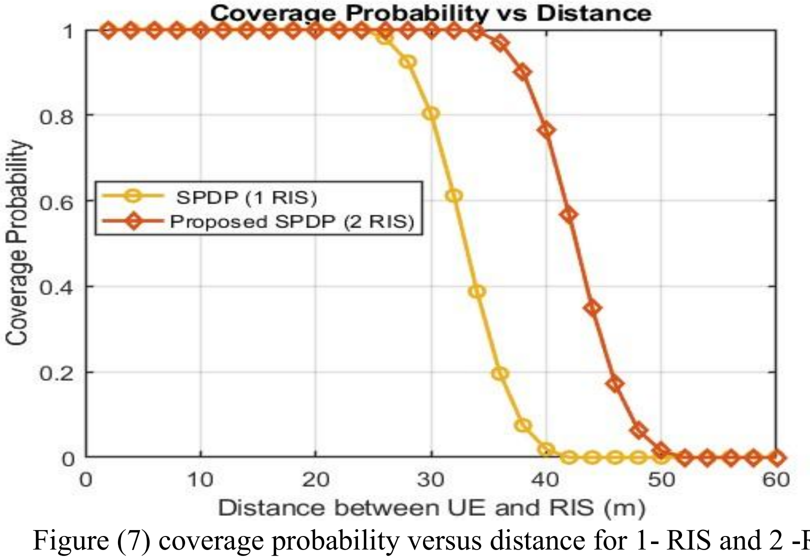

Figure (7) coverage probability versus distance for 1- RIS and 2 -RIS

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The results show that the outage probability remains very low at short distances, indicating strong received signal power and reliable communication. As the distance increases, the outage probability increases significantly due to higher path loss and signal attenuation, which is expected in THz communication systems.

On the other hand, the coverage probability is high at short distances and gradually decreases as the distance increases. This behavior reflects the degradation of signal quality and the reduction in signal-to-noise ratio with increasing distance.

A comparison between the two configurations shows that the parallel RIS system (2 RIS) outperforms the single RIS system (1 RIS).

Specifically, the 2-RIS configuration achieves lower outage probability and higher coverage probability over a wider range of distances.

This performance improvement is mainly due to the presence of multiple reflection paths in the parallel RIS system, which enhances the received signal power and improves system reliability. In addition, the parallel RIS configuration provides better signal diversity, which helps mitigate fading effects.

Furthermore, the use of two RISs extends the effective communication range and delays performance degradation compared to the single RIS system, making it a more robust solution for wideband communication scenarios.

5-6. Energy Efficiency Analysis

Figure (8) illustrates energy efficiency versus the distance between the user and the RIS for both single RIS (1 RIS) and parallel RIS (2 RIS) configurations.

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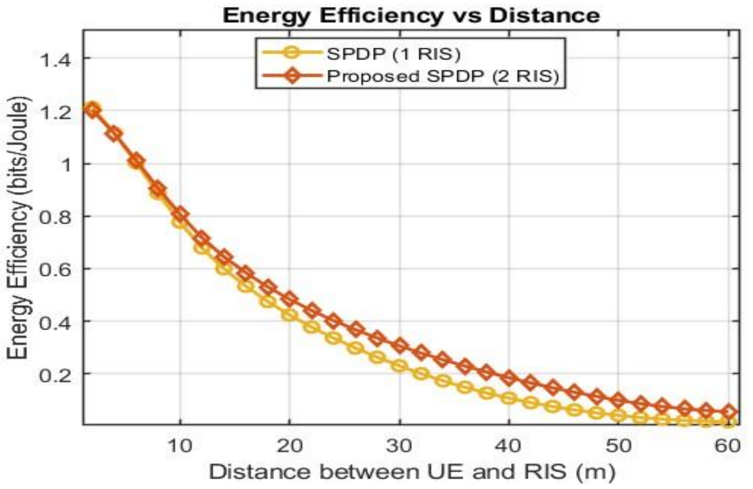

Figure (8) Energy efficiency versus the distance RIS for 1- RIS and 2 -RIS

It can be observed that energy efficiency is high at short distances, where the received signal is strong and less transmitted, power is required to achieve reliable communication. As the distance increases, energy efficiency gradually decreases due to increased path loss, which reduces the received power and requires higher transmit power to maintain the communication quality.
At larger distances, the energy efficiency drops significantly, indicating that the system becomes less efficient in terms of energy consumption.
Moreover, the parallel RIS configuration (2 RIS) consistently achieves higher energy efficiency compared to the single RIS case (1 RIS) across all distances. This improvement is attributed to the availability of multiple reflection paths, which enhance the received signal strength and reduce the need for excessive transmitting power.

6- Conclusion

This paper addressed the critical challenge of the beam split effect in wideband RIS-aided THz communication system. We analyzed the mathematical foundation of the beam split and double beam

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split phenomena, demonstrating how frequency-dependent phase shifts cause severe spatial dispersion of signal energy. To resolve this we implemented the SPDP architecture, which integrates true time delay modules with phase shifters. MATLAB simulations were used to evaluate the performance of the proposed system. Simulation results confirmed that SPDP effectively neutralizes the beam split effect, achieving near optimal achievable rates
Furthermore, we proposed and evaluated a novel parallel 2-RIS system model. By exploiting spatial diversity and multiple propagation paths, the 2-RIS configuration significantly outperformed the traditional single-RIS setup. It provided substantial gains in achievable rate, extended the coverage range, reduced outage probability, and improved overall energy efficiency.

7- Future work

Extending the proposed system to multi-RIS configurations involving more than two RIS surfaces to further enhance system performance and coverage, developing advanced optimization algorithms for the joint design of phase shifts and time-delay parameters under dynamic channel conditions, investigating the impact of user mobility and designing adaptive techniques to maintain beam alignment in time-varying environments.

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