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Substrate Materials and Characterisation Methods for Sub-6GHz 5G Antennas: A Comprehensive Review

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Abstract: The deployment of fifth-generation (5G) wireless networks in the sub-6 GHz frequency range has increased the importance of substrate materials in determining antenna performance. Unlike millimeter-wave systems, sub-6 GHz antennas face challenges such as larger physical size, mutual coupling in compact arrays, and material dispersion over wide bandwidths. This review focuses on substrate selection criteria, optimization strategies, and characterization techniques for sub-6 GHz 5G antenna applications. Various substrate materials, including conventional laminates, flexible polymers, and emerging materials, are compared in terms of dielectric properties, loss characteristics, cost, and ease of fabrication. Optimization techniques such as dielectric constant tuning, substrate thickness adjustment, and structural modifications are discussed to enhance bandwidth and efficiency. In addition, commonly used characterization methods are outlined for accurate evaluation of material properties at sub-6 GHz frequencies. Optimized substrate designs demonstrate improved bandwidth and high radiation efficiency across major 5G bands. Future research directions include the development of sustainable materials, advanced fabrication methods such as 3D printing, and artificial intelligence-driven material optimization for next-generation wireless systems.

Keywords: Substrate materials, sub-6GHz, 5G antenna, dielectric characterisation, FR-4, Rogers.

I. INTRODAUCTION

The rapid expansion of wireless communication technologies has positioned fifth-generation (5G) networks as a key enabler of high-speed connectivity and ubiquitous coverage. These systems operate across two major frequency domains: millimeter-wave bands (24–100 GHz) for high-capacity short-range links and sub-6 GHz bands (0.45–6 GHz) for broader coverage and improved indoor penetration [1], [13]. The sub-6 GHz spectrum serves as the foundational layer of 5G, supporting essential services such as enhanced mobile broadband (eMBB) and massive machine-type communications (mMTC) [20].

In this frequency range, antenna performance is strongly influenced by the properties of the substrate material used in fabrication. Compared to mmWave systems, where conductor and surface wave losses are dominant, sub-6 GHz antennas are more sensitive to dielectric losses, substrate thickness, and frequency-dependent material dispersion [6], [9], [18].

The substrate plays a crucial role in defining key antenna characteristics, including resonant frequency, bandwidth, radiation efficiency, and physical size. Parameters such as dielectric constant (ε_r) and loss tangent (tan δ) directly affect these performance metrics. For compact 5G devices, antenna miniaturization is necessary, often leading to the use of high-ε_r materials, which introduces a trade-off between reduced size and increased losses [2], [4].

Accurate characterization of substrate materials is essential for reliable antenna design at sub-6 GHz frequencies. This typically involves determining complex permittivity across the operating band using techniques such as resonant cavity methods, transmission line approaches, and free-space measurements [7], [10], [17] [21][22]

II. SUBSTRATE MATERIALS FOR SUB-6GHZ 5G ANTENNAS

The selection of substrate material for sub-6GHz 5G antennas involves trade-offs among electrical performance, mechanical properties, cost, and manufacturability. Unlike specialized mmWave substrates, sub-6GHz designs can leverage a wider range of materials including low-cost options [6], [9].

A. Conventional Rigid Substrates

- FR-4 (Flame Retardant 4) is the most widely used substrate for consumer electronics due to its low cost and widespread availability.
- Rogers RO4000 series (RO4003C, RO4350B) offers stable dielectric properties with ε_r = 3.38–3.66 and tan δ = 0.0021–0.0037 up to 6 GHz.
- Rogers RT/Duroid 5880 (ε_r = 2.20, tan δ = 0.0009) offers the lowest loss but at higher cost.

B. Flexible and Conformal Substrates

- Liquid Crystal Polymer (LCP) has emerged as a leading flexible substrate for sub-6GHz 5G antennas in foldable devices and wearables.
- Polyimide (Kapton) offers ε_r = 3.3–3.5, tan δ = 0.003–0.008 and is widely used in flexible circuits.
- Textile substrates (denim, cotton, felt) enable wearable 5G antennas. These materials have low ε_r (1.2–1.8) but high loss (tan δ = 0.01–0.05) and require conductive fabrics or embroidered conductors.

Table I. Substrate Materials for Sub-6GHz 5G Antennas

Material	*ε_r (at 1-6 GHz)*	*tan δ*	*Thickness Range (mm)*	*Cost*
FR-4	*4.2–4.8*	*0.016–0.025*	*0.5–3.0*	*Very low*
RO4003C	*3.38*	*0.0021*	*0.2–1.5*	*Moderate*
RO4350B	*3.66*	*0.0037*	*0.2–1.5*	*Moderate*
RT/Duroid 5880	*2.20*	*0.0009*	*0.25–3.0*	*High*

C. *Emerging Substrate Materials*

Metamaterial-inspired substrates incorporate periodic structures to achieve effective permittivity values not available in natural materials, enabling unusual antenna behaviours such as enhanced bandwidth or reduced mutual coupling [11].

III. Optimisation of Substrate Parameters for Sub-6GHz 5G Antennas

Optimization of substrate parameters for sub-6GHz 5G antennas involves balancing dielectric constant, thickness, and loss tangent to achieve desired performance metrics [5], [11], [14]. Dielectric constant (ε_r) is optimized through composite blending or substrate stacking, where higher ε_r reduces antenna size but narrows bandwidth, while lower ε_r enhances bandwidth at the cost of larger footprint [2], [4]. Substrate thickness (h) is selected within the range of $0.01\lambda_0$ to $0.05\lambda_0$, where thicker substrates improve bandwidth (15–18%) and efficiency (up to 86%) but increase surface wave losses [2], [18]. Loss tangent (tan δ) is minimised by selecting low-loss materials (tan δ < 0.005) such as Rogers laminates, achieving radiation efficiencies above 85% [6], [14]. Defected ground structures (DGS) are employed to modify effective substrate properties, reducing mutual coupling by 10–15 dB and suppressing harmonic frequencies [5], [11]. Multi-layer substrate stacking with varying permittivity values enables wideband (20% bandwidth) and dual-band operation for 5G bands n77, n78, and n79 [3], [10], [12].

IV. Optimization Techniques for mmWave Patch Antennas

Optimization Accurate characterisation of substrate dielectric properties is essential for reliable antenna design. At sub-6GHz frequencies, several well-established methods exist for measuring complex permittivity (ε_r and tan δ) [7], [10], [17].

- Transmission Line Methods
  Microstrip ring resonator method is the most common for substrate characterisation at 1–6 GHz. A ring resonator is fabricated on the substrate under test, and its resonant frequencies are measured using a vector network analyser (VNA) [7], [10].
- Resonant Cavity Methods
  Split-post dielectric resonator (SPDR) is a commercial measurement system (QWED, Keysight) offering high accuracy.
- Free-Space Methods
  For large substrate panels or materials that cannot be easily cut into samples, free-space methods using horn antennas and a VNA are employed. The substrate is placed between two horn antennas, and transmission/reflection coefficients are measured [7], [10].
- Time-Domain Reflectometry (TDR)
  TDR measures impedance variations along a transmission line. By launching a fast rise-time pulse into a stripline embedded in the substrate, reflections indicate permittivity variations. TDR is useful for characterising inhomogeneous or multilayer substrates [7].

Table II. Comparison of Substrate Characterisation Methods for Sub-6GHz

Method	*Frequency Range*	*Accuracy (ε_r)*	*Accuracy (tan δ)*
Microstrip ring resonator	*1–6 GHz*	*±0.5%*	*±5%*
SPDR	*1–15 GHz*	*±0.1%*	*±3%*
Free-space	*1–10 GHz*	*±2–5%*	*±10–20%*
TDR	*DC–10 GHz*	*±2%*	*N/A*

V. Conclusion

This This review presented an overview of substrate materials, optimization techniques, and characterization methods for sub-6 GHz 5G antennas. Various substrate options, ranging from low-cost conventional materials to advanced flexible and emerging alternatives, play a crucial role in determining antenna performance. Key optimization approaches focus on dielectric constant selection, substrate thickness control, and structural modifications to achieve improved bandwidth, efficiency, and compact size. Accurate characterization of material properties is essential for reliable antenna design across the operating frequency range.

Optimized designs demonstrate enhanced bandwidth and high radiation efficiency suitable for major sub-6 GHz 5G bands. Future research is expected to focus on sustainable materials, advanced fabrication techniques, and intelligent design approaches to further improve antenna performance for next-generation wireless systems.

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