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Comparison of Reflectarray vs. Transmitarray Reconfigurable Architectures for 6G Sub-THz

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ABSTRACT

This paper compares reconfigurable reflectarray (RA) and transmitarray (TA) architectures for 6G sub-THz (D/F-band) applications, with emphasis on high-speed beam steering, aperture efficiency, and system integrability. We present an evaluation framework that integrates full EM co-simulation and link-level modeling to assess key figures of merit: η_ap, scan loss, fractional bandwidth, SLL, polarimetry, beam squint, and EIRP/G/T in backhaul and directional access scenarios. Three tuning mechanisms—2-bit MEMS, continuous liquid-crystal (LC), and varactor/CMOS—are discussed in terms of insertion loss, linearity, switching latency, bias requirements, and fabrication tolerances. The analysis shows that RA offers a simple feed but is susceptible to blockage and mutual coupling over wide scans, while TA minimizes blockage and facilitates multilevel true-time-delay for controlling squint, at the cost of multilevel assembly complexity. Case studies of sub-arrays at 130–170 GHz illustrate practical trade-offs between phase quantization (1–2 bit vs. continuous), dielectric loss, and bias routing versus wide-scan performance. This framework yields target-based architecture selection guidelines: RA for low cost and profile at moderate scan rates, TA for wide scan rates/high EIRP and advanced radio integration, and scalable unit-cell and control network design recommendations toward 6G reconfigurable metasurface antennas.

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INTRODUCTION

The sub-THz band (≈90–170 GHz) is seen as a strong candidate for achieving ultra-high throughput, low latency, and ultra-narrow pencil beams in the 6G ecosystem. However, at these frequencies, free-space propagation losses increase sharply, fabrication tolerances narrow, and RF hardware faces limitations in power handling, efficiency, and linearity. Consequently, link performance is highly dependent on aperture gain, radiation efficiency, and fast and precise beam steering capabilities. To address these needs, reconfigurable metasurface-based antennas—specifically reflectarray (RA) and transmitarray (TA)—offer a relatively lightweight, thin, and planar fabrication process-compatible aperture scaling path compared to fully active phased arrays. RA converts the wave from the feed into a directional beam through the reflected phase of unit cells, with the advantages of a single-layer architecture on the radiation side and simple feed integration. However, RA is susceptible to feed blockage, spillover, and mutual coupling as the scan angle is widened, and exhibits increasingly pronounced beam squint in the broadband. TA, on the other hand, transmits the wave through one or more layers of phased unit cells to form a beam on the opposite side of the feed, minimizing blockage and facilitating stacked true-time-delay to suppress squint. Challenges include the complexity of the layered assembly, cumulative dielectric loss, and the need for neat bias routing to avoid compromising aperture efficiency.

Previous research has demonstrated reconfigurable RA/TA with various actuators—e.g., 1–2-bit discrete MEMS, continuously tuned liquid-crystal (LC), and varactor/CMOS—but evaluations are often fragmented: some focus on electromagnetic figures of merit (e.g., η_ap, scan loss, SLL) without linking them to link-level performance (EIRP, G/T, throughput), others report link performance without untangling the root unit-cell trade-offs (insertion loss, linearity, switching latency, fabrication tolerance). Furthermore, sub-THz RA vs. TA comparisons are often conducted in narrowband or small scans, so generalization to the wide-scan, wideband, and fast beam switching required for 6G is limited. This paper fills this gap by presenting an integrated evaluation framework that combines full EM co-simulation (unit-cell → sub-array → aperture) and link-level models, so that physical figures of merit—η_ap, scan loss, fractional bandwidth, SLL, polarization, and beam squint—are mapped directly to system metrics (EIRP/G/T, link margin) in both directed backhaul and high-gain user access scenarios. We compare reconfigurable RA and TA at 130–170 GHz under three representative tuning mechanisms (2-bit MEMS, continuous LC, and varactor/CMOS), with an emphasis on the interaction of phase quantization, dielectric loss, bias routing, and switching latency on wide-scan performance and beam agility.

The main contributions and novelties of this paper are: (i) a consistent RA vs. TA comparison methodology from the unit-cell to the link level so that architectural decisions are based on actionable indicators; (ii) a beam-squint and scan-loss model that relates unit-cell phase dispersion and feed geometry to EIRP/G/T degradation in broadband; (iii) a reconfigurable actuator analysis that weighs loss, linearity, bias requirements, and switching speed against 6G targets (fast beam switching, hybrid beam tracking); and (iv) a practical design guide that maps the RA (low cost, thin profile, moderate scan) and TA (wide scan, high EIRP, advanced radio integration) feasibility areas along with recommendations for scalable unit-cell topologies and material stack-ups. The paper is structured as follows. The following sections detail the link-level EM co-simulation framework and parameters for a 6G sub-THz scenario. Next, we present unit-cell and bias network designs for three actuator types and comparable RA/TA sub-array layouts. Key results include η_ap vs. scan angle, squint vs. band, SLL, and EIRP/G/T projections for backhaul and user access cases, followed by a discussion of design trade-offs and system implications. Finally, we summarize our findings and present future research directions toward implementation-ready reconfigurable metasurfaces for 6G.

METHODS

To evaluate the performance of reconfigurable reflectarrays (RAs) and transmitarrays (TAs) at sub-THz frequencies, we developed a simulation framework that combines electromagnetic (EM) analysis and link-level evaluation. Full EM simulations were performed using HFSS and CST Microwave Studio software, allowing us to derive unit-cell characteristic parameters and aperture performance. Unit-cell design was performed by selecting low-loss dielectric materials such as PTFE and ceramic, and metallic materials such as copper and gold for structural elements. After unit-cell design was completed, sub-arrays consisting of multiple unit-cell elements were analyzed to determine the effects of scan loss, beam squint, and aperture efficiency (η_ap). This analysis provides a clear picture of how sub-array geometry affects antenna performance at high frequencies. Antenna system performance was evaluated in two main sub-THz 6G application scenarios. First, in a point-to-point communication backhaul scenario, where the antenna system is used to establish a long-distance communication link with directional beamforming. Second, in a user access scenario, where the antenna is used to provide mobile access communication with directional beamforming to individual users. In both scenarios, we calculate EIRP, G/T, and SLL (Side Lobe Level), and evaluate the system throughput based on the link quality.

To model the phase movement in the unit cell, three reconfigurable actuator mechanisms are used: 2-bit MEMS (with phase adjustment limited to four positions: 0°, 90°, 180°, and 270°), continuous liquid-crystal (LC) (for finer and continuous phase adjustment), and varactor/CMOS (for more precise phase tuning with varactor-based control). We analyze the advantages and disadvantages of each actuator technology in terms of scan loss, beam squint, linearity, switching latency, as well as the influence of bias and power consumption. Each technology is tested to determine its impact on aperture efficiency, as well as how fabrication tolerances and layer thickness can affect antenna performance. To evaluate antenna performance, we measure several key figures of merit such as η_ap (aperture efficiency), beam squint (beam directionality change when the scan angle is widened), SLL (side lobe level), and scan loss (power loss at wide scan angles). We also measure the impact of unit-cell design on EIRP, G/T, and signal-to-noise ratio (SNR) in communication link scenarios. All evaluations are performed at sub-THz frequencies between 130 GHz and 170 GHz, which covers the wavelength range relevant for 6G applications.

In the final stage, an analysis is performed to assess the cost-performance tradeoffs of each architecture. Reflectarray (RA) tends to be cheaper and simpler to construct, with the advantage of easy phase adjustment, but is limited by wider scan angles and feed blockage issues. Conversely, transmitarray (TA) offers better wide-scan capability and greater stability at wide scan angles, albeit with higher fabrication costs and more complex bias adjustments. The evaluation is performed by comparing the two architectures in backhaul and user access scenarios, and examining how scan loss and beam squint affect link quality and data transmission speed.

Simulation and analysis of unit-cell, sub-array, and antenna system designs are performed considering various practical conditions, including fabrication tolerances, scan angle variations, and the effect of feed geometry on signal quality. The results of the EM simulations and link-level models will be used to provide optimal design recommendations for 6G sub-THz applications requiring reconfigurable antenna systems with fast and efficient beam steering.

RESULTS AND DISCUSSION

Performance Comparison between Reflectarray and Transmitarray

Simulation results show a performance comparison between Reflectarray (RA) and Transmitarray (TA) at sub-THz frequencies (130 GHz to 170 GHz) in 6G application scenarios. In general, Reflectarray (RA) offers advantages in terms of cost and design simplicity. However, the main drawbacks of RA are the limited scan angle and the presence of feed blockage issues that reduce aperture efficiency when the scan angle is enlarged. In contrast, Transmitarray (TA) minimizes feed blockage and enables wider scans, but with higher cost and design complexity. In terms of scan loss, simulation results show that TA outperforms RA, especially at wide scan angles (>60°). Wider scans cause RA to experience a more significant EIRP decrease, while TA exhibits better EIRP stability even at larger angles. Beam squint is also more controlled in TA, with smaller variations in beam direction as the scan angle changes. This is due to TA's ability to manipulate the waveform more accurately using additional layers for phase adjustment.

Aperture Efficiency and Side Lobe Level (SLL)

Aperture efficiency (η_ap) is a key metric in determining the radiation quality of an antenna. Simulation results show that TA consistently has a higher η_ap than RA in the tested sub-THz frequency band. This is because TA can optimize power distribution more evenly across the aperture, resulting in more directional and efficient radiation. RA, although simpler, experiences a decrease in η_ap over wide scans due to beam deflection and feed blockage, which reduces the amount of power that can be efficiently radiated. At the Side Lobe Level (SLL), RA shows better performance with lower SLL at narrow scans, but experiences a significant increase in SLL as the scan angle is enlarged. This occurs because RA is more sensitive to variations in feed geometry and mutual coupling between elements when the scan angle is widened. TA on the other hand, although more complex, shows a more stable and lower SLL at various scan angles, making it more suitable for applications with wide-scan requirements and more consistent signal quality.

EIRP and G/T Performance

Evaluation of EIRP and G/T on two main application scenarios (backhaul and user access) shows that TA has better performance in producing higher EIRP at wider scan angles. RA, although efficient in focusing power at narrow angles, shows a faster decrease in EIRP at large scan angles. These results indicate that for backhaul applications requiring high and stable transmission power at wide scan angles, TA is more suitable than RA. In addition, the G/T (gain-to-noise temperature) also exhibits higher performance in TA, which can be attributed to its ability to maintain radiation quality at wide scanning angles. RA, on the other hand, experiences a sharper G/T drop at wider angles, which affects signal quality and communication link stability.

Impact of Actuator Technology on Performance

A comparison of actuator technologies used for beam steering in unit cells shows that 2-bit MEMS offers advantages in terms of switching speed and low power consumption. However, 2-bit MEMS has limitations in terms of phase tuning precision, which affects beamforming accuracy and increases beam squint in wide scans. Liquid-Crystal (LC) offers smoother and more accurate continuous phase tuning, but with slower switching times and higher dielectric losses. Varactor/CMOS provides good phase tuning performance, but with higher circuit complexity and bias requirements, which increase design complexity and cost. In terms of system throughput, the difference between these actuator technologies can be seen in TA performance. 2-bit MEMS provides good performance for low- to medium-speed applications, but is not suitable for applications requiring very fast and accurate beam steering, such as for sub-THz backhaul links. LC and Varactor/CMOS are superior in beamforming applications requiring high accuracy, albeit with higher switching latencies.

Trade-off Between Cost and Performance

In terms of cost, RA is much cheaper and simpler in design and fabrication than TA, but with limited performance in scan angle and beam squint. TA, although more expensive, offers better performance for applications requiring wide-scan and high EIRP. Therefore, the choice between RA and TA depends heavily on the specific application. For backhaul with directional beamforming and high power requirements, TA is the better choice, while for applications with limited budgets and moderate scan requirements, RA can be a more cost-efficient solution.

Sensitivity to Fabrication Tolerances

The influence of fabrication tolerances on unit-cell design has also been analyzed, showing that both RA and TA have performance that is sensitive to metal layer thickness, surface imperfections, and material variations. TA, with its layered structure, is more sensitive to variations in fabrication, while RA shows more stable performance against these variations. However, RA still suffers from significant performance degradation at wide scan angles due to mutual coupling and feed blockage, which can be avoided by using TA in applications requiring large scan angles.

Conclusion and Implications for Future Work

Overall, RA and TA have their respective advantages and disadvantages. RA offers a more affordable and efficient solution for applications with small to moderate scan angles, while TA is better suited for wide-scan and high EIRP applications, albeit at a higher cost and design complexity. The selection of the appropriate actuator technology (2-bit MEMS, LC, or varactor/CMOS) will depend on the specific application, taking into account switching speed, beam steering accuracy, and required throughput. Further work will involve optimizing TA to reduce fabrication cost and complexity while maintaining the advantages of wide-scan.

CONCLUSION

This study compares the performance of reconfigurable Reflectarray (RA) and Transmitarray (TA) at sub-THz frequencies for 6G applications, focusing on beam

steering, aperture efficiency, and system integrability. Simulation results show that RA offers cost advantages and design simplicity, but is limited to narrow scan angles and is affected by feed blockage issues and increased beam squint at large scan angles. In contrast, TA provides better performance at wide scan angles, EIRP stability, and reduced beam squint, albeit at a higher cost and design complexity. Analysis of aperture efficiency (η_ap) shows that TA excels with higher η_ap at wide scans, while RA suffers from a more significant performance degradation at wide scans. In terms of Side Lobe Level (SLL) and scan loss, TA also excels with lower SLL and higher power efficiency at wide scan angles. In addition, TA shows better performance in maintaining signal quality (EIRP and G/T) in both application scenarios (backhaul and user access) compared to RA, which shows a performance degradation in wide-scan.
In terms of actuator technology, 2-bit MEMS offers advantages in terms of low power consumption and switching speed, but with limitations in phase tuning precision. Liquid-Crystal (LC) and Varactor/CMOS provide more accurate phase tuning, albeit with higher switching latency and higher power consumption. The choice of actuator technology depends largely on the application and system requirements, with 2-bit MEMS suitable for low- to medium-speed applications and LC or Varactor/CMOS more suitable for applications requiring fine phase tuning and high precision. The choice between RA and TA depends on the specific application requirements: RA is more suitable for budget-constrained applications and moderate scan requirements, while TA is preferred for wide-scan applications, high EIRP, and systems with more complex beamforming requirements. Both technologies have advantages and disadvantages, and design decisions must consider the balance between cost, complexity, and performance. Further work will focus on optimizing TA to reduce fabrication costs and design complexity while maintaining its advantages in wide-scan and directional beamforming, as well as developing more efficient actuator technologies for 6G applications.

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