

Fig. 6. The relationship between normalized array gain and no. sub-carrier for different numbers elements of IRS

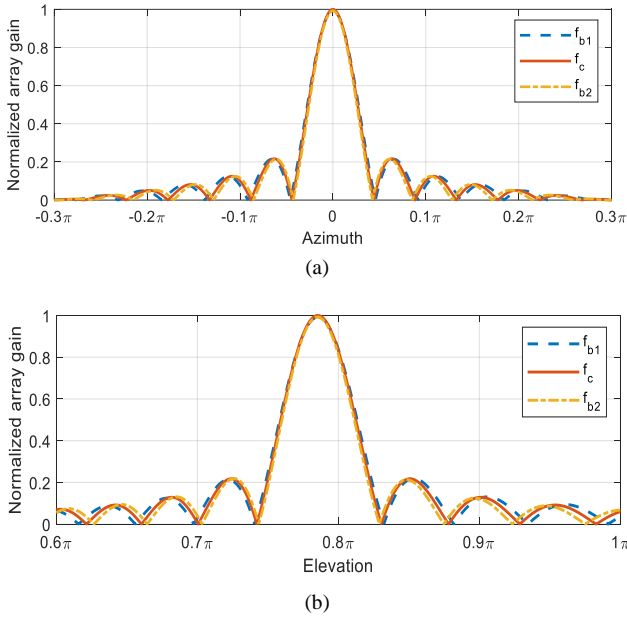


Fig. 7. The normalized array gain against (a) Azimuth angle and (b) Elevation angle using proposed PTDP

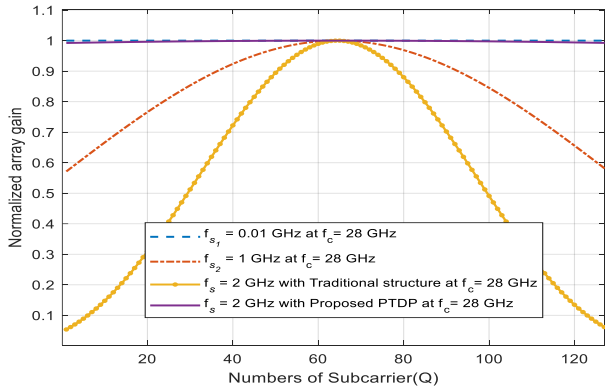


Fig. 8. The relationship between the number of sub-carriers and normalized array gain using the proposed PTDP structure

It is shown that the proposed system, with its frequency-based precoding design, achieves the highest possible performance when each element is equipped with a TD. The

design was based on traditional narrowband beamforming technology, with an emphasis on improving phase control performance. The performance of this technique was evaluated using continuous phase shifting and phase shifting at low resolutions (1 and 2 bits), compared to the traditional technique. The proposed design was also matched with the optimal precoding. Traditional narrowband beamforming design has been based on simple phase shift techniques. The proposed PTDP system relied on more complex phase-shifting techniques, which allowed for significant performance improvement. The results showed that using TD in Phase shift-Time Delay-Phase delay (PTDP) resulted in a 54% increase at transmitted power=30 dBm in data rate compared to the traditional design. The achievable rate per subcarrier is given [43, 44]:

$$R_{optimal} = \frac{1}{Q} \sum_{q=1}^Q \log_2 \left(1 + \frac{|G_q|^2 \cdot SNR}{\sigma^2} \right) \quad (35)$$

The signal-to-noise ratio is [45]:

$$SNR = P_t / \sigma^2 \quad (36)$$

where P_t is the total transmitted power, while $\sigma^2 = -90dBm$ [11, 46]. The achievable rate for continuous precoding is given [23]:

$$R_{con} = \frac{1}{Q} \sum_{q=1}^Q \log_2 \left(1 + \frac{|\psi_1 G_q \psi_2|^2 SNR}{\sigma^2} \right) \quad (37)$$

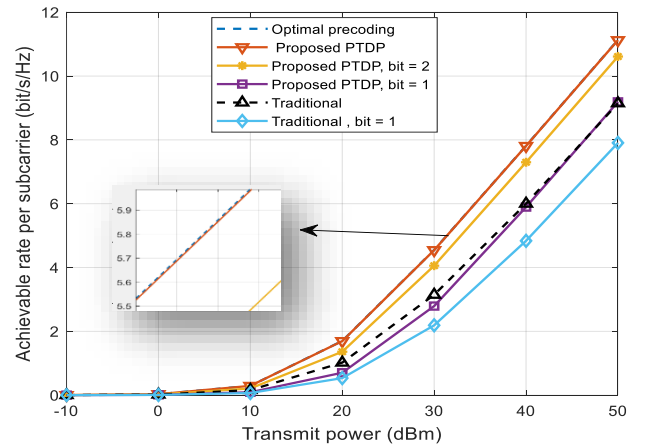


Fig. 9. The relationship between the transmitted power and achievable rate per subcarrier at the number of BS antennas B=1

Figure 10 shows that as the number of subarrays increases, this leads to an increase achievable rate per subcarrier and its value approaches the optimal precoding. Figure (11) shows the relationship between the transmitted power and the achievable rate of each sub-carrier when the number of base station antennas is B=256 antenna, and the RIS uses 16-TD units. Each simulation randomly selected the base station transmission angle from a uniform distribution between $-\pi/2$ and $\pi/2$. The performance of a PTDP-based wideband precoding scheme,

which used continuous phase shift and 256 RIS subarray, was analyzed.

An optimal precoding design was adopted for both the base station and the IRS to achieve maximum performance. A narrowband beamforming design without TD modules was considered a baseline for comparison. This baseline scenario provides an example of the double beam splitting phenomenon. For comparison, the performance of TD-based precoding that is limited to beam splitting processing in either IRS or BS. only, based on a proposed design, was also evaluated. Compared with single-antenna base stations, multi-antenna base stations with large antennas suffer greater data rate degradation due to the double beam split phenomenon when using a narrowband beamforming design.

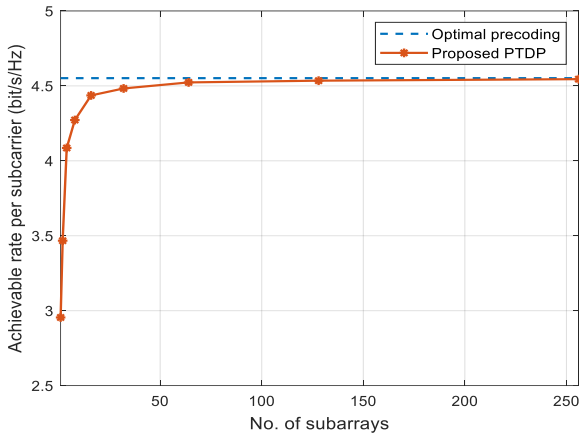


Fig. 10. The relationship between the number of subarrays and the achievable rate per subcarrier

While TD modules-based precoding can help address the beam-splitting effect, focusing on only the BS or the IRS does not fully compensate for the performance degradation caused by double beam splitting. The PTDP-based joint wideband precoding design is able to enhance a performance that is close to the optimal achievable rate, and this is particularly effective in mitigating the double beam splitting effect. Figure (12) The relationship between the transmitted power and achievable rate per subcarrier at the number of BS antennas $B=256$. The results showed that both the PTDP design with a 16-TD and the conventional narrow-beamforming technique led to lower-than-expected performance when operating in narrow frequency bands. In contrast to the proposed PTDP-based design, the frequency-independent narrowband beamforming scheme experiences a significant decrease in achievable rate as the bandwidth increases.

The proposed PTDP-based wideband precoding design is shown to be able to effectively handle the challenge of dual beam splitting in wide frequency bands and this makes it a flexible and applicable solution in IRS-based millimetre wave communication systems.

Finally, the proposed method was compared with a number of other methods in Table II.

TABLE II
COMPRESSION BETWEEN THE PROPOSED PAPER WITH NUMBERS OF PAPERS

	[19]	[44]	[47]	[29]	The proposed
Single user	✓			✓	✓
Multi-user		✓	✓		✓
Narrowband					✓
Wideband	✓	✓	✓	✓	✓
Beam Squint	✓		✓		✓
Beam split		✓		✓	✓
With IRS		✓	✓	✓	✓

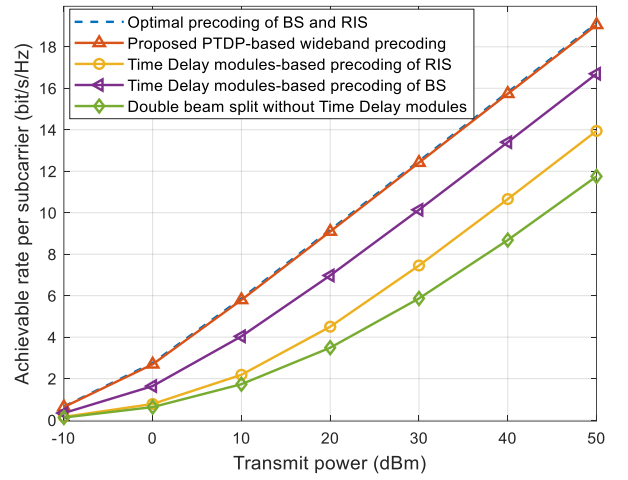


Fig. 11. The relationship between the transmitted power and achievable rate per subcarrier at the number of BS antennas $B=256$.

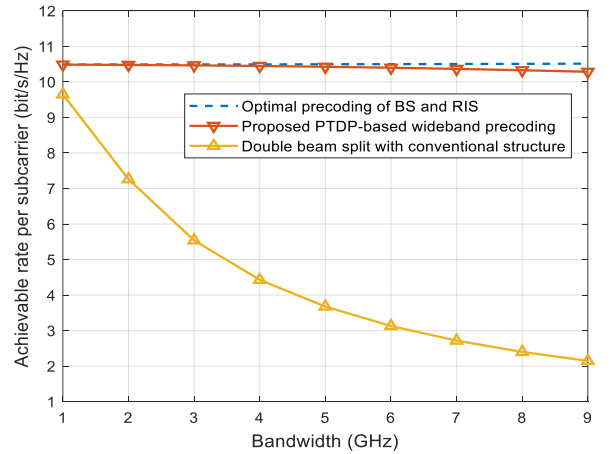


Fig. 12. The relationship between Bandwidth and achievable rate per subcarrier at the number of BS antennas $B=256$ and the transmitted power=30dBm.

VII. CONCLUSION

Millimetre wave communications supported by IRS have faced the major challenge of beam splitting, resulting in a decrease in received signal strength, while to solve this problem, precoding techniques based on phase control and TD of the signal have been studied. By analyzing the effect of beam splitting and gain drop, a structure of IRS consisting of several

interconnected layers is presented. This structure allows the application of a frequency-based and error-tolerant precoding technique in estimating communication channels. The effect of double beam splitting at both BS and RIS is studied. The results show that this technology can significantly reduce the effect of beam splitting, making IRS-supported millimetre wave technology more efficient. The proposed PTDP structure achieved a 94.5% enhancement in gain compared to the traditional structure. The proposed PTDP-based wideband precoding design has been demonstrated to be able to compensate for the array gain loss caused by the double beam splitting effect occurring at both BS and IRS, even in scenarios with large bandwidths.

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