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Overcoming Antenna Design Challenges in 6G Wireless Systems

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Abstract

The 6G wireless systems present a various set of antenna system challenges. These challenge exist due to the huge number of antennas, the frequency range and the need to support many diverse environment such as Urban, Rural, Indoor and High mobility. Emerging use cases such as holographic communication, holographic telepresence, ultra-high data rate communications, and AI in the loop are driving radically new sets of requirements. The antennas are likely to operate at higher frequencies and designed to be smaller, thinner, lighter, cheaper and more efficient while maintaining the same optical aperture for improved link gain. Other requirements such as wider steering angle and wider frequency band with less beam squint and lower power consumption become critical constraints during designing. Beside these, low cost of production and energy conscious handling become an important factor to be considered during antennas development. The above factors along with electrical performance of the antennas play a key role for next generation design.

The very high frequency range typically higher than 100 GHz suffer because of possibility of very high path loss combined with the narrow beam width. Therefore a stringent link budget accounting for these path loss are particularly important for design of antennas at high frequency band. Another challenge that must be taken into account is the limited ability of these millimetric range signals to penetrate blocking objects such as window reflection, wall penetration etc. where in case of non-line of sight the antenna systems have a higher dependability on beam steering angle and speed.

Keywords: 6G Antenna System Challenges, Massive Antenna Arrays, Sub-Terahertz And Terahertz Frequencies, High-Frequency Path Loss, Narrow Beamwidth Effects, Holographic Communication Use Cases, Holographic Telepresence Systems, Ultra-High Data Rate Requirements, AI-Driven Wireless Systems, Compact And Lightweight Antenna Design, Wide Beam Steering Angle, Wideband Antenna Operation, Beam Squint Reduction, Energy-Efficient Antenna Systems, Low-Cost Antenna Manufacturing, Link Budget Optimization, Non-Line-Of-Sight Communication, Beam Steering Speed Requirements, High-Mobility Wireless Environments, Urban Rural And Indoor Deployment Scenarios.

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1. Introduction

Antenna systems are critical components of 6G networks and are placed at the forefront of technology development. Achieving the ambitious 6G goals requires the design of large antenna systems for operation in very-high-frequency bands, as well as in new 6G environments and use cases. The paper identifies the antenna-system-related challenges of 6G, discusses why these challenges arise, and outlines priorities and future investigations.

6G is expected to enter service by 2030, with initial phase-one deployments in 2027–28 targeting a USA–EU operational agreement. Major global organizations have submitted technology white papers outlining diverse future communication use cases, including holographic communications, support for AI-enabled networks, and ultra-high data-rate services. The extremely high frequencies available in the sub-terahertz and terahertz bands allow unprecedented data-rate access, while dense networks of low-cost access nodes enable ubiquitous coverage.

1.1. Overview of 6G Development and Context

The mainstream operation of 6G technology is anticipated from 2030 onwards. This system will utilize novel frequency bands in the THz region and consider AI-assisted networks. Various AR, VR, and MR service scenarios demand ultra-high data transmission rates. Since the use of THz bands causes severe path loss, it is necessary to collaborate with lower-frequency bands through multiple layers in the vertical direction. Millimeter waves will also suffer from severe blockage and penetration loss. Properly designed antennas, channels, and links are critical for communication system performance and therefore have received much attention. Research on the powerful antenna designs required by different communication environments in future 6G networks has become an important issue. Extensive studies are currently being performed on the requirements for antennas used in scenarios such as urban, rural, indoor, and high-mobility

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applications.

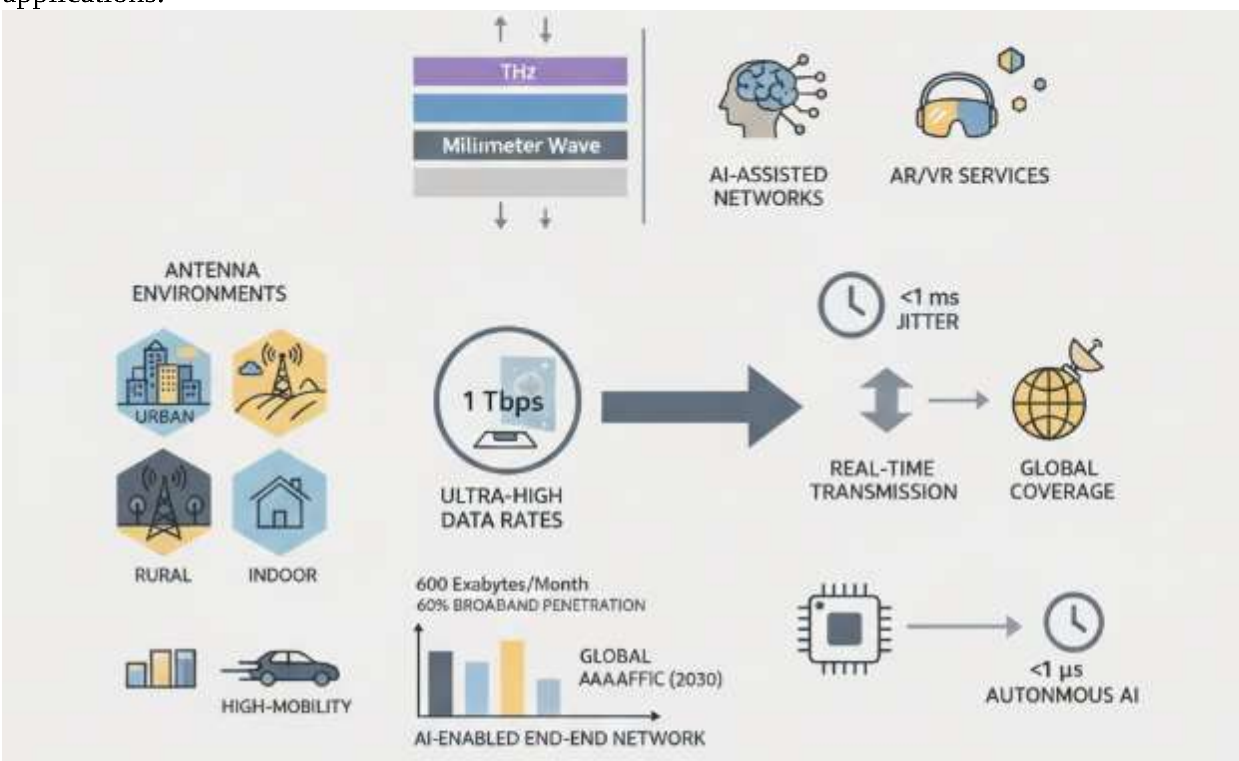

Fig 1: Next-Generation 6G Ecosystems: Synergizing THz Spectrum, Multi-Layer Architectures, and AI-Native Networks for Terabit-Scale Communication

According to the ITU, future networks will provide unprecedented capacity and support massive amounts of information-hungry, visually intensive services. Based on the defined service requirements, a number of technical goals have been proposed. To provide holographic-type services, information transmission rates will need to reach a scintillating value of $\tau b \geq 1$ Tbps per user. Resource control jitter will need to be less than one millisecond to support real-time transmission of huge amounts of highly sensitive data; global coverage will need to be achieved; and proactive reasoning and action time in the autonomous control system will require one microsecond. Further, by 2030, the global mobile data traffic volume is expected to approach 600 exabytes per month and global broadband penetration will exceed 60%. This unprecedented spate of new commands demands an inflection point in the teleportation capability of the network, with the aim of creating the ultimate AI-enabled network with a

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10,000 times acceleration in end-to-end response capabilities and an interaction response capability comparable to human perception.

Equation 1: Data-rate requirement → Shannon capacity (links "Tbps/user" to antenna + link budget)

1.1 Start from Shannon

$$C = B\log_2(1 + \mathrm{SNR})$$

Where:

- C = achievable rate (bps)
- B = bandwidth (Hz)
- SNR = signal-to-noise ratio (linear)

1.2 Solve step-by-step for required SNR (given target rate C)

1. Divide both sides by B:

$$\frac{C}{B} = \log_2(1 + \mathrm{SNR})$$

2. Convert log base-2 to exponential form:

$$2^{C/B} = 1 + \mathrm{SNR}$$

3. Subtract 1:

$$\boxed{\mathrm{SNR} = 2^{C/B} - 1}$$

2. Key 6G Environments

Urban, rural, indoors, and high mobility are the main environments foreseen for the development of sixth-generation (6G) technology. The antenna links in these environments require specific developments. For example, the deployment of meta-architectures in urban areas

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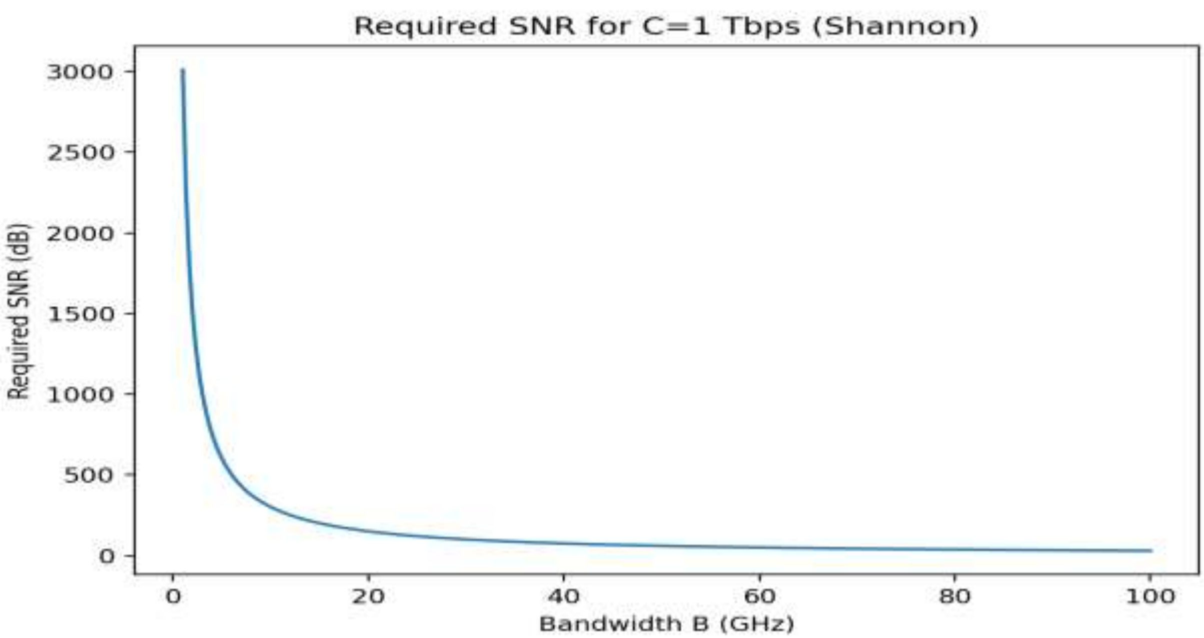
would complement what 5G has to offer, pushing for more advanced, complex optical holographic communications. In rural areas, the coverage through long-range transport links for the support of ultra-high data rates and ultra-low latency is the challenge. The support of ultra-high data rates by means of ultra-dense networks in harsh indoor environments is another key 6G requirement. And finally, the support of high speeds in terrestrial, aerial, and deep-space environments represents the last major consideration for antenna development in 6G.

These environments give rise to the following specific use cases: holographic communications, ultra-high data rates, networks aided by artificial intelligence (AI), networks that can be considered as a "living entity," and the network of everything incorporating things of all types, shapes and sizes, including humans, animals, and machines, into AI-enabled networks. The antenna system challenges are strongly related to those emerging use cases.



2.1. Emerging Use Cases for 6G Technology

With Key environments for 6G characterized, this section considers the technology's most likely use cases, as identified by 3GPP. The proposed requirements for each use case may be directly linked to antenna needs and the related challenges. Some of the considered use cases

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are holographic-type communications (with connections requiring ultra-high data rates of several 100 Gb/s), indeed visual communications appear highly promising, Ultra-reliable and Low Latency Communication for AI-based, smart connected automotive system research (with a target accident ratio of 10-9), support for Sensing-only Network (SON), full-duplex communications, even smarter-type Virtual and Augmented Reality etc,. Researchers predict these type of services will be realised by 2030 and beyond after full commercial service become available, 6G technology is expected be 1000 times more capable than 5G And 10 Tbit s-3 b.

The considered environments both differ from those of their predecessors (with larger, rural scenarios being explored) and retain intrinsically distinct characteristics. In all cases, antenna design and placement remain critical to establishing communication links with satisfactory performance to meet coverage, quality, data-rate, mobility, or latency demands technology-specific use cases under con–stated conditions. 6G build-out strategies should therefore be further informed by use-case capabilities and requirements, providing guidance on network architecture and engineering. 3rd Generation Partnership Project describes short-term use cases within technology to be realised in the period from 2029 to 2035, focusing on either future radio access foundation-type technologies.

3. Antenna Design Challenges

A number of design issues will need to be resolved in the implementation of antenna arrays for 6G applications. These include the operation of antennas at very high frequency, where efficiency is severely compromised by impedance matching, conductor and dielectric losses, and skin effect; the integration of large antenna count within a small area, yet maintaining low unit costs; the formation or steering of narrow beams by aperture arrays, which is critical in overcoming the inherent high path loss, potential blockages, and the need for very large bandwidth; and an improved correspondence between the physical array and the channel characteristics.

With a technology clearly defined and a number of solutions proposed, locations for the initial deployment of 6G networks are starting to emerge. Antennas for these environments need to satisfy challenging new requirements, arising not only from the operating band but also from the anticipated ultra-rigid broadband and ultra-high capacity services they will support. These requirements will drive both the design of the antennas, such as the need for reconfigurability or low-energy operation, and their interdependence.

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Frequency	FSPL @100 m (dB)	FSPL @1 km (dB)
3.5 GHz	83.3	103.3
28 GHz	101.4	121.4
100 GHz	112.4	132.4
300 GHz	122.0	142.0
1 THz	132.4	152.4

3.1. High Frequency Impedance and Losses

The quest for ultra-wideband antennas on the mmWave frequency spectrum has brought attention to high-frequency propagation effects such as skin effect and RF losses. Even with a relatively small number of antennas, both impedance matching and resistive losses markedly impact efficiency. Radiated power mainly proceeds through a relatively small conducting area for any practical bandwidth. At microwave frequencies, the effective width of a conductor along the propagation direction is typically assumed to be equal to the skin depth plus one skin depth, but this assumption becomes less valid at mmWave and THz frequencies. Over this frequency band, skin effect is one of the primary causes of loss in metallic conductors. Dielectric loss per wavelength in dielectrics (plastic substrates) with high dielectric constant also becomes important.

Typically expressed in [dB/m], these losses decrease with increasing dielectric constant, and become especially important for dielectric-filled antennas and cavity resonators. Where low loss can be assured and when very small size is required, CPW-type antennas on ferrite or semiconductor substrates with large dielectric constants may prove attractive. Conductor and dielectric losses at high frequencies would not be limiting in a realistic antenna design if, on the one hand, a suitable conducting material were used, and on the other hand, low loss dielectric substrates were chosen.

3.2. Beamforming and Steering

Beamforming relies on antenna arrays to direct signal power in specific directions. Phased array systems can vary the radiation pattern with a phase difference in the transmitted or received signals, while beam steering refers to the ability to shift the beam direction in real time. In the simplest configuration, the phase difference can only be changed electronically at the transmitter

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and centrally decoded at the receiver, known as digital beamforming. Alternatively, the delays can be optimized at both ends using an analog network like a phase shifter or delay unit to reduce power consumption. A more complex system would allow phase shifts with respect to both antennas, called hybrid digital-analog beamforming.

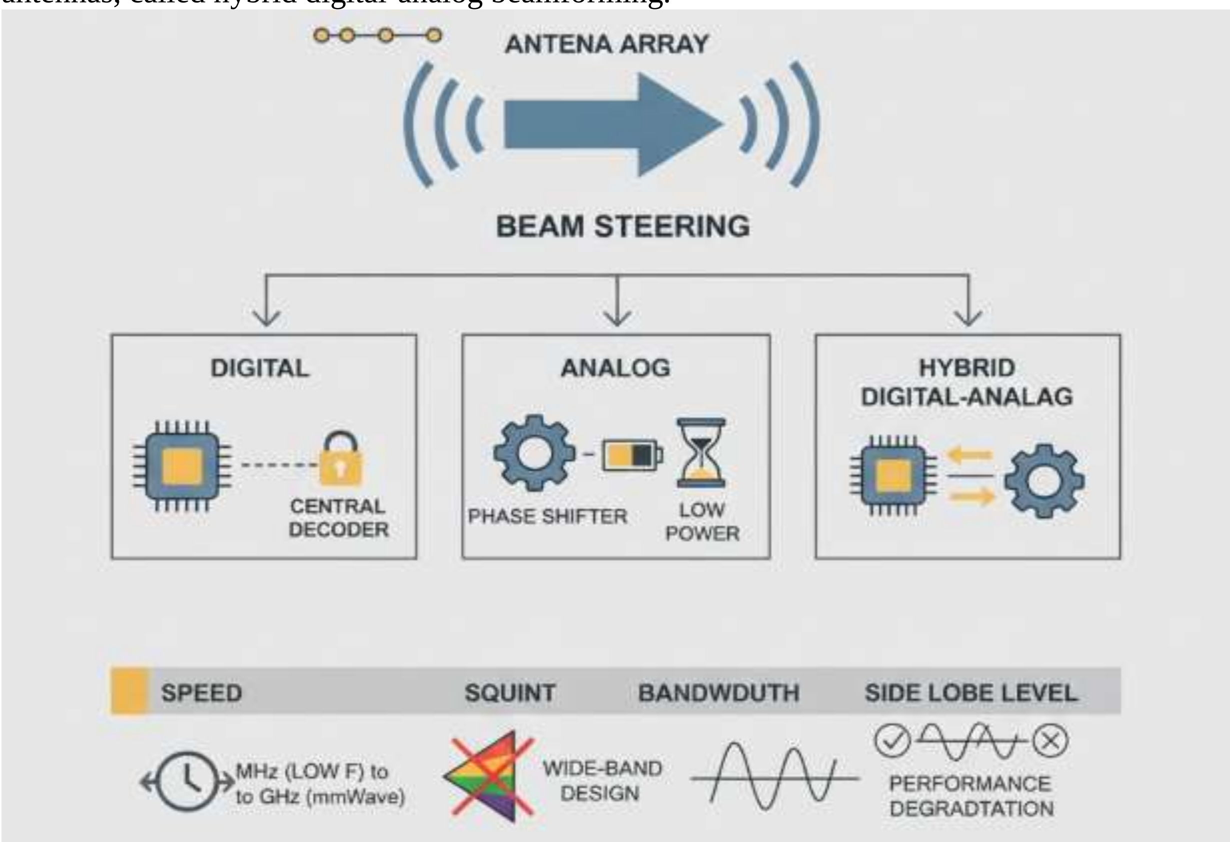

Fig 2: Optimizing Hybrid Digital-Analog Beamforming: Mitigation of Frequency-Dependent Squint and Calibration Errors in mmWave Phased Arrays

The speed of beam pointing, squint, bandwidth, side lobe level, and the need for calibration are all critical to the design of the array. These parameters are frequency-dependent; such antenna arrays can reach MHz-scan speeds at low frequencies but must be GHz-quick at mmWave. Such wide-band phased array antennas are limited by beam squint, which causes a frequency-dependent change in the beam direction; array designs have been proposed to reduce this squint and obtain the same steering angles across a large frequency band. Calibration—removing the small differences in the time delays and amplitude ratios of feeding signals to antennas—is critical, as errors lead to unintended beam tilting and squint and performance degradation in seamless handover.

4. Channel and Propagation Issues

Early work on antenna systems for sixth-generation (6G) networks indicated that links will operate at millimetre (mmWave) and terahertz (THz) frequencies. These frequencies are already known to be affected by physical phenomena that do not substantially impact links at lower frequencies. These include dramatically high path loss, severe susceptibility to obstruction, and significant temperature effects on performance. Furthermore, complex environmental factors such as buildings, forests, and rain have canonically been shown to dramatically influence channel behaviour.

Many THz signalling requirements are entirely different from those for existing cellular systems. First, a large number of users are likely to be receiving and sending signals at the same time. This will require specific directional patterns that allow very narrow beams, as found in phased arrays, although their use is more common in radar channels than in mobile communications. Second, the signals produced are weak and require extremely high power levels at the transmitter and very sensitive receivers. Although ambient energy harvesting methods in the stratosphere or ionosphere seem to be emerging, the effective power-budgets remain crucial and need very-high-efficiency products. Detailed weather effects, especially during heavy rains, need special consideration because they can cause deep fades in the order of 20dB in very short temporal windows.

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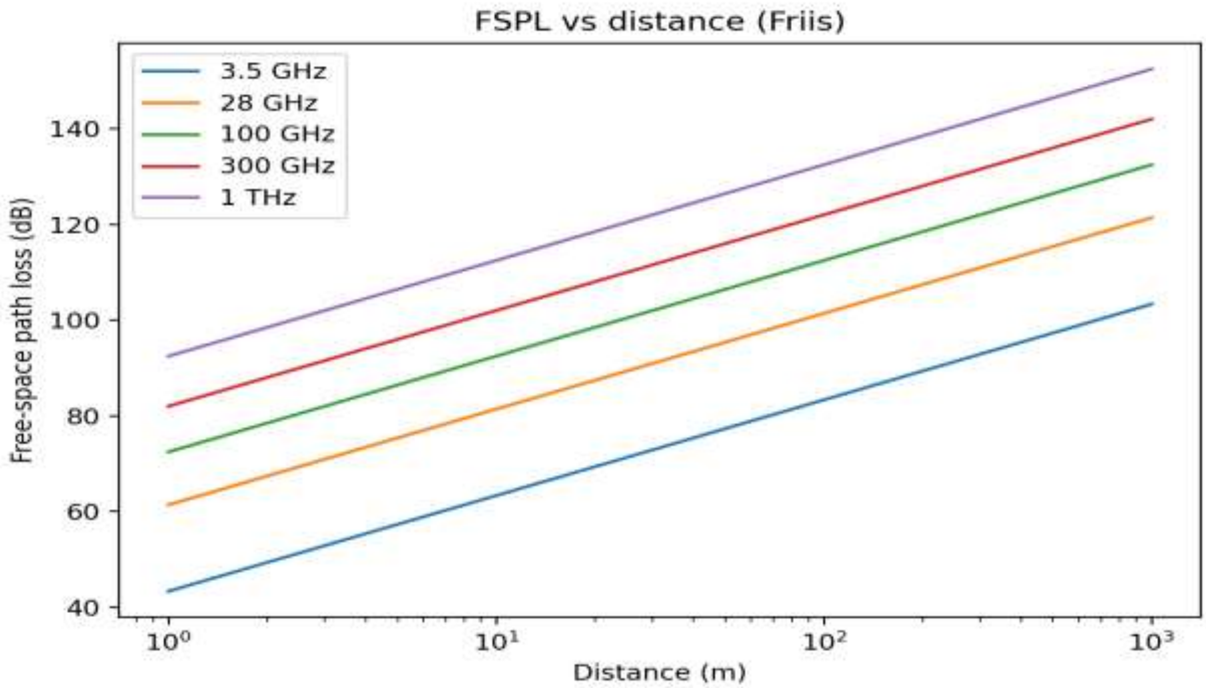

4.1. Ultra High Path Loss

Path loss models at mmWave and THz are significantly greater than those at lower frequencies, contributing to short-range links. Atmospheric absorption, thermal noise, and rain at mmWave frequencies result in reduced coverage and additional fade margins; however, this effect is compensated somewhat at THz frequencies by the higher level of available bandwidth. The use of radio wave bands above 1 THz introduces new phenomena, such as the effect of molecular resonance on propagation—at these frequencies, radiation moves in precision firearms to their targets—and requires new models to characterize the propagation of radio signals in a turbulent medium. Therefore, link budgets at very high frequencies must account for high path loss. At mmWave frequencies, where the signal is absorbed in the rain, the range of radio communication is determined not only by the level of rain but also by the radar cross-section of drops; the larger the area of evaporation, the greater the absorption losses.

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Equation 2: Link budget foundation → Friis transmission equation → Free-space path loss (FSPL)

2.1 Power density at distance d (from transmitter)

If transmit power is P_t and transmit antenna gain is G_t, then power flux density (W/m²) at range d is:

$$S(d) = \frac{P_t G_t}{4\pi d^2}$$

2.2 Receiving antenna captures power using effective aperture A_e

$$P_r = S(d)\, A_e$$

Antenna theory relates receive gain G_r to effective aperture:

$$A_e = \frac{G_r \lambda^2}{4\pi}$$

2.3 Substitute $S(d)$ and A_e into P_r

$$P_r = \left(\frac{P_t G_t}{4\pi d^2}\right)\left(\frac{G_r \lambda^2}{4\pi}\right) \boxed{P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi d}\right)^2}$$

This is the **Friis** equation.

2.4 Define free-space path loss (FSPL)

Rearrange Friis into "loss form":

$$P_r = P_t G_t G_r \frac{1}{L_{fs}} \quad \Rightarrow \quad L_{fs} = \left(\frac{4\pi d}{\lambda}\right)^2$$

Convert to dB:

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$$\boxed{L_{fs}(\mathrm{dB}) = 20\log_{10}\left(\frac{4\pi d}{\lambda}\right)}$$

2.5 Substitute $\boldsymbol{\lambda = \frac{c}{f}}$

$$L_{fs}(\mathrm{dB}) = 20\log_{10}\left(\frac{4\pi d f}{c}\right)$$

2.6 Practical link budget form (in dB / dBm)

$$\boxed{P_r(\mathrm{dBm}) = P_t(\mathrm{dBm}) + G_t(\mathrm{dBi}) + G_r(\mathrm{dBi}) - L_{fs}(\mathrm{dB}) - L_{\mathrm{other}}(\mathrm{dB})}$$

4.2. Blockage and Penetration

For transmission at mmWave and terahertz frequencies, high path loss is the primary concern. In addition to path loss, blockage by objects in the environment is a significant factor that needs consideration. Experience with existing mmWave systems has shown that the reliability of communications links is highly sensitive to shadow fading. Several factors contribute to this sensitivity. First, communications links at mmWave frequencies are more likely than at lower frequencies to have little or no excess delay spread, making them more sensitive to blockages than those with larger multipath components. Second, buildings, vehicles, or heavy rainfall can all attenuate links even when they are not in the direct path. Third, people can also block signals, and at very high speeds the risk of sudden blockages increases.

The line-of-sight nature of mmWave communication means that a hand does not have to come very close to the transmitter or receiver to block the communication. The 6G vision of massive 3D connectivity aims for coverage with an effective bit rate above a certain threshold across the entire space around a user. This ambition is rarely met in real-life scenarios, and the bandwidth-delay product in real conditions is much smaller than expected. Furthermore, it has been observed that people participating in connection-oriented communications exchange might significantly damage the wireless link with their movement but do not affect the end-to-end conversation efficiency.

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5. Materials and Manufacturing

Antennas must be produced using materials that facilitate performance while minimizing size, losing weight, and allowing for more compact and integrated structures. Traditional metal conductors provide the best performance in terms of conductivity and thermal management. However, the conductivity of these metals becomes even more critical at especially high frequencies, where the increasing skin depth leads to more severe conductor loss.

Conventional structural materials, such as FR-4, are more than sufficient for most RF applications, but stricter requirements related to losses and heat dissipation need to be pursued. Several sensor applications in various types of remote and extreme environments may benefit from the deployment of reconfigurable antennas, which demand flexible polymers or ultra-low-loss reconfigurable materials. In other cases, the demand stems directly from potential business cases for adaptive antennas supported by material properties allowing user-defined modification of behavior. These specifications naturally point to tunable dielectric and conductive materials, artificial-frequency selective surfaces, or metasurfaces that consist of photonic components with fixed geometry but reconfigurable optical properties. Scalability and affordability are key factors over and above the needs of advanced and extreme applications.

Antennas should be manufactured using materials that enable required performance while reducing size, weight, and volume. Metal conductors maximize conductivity and thermal management, but higher frequencies necessitate evaluation of conductivity in the context of increasing skin depth. Conventional FR-4 sufficiently meets most RF needs, although reconfigurable sensors for remote or harsh conditions require flexible polymers or ultra-low-loss materials. Demand also arises from potential business cases for adaptive antennas, pointing to tunable dielectric and conductive materials or photonic components with fixed geometry but reconfigurable optical properties. Scalability and affordability remain essential alongside pursuit of extreme applications.

5.1. Advanced Materials for Reconfigurability

Tunable dielectric materials offer extra degrees of freedom in antenna design. The dielectric properties can be tuned dynamically by applying an external control signal, such as DC voltage in dielectric elastomers or dielectric liquid-injection actuators. This technology enables the adjustment of antenna frequency response without mechanical moving parts. Another possible material is a tailorable dielectric elastomer, which is used to design a low-cost, low-profile tunable dielectric antenna. Because dielectric elastomers can be mounted on a flat

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surface, they are attractive for rapid and mass production. However, the achievable bandwidth is narrow.

Recently, some attention has also been directed to metasurfaces funded with vanishingly small thickness. The phase shifts can be modulated to achieve beam steering capabilities by patterning the voltage-controlled pixelated liquid-crystalline polymer film on the metasurface. Other tunable metasurface technologies rely on tunable passive components incorporated in the metasurface unit cells. For instance, the liquid crystal filled unit cell and the sequencing of varactor diodes embedded in approximation unit cells. The tunable capabilities of the metasurfaces can be employed as beam steerable reflectors or absorbers while maintaining low cost.

Moreover, plastics and flexible substrates can also be employed for reconfigurable antennas to satisfy requirements for compactness, light and soft characteristics, low cost, and readiness for mass production. Flexible and stretchable antenna systems allow extensive deformation without disintegration. They can be mounted on non-planar surfaces, thus contoured toward enhanced environmental selection. With integrated mechanical deformation, electrical characteristics such as impedance and resonant frequency are changeable.

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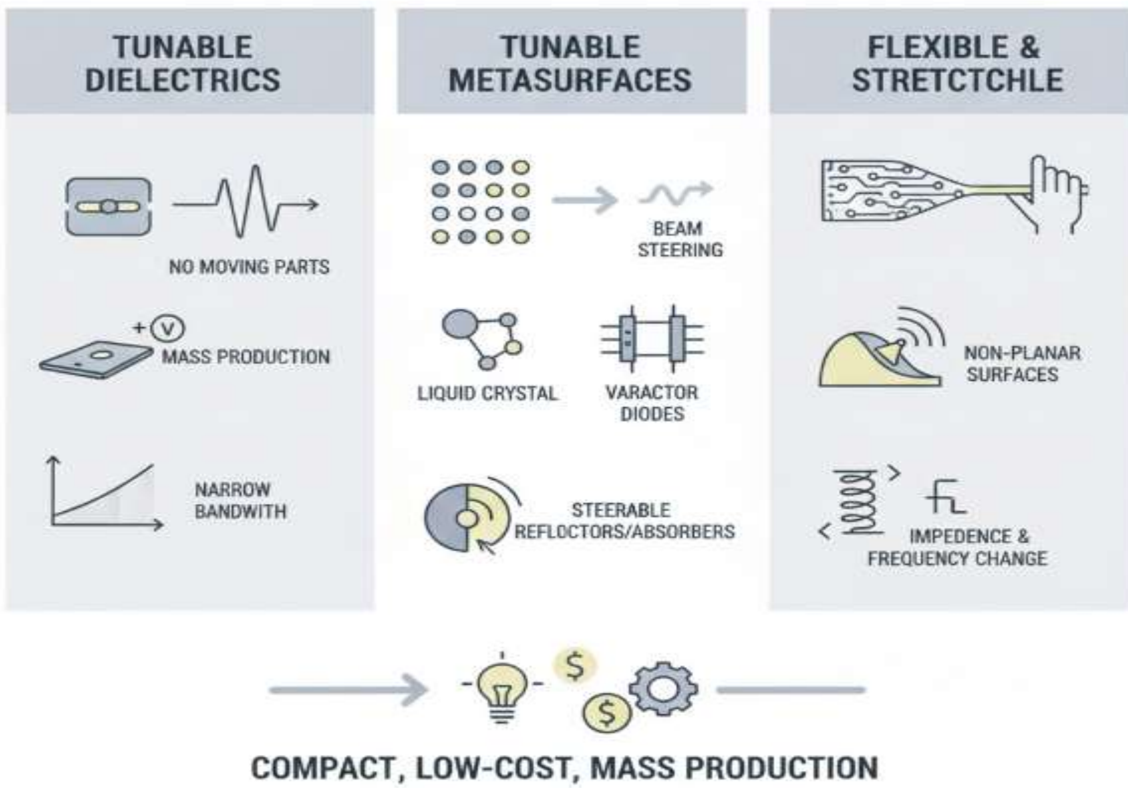

Fig 3: Advanced Reconfigurable Radiating Systems: Integrating Tunable Dielectric Elastomers, Flexible Substrates, and Pixelated Metasurfaces for Dynamic Beam Steering

5.2. Cost and Production

Designing antennas for 6G presents not only a complex set of engineering challenges, but also a very high cost in Research & Development. This makes it even more important to wreck R&D funding into solutions that can scale. Scalability is an important factor. Even if an antenna has the necessary properties for a specific application or use case, but cannot be produced at scale or at a reasonable cost, it is very unlikely that it will be of benefit to the larger 6G ecosystem.

Cost-effectiveness and manufacturability have been less of a concern at mmWave frequencies, but at frequencies 5G and above it is sensible to start addressing them at an early

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stage. Advanced materials, non-metallic components, multilayer manufacturing technologies, and high-volume cost reduction can all ultimately increase accessibility, especially if the resulting devices can retain acceptable performance specs.

6. Energy and Thermal Management

Antenna arrays, especially large ones, consume substantial energy when generating, receiving, and processing signals. Networking systems as a whole will also consume substantial energy; high data-rate traffic, together with densely clustered networks, pushes total energy levels even higher. The resultant heat will be hard to manage by conventional cooling methods.

More power-efficient materials and multiplexing and channel use and scheduling methods will all help in reducing power consumption. These additions will open new design options for cooling and temperature management of antenna systems, and these aspects should be included in the overall antenna system design process from the beginning.

Antennas clearly play a key role in the emerging 6G era with its extreme use cases, and many challenges and opportunities in antenna design are emerging. The antenna sub-system is crucial, since it ultimately connects the RF to the free-space optical channel. Therefore all requirements and strategies throughout the research and development timeline should clearly factor in these challenges and opportunities found in the antenna sub-system. A holistic view of the overall link budget is thus strongly recommended—taking care of all aspects of the RF-optical channel, antenna, and beyond—while promoting and addressing the specific challenges and opportunities.

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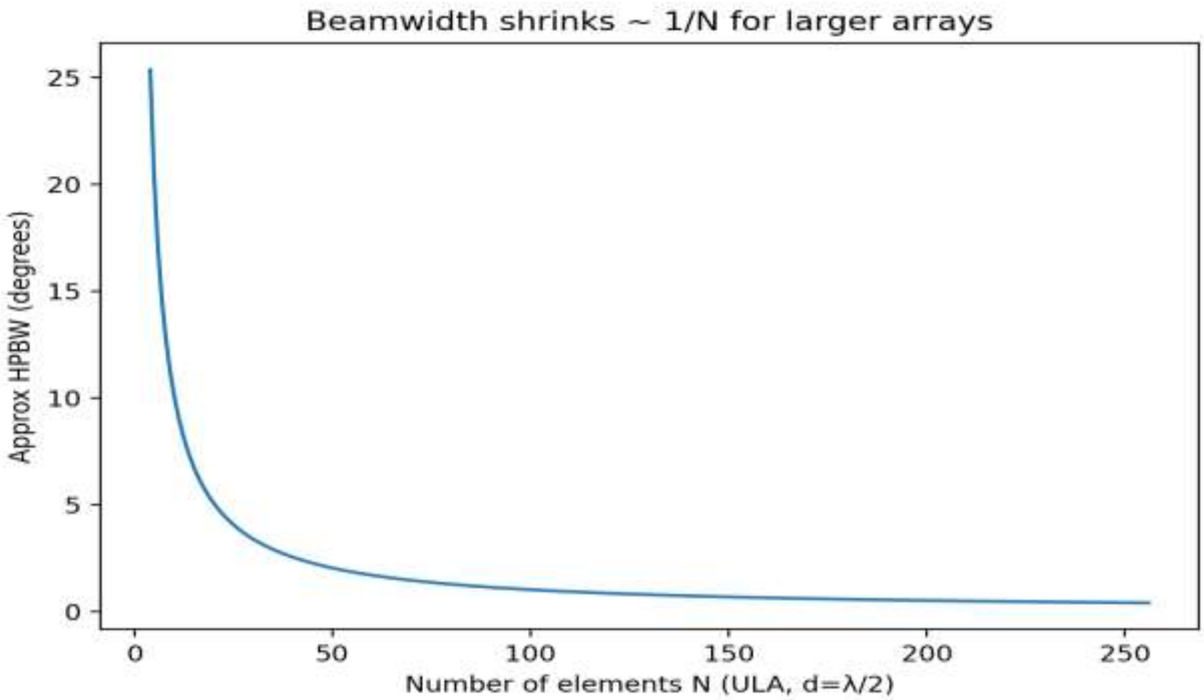

Equation 3: Antenna gain vs aperture (why "same optical aperture" matters at higher f)

3.1 Gain–aperture relationship

A standard antenna identity:

$$\boxed{G = \frac{4\pi A_e}{\lambda^2}}$$

If efficiency η connects effective aperture and physical aperture A:

$$A_e = \eta A$$

Then:

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$$G = \eta \frac{4\pi A}{\lambda^2}$$

6.1. Strategies for Efficient Energy and Heat Regulation

As the quantity of antennas greatly increases in dense networks, the total energy consumed also rises. In addition to becoming a subsystem that consumes large amounts of electricity, base and network stations in general can generate great amounts of heat, especially when CLF and other types of high-frequency amplifying components are present. This heat must also be dissipated or properly managed so that other network components are not harmed. Energy consumption and heat generation caused by antennas are two intertwining problems because of the array architecture. When antenna elements consume less energy, they generate less heat at the same time. Therefore, when the cooling systems (if any) or the installation designs cannot guarantee that excess heat is dissipated away from antennas and the vicinity region, energy-efficient design and or materials become important strategies. Other strategies to be employed include the fabrication of antennas for very short period of energy consumption and switch-off when not being used, the selection of materials that are resistive in order to consume energy during their function and not generate harmful heat, and finally, the integration of both passive and active cooling systems.

In these cases, a first direction could be the use of tunable dielectrics that are non-linear under average conditions, thus behaving like conventional dielectrics but switching towards low dissipative at high power levels; the second one is to explore the photonic properties of materials to employ for photonic cooling. The demand for cooling systems increase when high-energy levels are required for just a low time, such as in CLF and beamforming technologies. In order to be efficient, antennas either must direct the radiation towards the base station (temporal beamforming) or switch-off the sections of the antennas that are not pointing towards the base station. Therefore, the utilization of thermal issues and energy consumptions as performance indicators during the design process can minimize the negative impact.

Frequency	Skin depth δ (μm) [Cu]	Surface resistance Rs (mΩ/□) [Cu]
1 GHz	2.09	8.25
10 GHz	0.661	26.09
100 GHz	0.209	82.502

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Frequency	Skin depth δ (μm) [Cu]	Surface resistance Rs (mΩ/□) [Cu]
300 GHz	0.121	142.898
1 THz	0.066	260.895

7. Conclusions

Antenna systems will play a vital role in the performance of 6G networks, enabling communication technologies capable of supporting diverse use cases such as ultra-realistic holographic communications and extreme data rates. A roadmap for the next generation of communication systems should address the main design challenges that 6G antenna technologies must overcome, including those related to frequency, size, efficiency, materials, and integration. The particular designs currently envisaged for specific environments, scenarios, and application requirements should be monitored closely to ensure the compatibility of antenna and link technologies and facilitate their successful deployment.

Key questions remain that the antenna research community can address in the coming years. Solving these problems will help determine what antenna designs, techniques, or materials warrant further attention in the long term. Research priorities should focus on supporting the development of cheap, vertically integrated, and high-performance manufacturing processes as well as high-GHz–THz–sub-THz meta–reconfigurable and meta–adaptive material technologies. The road beyond 2030 promises to be a period of change for antenna technologies in terms of design paradigms, materials, shapes, preferences, and paths of colonialization, thanks to the lighter, more effective, shorter-range, and more flexible networks that it will support.

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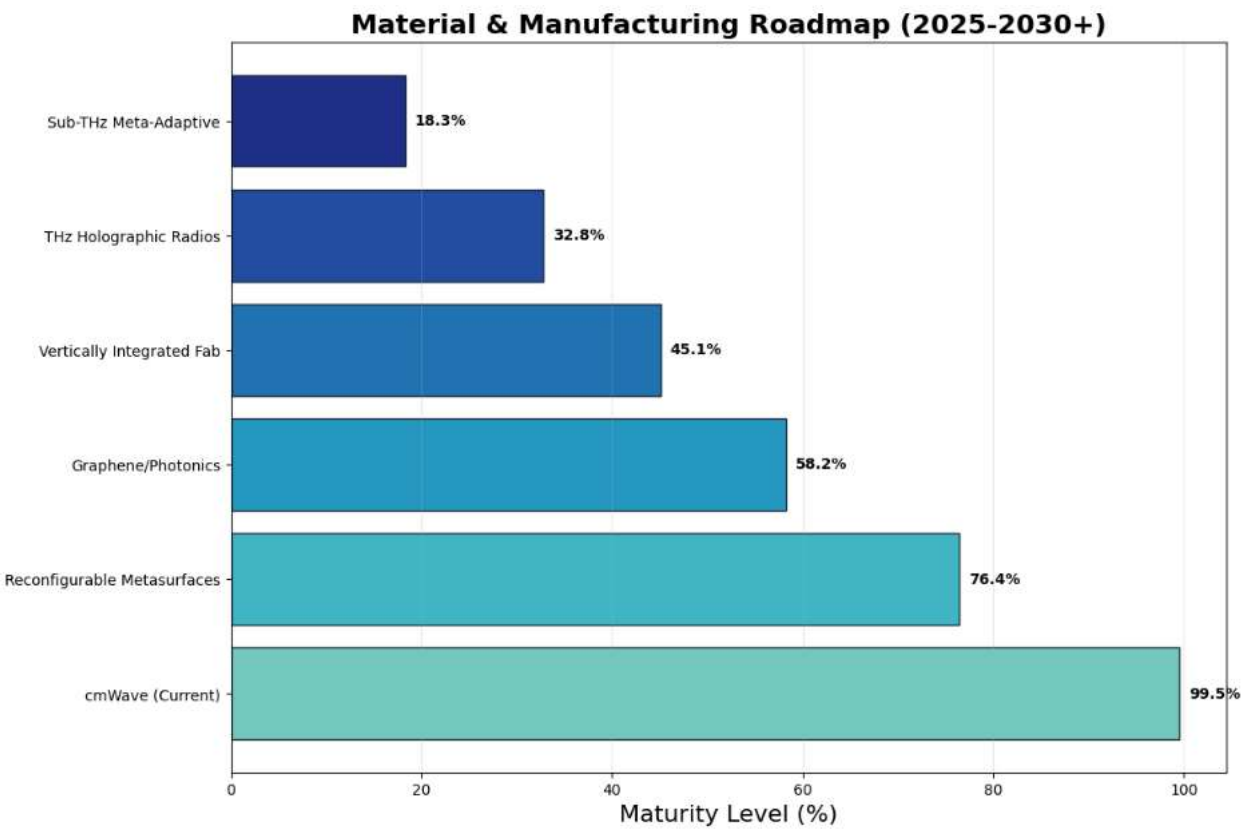

Fig 4: Material & Manufacturing Roadmap (2025-2030+)

7.1. Final Thoughts and Future Directions

The key implications of the discussion include: Many environments and use cases will impose strong requirements on the antennas or links, and many use cases will lead towards very challenging electric channel conditions. These challenges must be addressed so that 6G can achieve its potential. Reflecting this potential, the antenna challenges for 6G are diverse and significant.

The earlier sections have highlighted the key problems, but there is much more to say for a complete antenna development picture. Although the main experimental priority must surely remain the demonstration of key technology blocks, any problem that contributes to a complete

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antenna system picture should be addressed when a suitable opportunity arises. Many antenna foundries are now capable of realizing more complicated devices. It is wise to take advantage of their capabilities while they last, since the surviving manufacturers may later focus solely on higher-volume lower-cost higher-volume devices.

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