Implantable BLE antennas

Enabling reliable RF transmission through the human body

Continuous Glucose Monitoring (CGM) has become the cornerstone of modern diabetes care, providing real-time glucose data that helps patients manage glycaemic control, prevent complications, and improve quality of life.

However, traditional CGM systems typically depend on external transmitters and wearable patches, adding complexity and reducing user comfort. A new generation of implantable CGM sensors is emerging, aimed at eliminating the need for external hardware, for a more discreet and user-friendly experience.

The shift to implantable CGM sensors introduces significant wireless communication challenges, as maintaining a reliable RF data link becomes more difficult when moving to an implanted device. These systems must ensure dependable real-time connectivity – especially for transmitting critical alarms – to safeguard patient safety.

Size constraints are driven by user comfort and cosmetic expectations, limiting space for antennas and batteries. Additionally, with lifetime targets of up to 12 months, ultra-low power consumption is essential to extend battery life without the possibility of recharging or replacement.

Bluetooth Low Energy (BLE) provides a viable solution by enabling direct, low-power communication with smartphones, removing the need for external receivers. Integrating BLE into compact implants and similarly into other implantable biosensors - demands careful attention to system design, antenna miniaturisation, integration, and power efficiency to ensure reliable performance across varied use cases.

A well-designed implantable BLE antenna is critical to achieving reliable connectivity and a simplified system architecture - empowering patients with continuous, real-time access to critical health data.

Example development of an implantable antenna

The solution

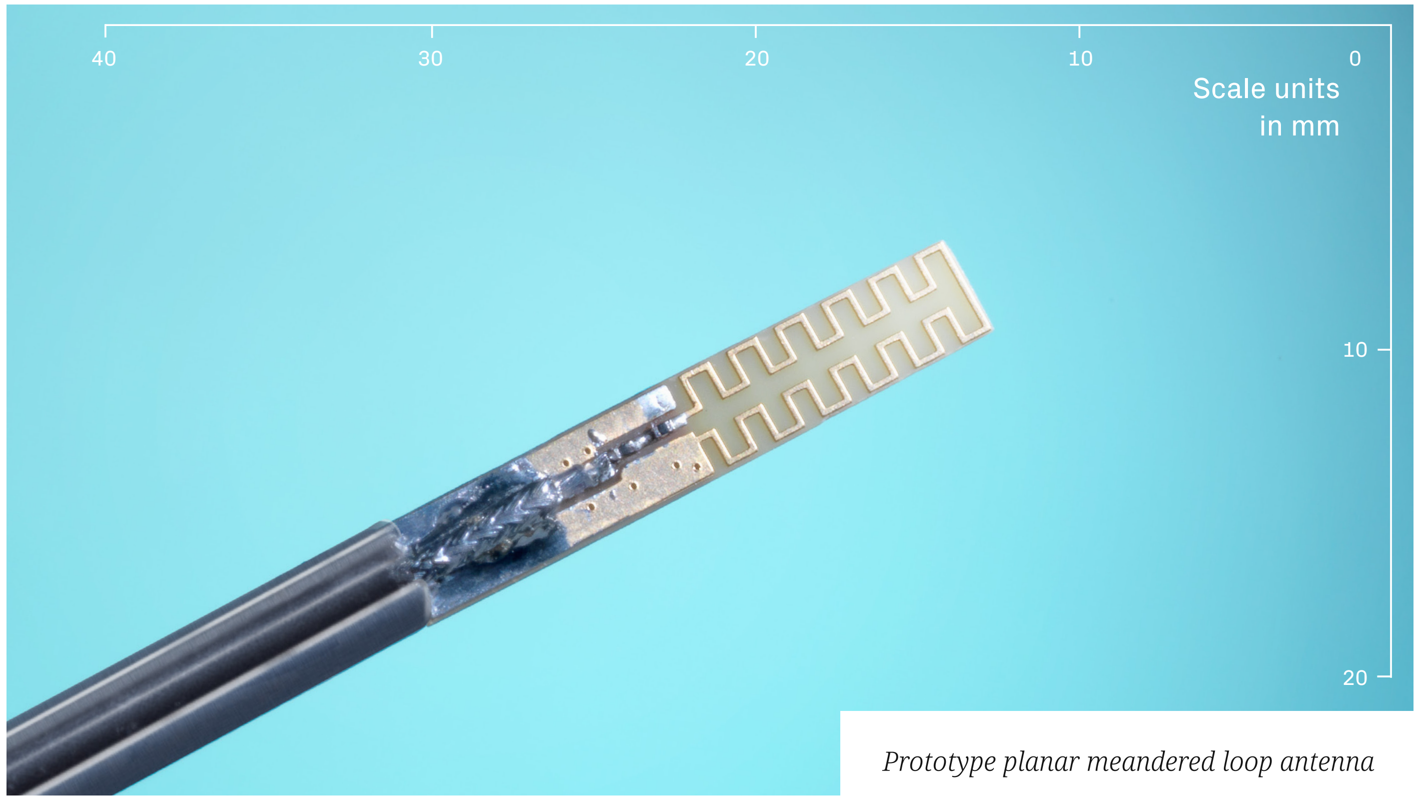
Developing a BLE antenna for an implantable sensor such as a continuous glucose monitor requires system-level thinking and precision engineering to balance size, power efficiency, human tissue interaction, and robust communication reliability. It is essential to understand how the design will perform in real-world scenarios across varied anatomies and in different use environments.

To illustrate this, we explore a representative implantable CGM device that highlights the practical considerations, design trade-offs, and verification steps involved in achieving high-performance wireless communication in a miniaturised form factor.

Implantable CGMs are typically designed for placement in the upper arm or abdomen, and whilst minimising device size is critical for all implantable applications, practical constraints - particularly battery and component sizes - necessitate compromise.

In this design, we target a cylindrical implant measuring 4 mm in diameter and 40 mm in length. While each application may vary, the selected scenario provides a practical reference point that is representative of many implantable sensor types. The BLE antenna occupies less than 25% of the total volume and is optimised for subcutaneous implantation in the upper arm at a depth of 10 mm.

The device transmits at up to +3 dBm, and must communicate with a smartphone; either handheld, or placed on a nearby surface (≥1 m distance). A system-level link budget analysis estimates that the implant antenna in the body must achieve a minimum gain of approximately -19 dBi to ensure reliable connectivity.



Prototype planar meandered loop antenna

Prototype helical antenna

TTP explored multiple antenna topologies to identify those best suited for the BLE band and realistic body environments. This effort led to two high-performance implantable BLE antenna designs, each optimised for compact cylindrical form factors and validated under worst-case anatomical and RF conditions.

- **Planar Meandered Loop Antenna**
  9.5 mm (L) × 3 mm (W), integrated with the PCB, offering sufficient bandwidth and gain.

Fig 1.1 Planar meandered loop antenna

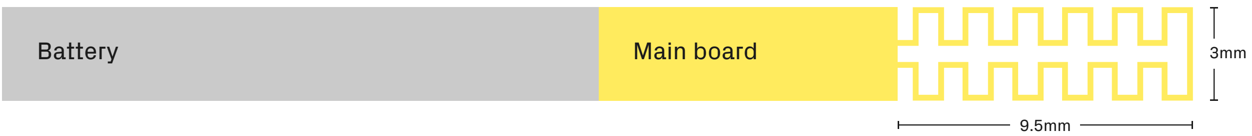


Fig 1.2 S-Parameters (Magnitude)

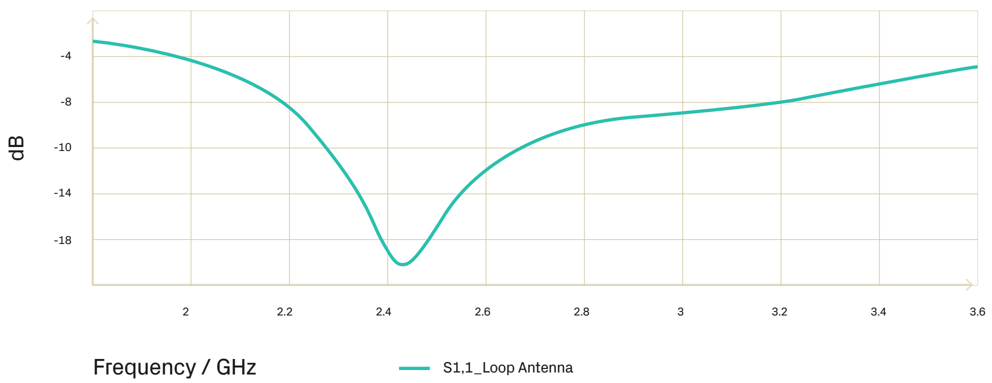
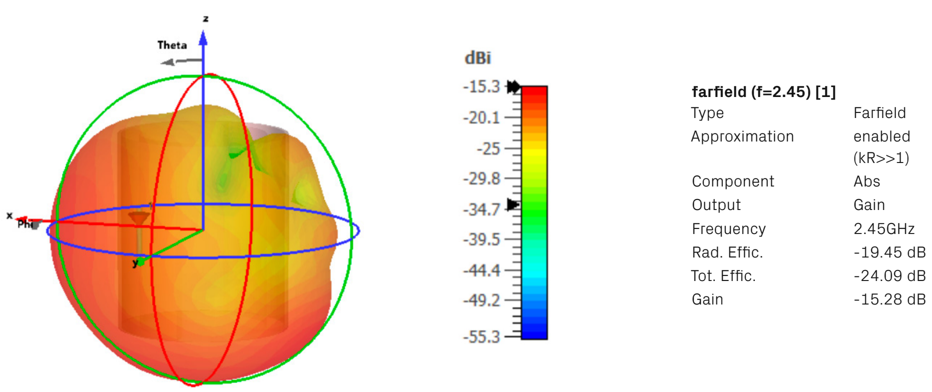


Fig 1.3 CST simulated meandered loop antenna performance in worst-case model



- **Helical Antenna**
  6 mm height × 3 mm diameter, free-standing, with comparable bandwidth and respectable gain.

Fig 2.1 Helical antenna

Fig 2.2 S-Parameters (Magnitude)

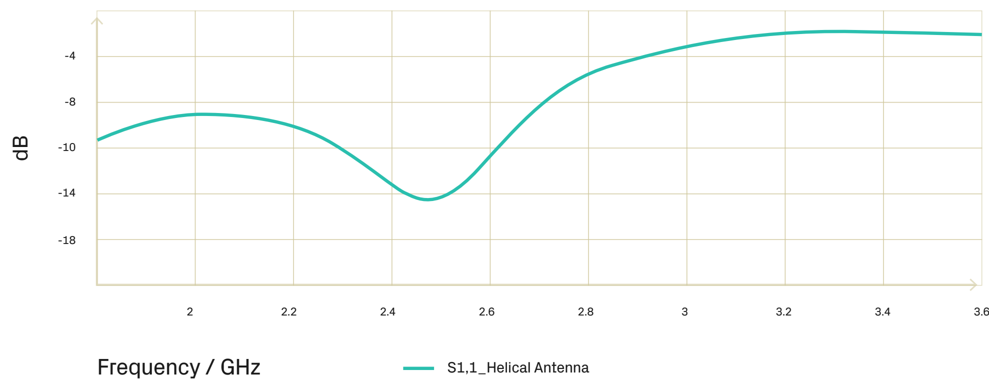
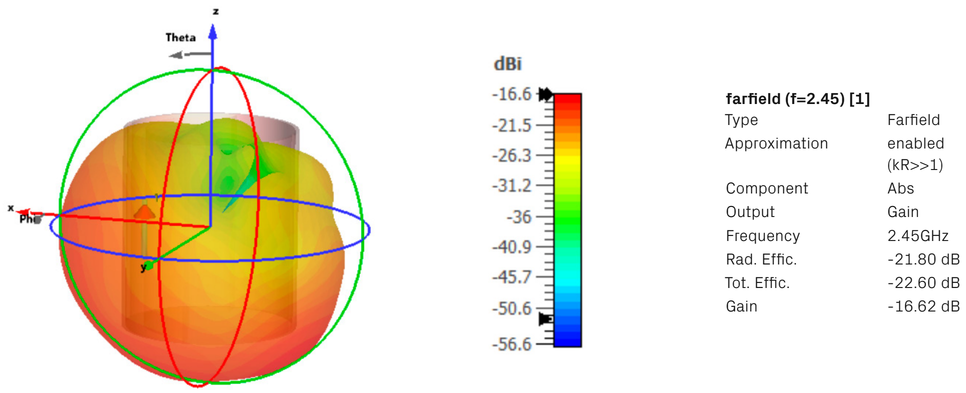


Fig 2.3 CST simulated helical antenna performance in worst-case model



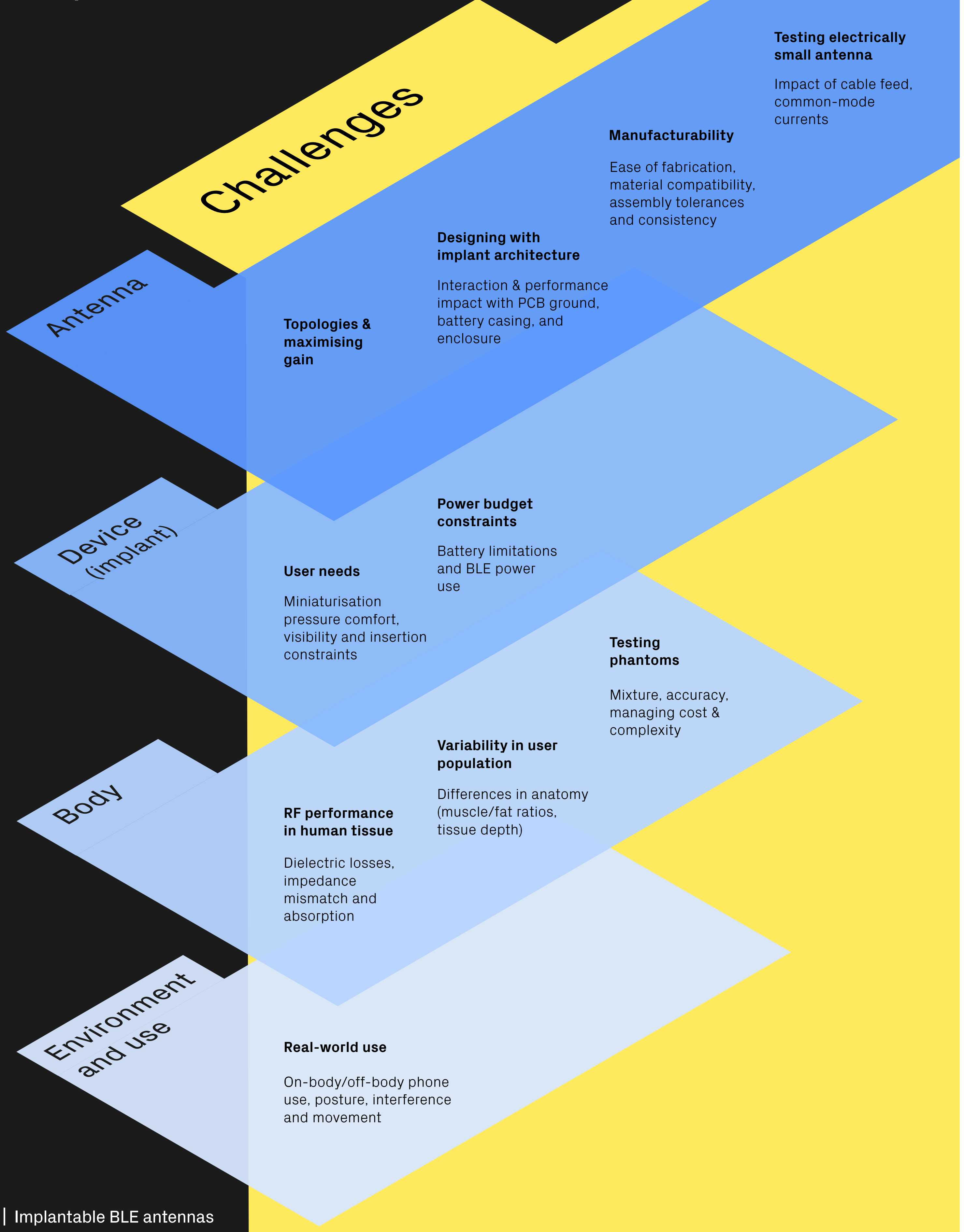


Fig 3. Designing implant RF connectivity requires overcoming a range of inter-dependent variables.

Key challenges in developing the designs

Communication system requirements and trade-offs

A key challenge in implantable CGM systems is maintaining reliable wireless communication with a smartphone. Performance is influenced by RF propagation characteristics, implant location, user posture, and phone placement.

Communication scenarios

- **Off-body links:** These occur when the phone is placed away from the user (e.g., on a table), relying on line-of-sight and multipath propagation. Performance is sensitive to distance, environmental reflections, and body movement, which can alter the multipath profile and cause signal fading.
- **On-body links:** These involve the phone being held or worn, with RF signals propagating via tissue penetration and creeping waves along the body. Creeping waves can interfere constructively or destructively depending on antenna design and placement; loop antennas couple more effectively to the body surface for instance, enhancing creeping wave propagation compared to monopoles. Although more stable, on-body links still depend heavily on implant and phone positioning.

Impact of implant location and phone position

On-body link quality can vary greatly depending on user scenarios. For an upper-arm implant, the optimal case occurs when the phone is held in the same-side hand, resulting in up to 12 dB improvement in uplink compared to the most challenging scenario – when the phone is placed in the opposite-side back pocket.

Implant location is also critical. Placing the device on the outer upper arm, away from the torso, reduces signal loss due to lower attenuation and less wave distortion. In contrast, the underarm region causes higher attenuation from anatomical complexity.

Determining the optimal antenna solution and accurately estimating system performance requires in-depth analysis tailored to specific conditions and user scenarios. The decision wasn't based solely on maximising antenna gain or radiation efficiency - it involved evaluating the full radiation pattern in the context of real-world use cases.

Human body tissue modelling

Variations in tissue composition, thickness, and anatomy significantly influence wireless performance. At the 2.4 GHz BLE band (2402–2480 MHz), tissues exhibit distinct dielectric properties; skin and muscle are highly lossy (loss tangent ≈ 0.28) and have high dielectric constants (~40 for skin, ~52 for muscle), while fat has a much lower dielectric constant (~5) and is less lossy (loss tangent ≈ 0.15).

These differences lead to variability in dielectric loading, causing shifts in antenna impedance matching and emphasising the need for wide bandwidth to maintain reliable operation. Additionally, differences in tissue loss factors directly impact absorption loss and antenna gain. Consequently, antenna performance is highly dependent on the surrounding tissue environment, particularly the relative volume fractions of different tissue types.

For subcutaneous upper-arm implants, we developed a simplified three-layer tissue model (skin, fat, muscle) to reflect typical arm anatomy. This model was validated through full-wave simulations in CST, showing closely agreement with the detailed CST Hugo human model, enabling faster, efficient design iterations.

To balance performance across user variability without excessive conservatism, we adopted a two-model strategy:

- **General model:** 42% muscle volume, representing the 30th–40th percentile in men; reflects average tissue composition for assessing typical performance across a broad population.
- **Worst-case model:** 73% muscle volume, above the 99th percentile; simulates extreme high-loss scenarios for robustness testing.

We begin antenna design using the representative general model to predict performance under typical patient conditions. To ensure reliability, each design is also evaluated under the worst-case model, verifying that minimum requirements for operational bandwidth and gain are still met.

By addressing both average and edge cases, we ensure the antenna maintains robust, user-independent performance in real-world conditions.

Electrically small antenna design

For a typical subcutaneous CGM implant, antenna and electronics must fit within a compact form factor - about 20 mm in length and enclosed in a 3 mm diameter cylinder. In contrast, a quarter-wavelength antenna at 2.4 GHz requires ~30 mm in free space, making miniaturisation critical.

However, antenna performance is strongly size-dependent, leading to a trade-off between compactness and efficiency. For example, in a ground-independent PIFA design, reducing the antenna length by just 5 mm resulted in a ~3 dB drop in both efficiency and gain.

Antenna topologies

Magnetic antennas, such as loop and helical antennas, perform better than electric types (e.g., monopole, PIFA) because they suffer less tissue loss in the near field.

Simulations show that magnetic antennas have path losses of 12.5 dB (meandered loop) and 12.6 dB (helical), while electric antennas like the monopole and PIFA experience higher losses (14.8 dB and 15.2 dB, respectively).

Ground plane impact

In electrically-small antenna design, integrating the antenna with the ground plane is crucial. For implants, the ground size (typically 10–30 mm) is comparable to the BLE antenna's wavelength, meaning it significantly impacts performance and becomes part of the antenna structure.

For instance, in a meandered loop design, reducing the antenna size from 5 mm to 3 mm while maintaining a 29 mm ground only slightly affected efficiency, dropping from -15.9 dB to -16.2 dB (a 0.3 dB reduction). This shows that optimising the available ground can enable further miniaturisation without significant performance loss.

Integrating antenna design with implant architecture

In implantable antenna design, the antenna cannot be treated in isolation – its performance is strongly influenced by integration with the overall implant structure. To improve efficiency while minimising size, designs should leverage the main PCB ground and battery casing as extensions of the antenna ground. This integrated approach supports effective miniaturisation without compromising RF performance.

Developing the antenna and system in unison is therefore essential, enabling optimisation of trade-offs across mechanical, electrical, and RF aspects. This approach aligns with TTP's key strength: deep, cross-disciplinary expertise in RF engineering, electronics, mechanics, and system integration to deliver high-performance implantable solutions.

Test setup

Custom phantom preparation

A well-controlled test setup – including both the antenna and a realistic body phantom – is critical for reliable RF performance measurement. Phantom selection depends on factors such as implant site, required accuracy, and budget, ranging from simple liquid models to complex multilayer tissue replicas.

A cost-effective and practical option is a homogeneous single-layer liquid phantom, designed through simulation to match the average RF properties of multilayer tissues. This statistically representative phantom is derived from simulation-based analysis, representing the combined dielectric effects of skin, fat, and muscle to closely approximate tissue-induced propagation losses and dielectric loading on the antenna.

While structurally simplified, this approach offers good reproducibility and is well-suited for antenna development and laboratory testing. For our design, a custom liquid phantom was formulated by precisely tuning NaCl and sucrose concentrations to replicate the dielectric constant and conductivity of homogeneous human arm tissue under worst-case conditions at ~2.45 GHz.

Experimental verification confirmed close alignment with target tissue properties, ensuring a reliable and repeatable test medium for implantable antenna evaluation. Regular monitoring of the phantom's dielectric properties is important, as liquid compositions can change over time due to evaporation, or biological degradation (e.g., mould growth), potentially affecting accuracy and consistency in testing.

Electrically small antennas testing with cable-feed

The meandered loop and helical antenna prototypes were fabricated and assembled with coaxial RF cable feeds for convenient lab testing, enabling impedance measurements with a Vector Network Analyser (VNA) and chamber-based radiation and gain evaluations using external transceiver equipment.

While practical, this method is prone to measurement errors due to unintended radiation from the feed cable. Common-mode currents induced on the cable's outer shield caused by feed imbalance, poor grounding, or coupling to the antenna - can turn the cable into a parasitic radiator.

This distorts key performance metrics such as gain, pattern, and impedance—especially for electrically small, low-power antennas, where even minor interference can mask true performance.

Minimising cable radiation

To improve measurement accuracy, it is essential to decouple the feed cable from the antenna to suppress unintended radiation. This primarily involves minimising common-mode currents on the cable's outer shield.

A common technique is to place ferrite beads or clamp-on ferrite cores along the coaxial cable - especially near the feed point - to increase impedance and suppress these unwanted currents.

Proper cable routing and grounding can further reduce coupling between the cable and antenna. Effective decoupling ensures that only the antenna contributes to radiation, eliminating cable-induced artifacts and enabling a more accurate assessment of the antenna's true performance.

Cable-free measurement using local transmitter

An alternative way to eliminate cable effects entirely is to use a self-contained local transmitter integrated directly with the implanted antenna. By removing the feed cable, this approach allows for more accurate, standalone evaluation of radiation performance for the compact implantable antenna devices.

For example, a low-power Bluetooth Low Energy (BLE) transceiver or a 2.45 GHz oscillator can be configured to transmit a continuous wave (CW) signal.

The chip is mounted at the antenna feed on the antenna board and powered by a small coin cell battery or similar compact source. The entire assembly must be carefully designed to maintain the antenna's intended form factor and electromagnetic properties.

Experimental results

The implanted antennas were tested using the cable-fed setup, with radiation pattern and gain measurements performed in our RF anechoic chamber.

At 2.45 GHz, the helical antenna showed a peak gain of -17.4 dBi (measured) versus -16.6 dBi (simulated), while the meandered loop antenna exhibited -17.7 dBi (measured) compared to -15.3 dBi (simulated).

Overall, the measured results matched simulations within a 3 dB tolerance, confirming the accuracy of the antenna design.

How can we help you

We recognise that every implant has a unique set of requirements, and therefore a different balance of design trade-offs. TTP's expertise, advanced simulation tools, and validated test setups enable rapid, low-risk development tailored to each client's needs.

We tackle complex RF challenges across implants, wearables, external readers, and RF sensing, each with its own unique considerations for connectivity, power, and usability. Beyond RF, our cross-disciplinary teams integrate electronics, firmware, and mechanical design to deliver truly system-level solutions.

We design with real-world performance and patient use in mind, ensuring reliability across body types, use scenarios, and daily life conditions. And with a deep understanding of regulatory requirements, scalability, and device longevity, we help clients move from concept to market-ready solutions with confidence.

About TTP's biosensing team

TTP's Biosensing Team specialises in wearable and implantable devices, bringing deep multidisciplinary expertise to support end-to-end development, from simulation and tissue modelling through to validated test setups and system-level integration.

With scientific and engineering rigour, we anticipate and resolve risks early, ensuring robust, high-performance solutions.

By flexing around your internal team, we provide the bandwidth and specialist expertise needed to keep milestones credible, investor confidence strong, and innovation moving forward, delivering tailored, human-centred results without unnecessary complexity.

Let's talk

Reach out to TTP's Biosensing team to learn more about how we can help you with your CGM development needs.

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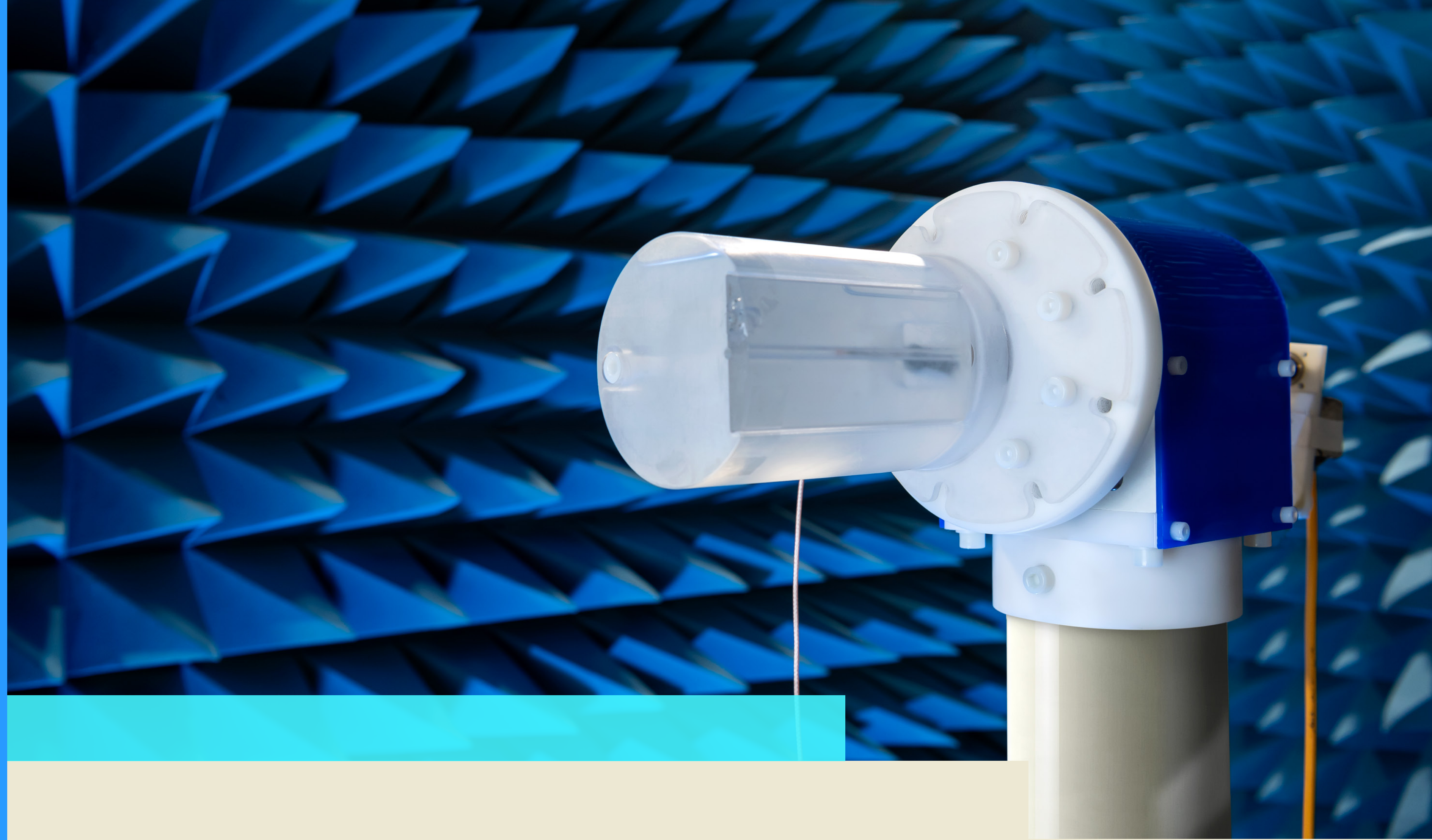

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