

ECE 445 Project Proposal

Adaptive Resonant Tuning System for Wireless Implantable Coil Coupling

Fall 2026

1. Introduction

1.1 Problem

Miniature implantable and wearable biomedical devices often require wireless delivery of power or signals because a wired connection through the skin is undesirable. Inductive wireless power transfer uses a transmitter (TX) coil outside the body and a smaller receiver (RX) coil near or inside the body. A time-varying magnetic field generated by the TX coil induces voltage in the RX coil. Reviews of implantable wireless power systems identify operating frequency, coil separation, receiver size, efficiency, and tissue safety as key design constraints, and note that the TX and RX resonant networks should be tuned to the same operating frequency to improve power-transfer efficiency [1].

The difficulty is that the electrical behavior of the coupled coils does not remain constant. Coil separation, lateral offset, angular misalignment, deformation, and the dielectric/conductive environment surrounding the coils can change the effective impedance and resonant point seen at the transmitter. Adaptive transcutaneous power-transfer literature specifically identifies coupling variation and tissue-related losses as reasons to monitor and retune implant links [2]. A fixed-frequency transmitter can therefore move away from its best operating point when the external coil shifts on the body or when the geometry of the link changes.

This problem is relevant to public health and safety because inefficient coupling can require more transmitter power for the same delivered power and can increase electrical and thermal losses. RF electromagnetic fields at sufficiently high levels can cause tissue heating, and current exposure guidance covers the 100 kHz to 300 GHz range [5]. This ECE 445 prototype will therefore be a low-power bench research platform using a receiver coil and tissue-equivalent or non-biological test setup; it is not intended for clinical use or direct testing on people.

The design will use 13.56 MHz as the nominal resonance target because this frequency is widely used for inductively powered bioelectronics [3] and lies in an FCC-designated ISM band centered at 13.56 MHz [4]. The controller will be designed to search a wider laboratory tuning window around this nominal value so that intentional detuning can be introduced and corrected during demonstration.

1.2 Solution

We propose an embedded closed-loop resonant tuning system. An STM32 microcontroller will control a programmable RF source, initially a Si5351A or equivalent frequency synthesizer, which will excite an external TX coil through an RF driver and passive L/C matching network. The TX coil will couple magnetically to a smaller RX coil representing the implanted device. The receiver side will use a fixed resonant network and load so that the coupled system has a measurable optimum operating point.

A measurement subsystem will monitor the electrical response at the TX coil. The minimum viable implementation will use a laboratory vector network analyzer (VNA) to obtain S11/input-impedance data. During automated testing, VNA data may be passed to the STM32 through a host PC using USB/serial if direct instrument communication is not practical. The MCU will execute a coarse frequency sweep, identify the frequency with the best matching metric, perform a finer local search, and command the RF source to the selected frequency. When the measured response indicates significant detuning, the controller will repeat the search. A stretch goal is to replace the laboratory VNA with a simplified custom reflection/impedance measurement circuit inspired by the open-source NanoVNA architecture [6].

1.3 Visual Aid

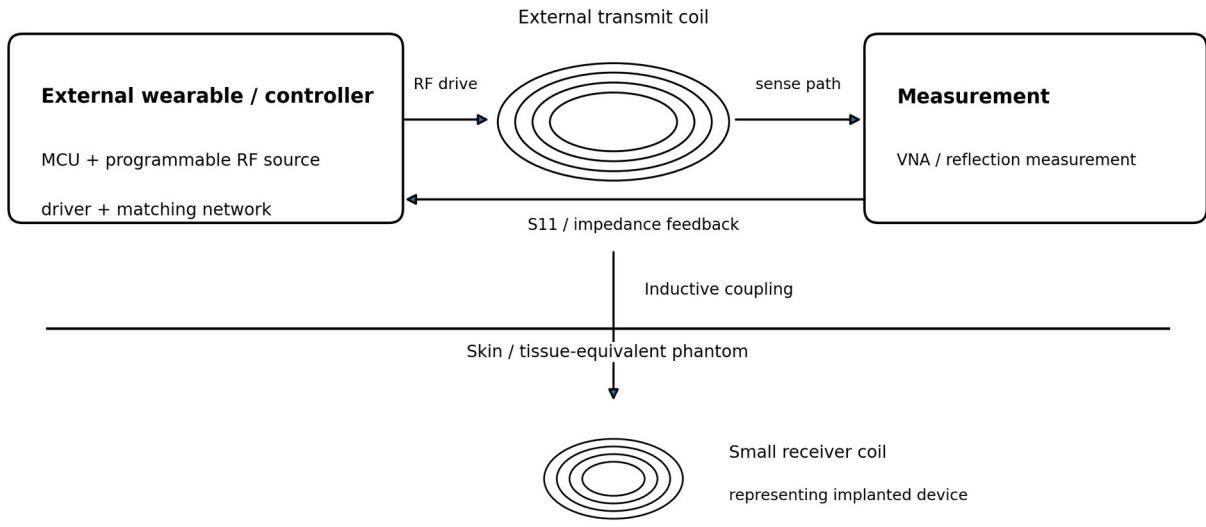


Figure 1. Intended use context for the bench prototype. The external controller drives a transmit coil positioned above a tissue-equivalent/non-biological test layer, while a smaller receiver coil represents the implanted device. The measurement path provides feedback used for automatic retuning.

1.4 High-Level Requirements

- The system shall identify the optimum operating frequency over a $\pm 7.5\%$ search window around the nominal 13.56 MHz resonance, and the selected frequency shall be within 50 kHz of the optimum frequency measured independently with the laboratory VNA.
- After a controlled change in coupling or resonance, the system shall complete detection, frequency search, and retuning within 2.0 seconds.
- For at least three controlled detuning conditions (coil separation, lateral/angle misalignment, or coil deformation), automatic tuning shall improve the measured return loss by at least 3 dB relative to operation at the untuned nominal frequency.

2. Design

2.1 Block Diagram

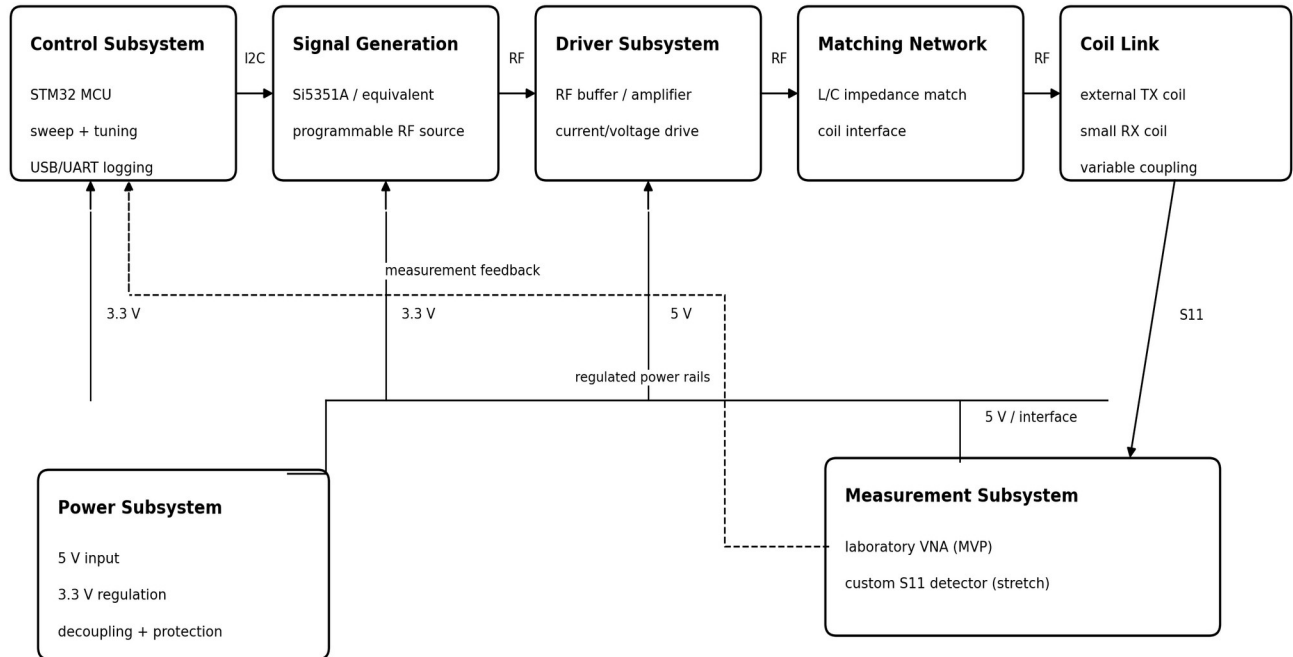


Figure 2. Proposed subsystem block diagram. Exact driver and matching values will be finalized after coil characterization. The laboratory VNA is the baseline measurement subsystem; a custom reflection measurement circuit is a stretch goal.

2.2 Subsystem Overview and Requirements

Control and Firmware Subsystem

The control subsystem is centered on an STM32 microcontroller. It commands the RF source, coordinates sweeps, receives measurement data, calculates the best operating frequency, and implements the retuning state machine. It also provides USB/UART logging for verification. This subsystem directly supports all three high-level requirements because it determines search accuracy, response time, and the decision to retune.

- The MCU shall command at least 200 distinct frequency points across the $\pm 7.5\%$ search window, corresponding to a frequency step of no more than approximately 10.2 kHz over the full 2.034 MHz span.
- The firmware shall support a two-stage search consisting of a coarse sweep followed by a local fine sweep with final frequency resolution of 10 kHz or better.
- The controller shall accept one measurement metric per commanded frequency point and associate that measurement with the correct frequency before advancing the sweep.
- The complete detection and retuning sequence shall finish within 2.0 s under the test conditions defined in the verification plan.
- The MCU shall provide serial logging of commanded frequency, measured feedback value, selected optimum, and retuning events for verification.

Signal Generation Subsystem

The signal-generation subsystem creates the programmable RF excitation used to drive the transmitter. The baseline design uses a Si5351A or equivalent synthesizer controlled by I2C because the NanoVNA reference design demonstrates MCU-controlled frequency synthesis with this class of device [6]. The output will be filtered/buffered as needed before the driver stage. This subsystem contributes primarily to the frequency-accuracy and retuning requirements.

- The source shall cover at least 12.54 MHz to 14.58 MHz, corresponding to $\pm 7.5\%$ around 13.56 MHz.
- The commanded output frequency shall be within ± 10 kHz of the programmed value across the test window, verified with an oscilloscope frequency counter or spectrum analyzer.
- The source shall accept frequency updates electronically from the STM32 without manual component changes.
- The source shall settle to the new commanded frequency within 5 ms before a measurement sample is accepted.

RF Driver and Matching Subsystem

The signal source alone is not intended to directly drive the resonant coil. A buffer or low-power RF driver will provide the required current, and an L/C matching network will transform the TX-coil impedance to a condition suitable for the driver and measurement interface. The initial matching network will be manually selected and fixed; electronically variable matching is a stretch goal. This subsystem determines whether the coil can be driven repeatably and whether changes in resonance produce a measurable reflection response.

- The driver shall operate from a nominal 5 V supply and shall not exceed 1 W of delivered RF power during ECE 445 bench testing.
- At the nominal tuned condition, the matching network shall achieve a measured return loss of at least 10 dB at or near 13.56 MHz with the baseline coil geometry.
- All components in the driver/matching path shall be rated for at least 2x the measured steady-state RMS voltage or current encountered during nominal operation.
- The matching network shall expose a 50-ohm measurement interface compatible with the laboratory VNA.

Inductive Coil Link Subsystem

The coil subsystem contains the external TX coil and a smaller RX coil representing an implanted receiver. The RX coil will be connected to a resonant capacitor and fixed load. The link will be tested on the bench with controllable spacing, alignment, and deformation. No human subject will be used. This subsystem creates the detuning conditions that the controller must detect and correct.

- The baseline coil pair shall exhibit a clear measurable resonance within the 12.54-14.58 MHz search window.
- The mechanical test fixture shall support at least three repeatable detuning configurations, including two distinct separations and at least one lateral/angle or deformation condition.
- Each test configuration shall be repeatable to within ± 1 mm in separation or lateral position when distance is the controlled variable.
- The RX coil and load shall remain electrically passive and isolated from the MCU/control electronics during the baseline demonstration.

Measurement and Feedback Subsystem

The measurement subsystem provides the feedback quantity used by the tuning algorithm. In the baseline implementation, a laboratory VNA will measure S11 or equivalent input impedance at the transmitter interface. S11 is appropriate because its magnitude indicates how much incident signal is reflected due to

mismatch. A custom embedded measurement circuit is a stretch goal; NanoVNA provides a useful reference for a low-cost synthesizer/mixer/ADC/DSP implementation [6].

- The baseline measurement system shall resolve the frequency of minimum measured reflection within 25 kHz when sweeping the prototype across the search range.
- At each frequency point, the measurement subsystem shall provide either complex S11, return loss, or another monotonic reflection metric to the controller or host interface.
- The measurement path shall not require physical reconnection between frequency points during an automated sweep.
- The reference VNA sweep used for validation shall contain frequency spacing of 10 kHz or less near the measured optimum.

Power Subsystem

The power subsystem supplies regulated rails for the MCU, synthesizer, and RF driver. Separating the low-noise digital/synthesizer rail from the higher-current driver supply reduces the risk that RF-drive transients disturb MCU operation. This subsystem supports reliable closed-loop operation and protects the prototype during repeated tests.

- The system shall accept a current-limited 5 V bench supply input during development.
- A 3.3 V regulator shall supply the MCU and synthesizer with 3.3 V +/- 0.1 V under maximum expected digital load.
- The 5 V rail shall support at least 1 A continuous current capability for the driver and auxiliary circuitry, even though RF output will be limited to 1 W or less.
- The design shall include local decoupling at each IC and a hardware-accessible power-disconnect method for emergency shutdown.

2.3 Firmware and Control Flow

The embedded firmware will use a state-machine structure rather than a single blocking sweep. The main states are IDLE, COARSE_SWEEP, FINE_SWEEP, LOCKED, and RETUNE. In COARSE_SWEEP, the MCU steps the source across the full search window and records the reflection metric. It then enters FINE_SWEEP around the best coarse point with smaller frequency increments. In LOCKED, the source remains at the selected frequency and the feedback metric is monitored periodically. If the metric degrades beyond a calibrated threshold, the system transitions to RETUNE and repeats the search. This structure keeps the embedded-software component substantial even when a laboratory VNA is used for measurement.

3. Tolerance Analysis

The principal technical risk is that the resonant frequency may shift outside the controller's search window when component tolerance or coupling changes. For a simple LC resonator, the resonant frequency is

$$f_0 = 1 / (2\pi\sqrt{LC})$$

Using a representative transmitter inductance of $L = 1.00 \mu\text{H}$ and choosing C so that $f_0 = 13.56 \text{ MHz}$ gives C approximately 137.8 pF. If the effective inductance increases by 10% because of geometry or coupling, while C remains fixed, the resonance becomes approximately 12.93 MHz, a -4.65% shift. If the effective inductance decreases by 10%, the resonance becomes approximately 14.29 MHz, a +5.41% shift.

For small perturbations, the approximate sensitivity is $\Delta f/f$ approximately $-0.5(\Delta L/L + \Delta C/C)$. Therefore, simultaneous +5% changes in effective L and C would shift resonance by roughly -5% to first order. The proposed +/-7.5% search window (12.54-14.58 MHz) provides margin beyond these representative shifts while remaining narrow enough for fast sweeping. With 200 coarse points, the full span can be searched with approximately 10.2 kHz spacing. At 5 ms per point, a full coarse sweep

requires about 1.0 s, leaving approximately 1.0 s for measurement overhead and the fine search while satisfying the 2.0 s high-level timing requirement.

This analysis demonstrates feasibility of the frequency-search approach. The final coil inductance, capacitance, and driver/matching values will be measured on the fabricated hardware and substituted into the same calculation before final verification. If measured detuning exceeds the assumed range, the firmware search limits can be widened because the synthesizer tuning range is substantially larger than the prototype window.

4. Verification Plan

Verification will be performed entirely on the bench. First, the coil pair will be placed in a reference geometry and characterized with the laboratory VNA over 12.54-14.58 MHz. The frequency of minimum S11 magnitude (or maximum return loss) will be recorded as the reference optimum. The automated controller will then perform its own search, and the selected frequency will be compared with the VNA reference. This process will be repeated for at least three controlled detuning configurations.

Retuning time will be measured from the instant a detuning configuration is applied or a retune command is issued until the controller enters LOCKED state at its new selected frequency. Return-loss improvement will be computed by comparing the measured return loss at the fixed nominal 13.56 MHz frequency against the return loss after automatic tuning. Serial logs from the MCU and stored VNA data will provide traceable evidence for all high-level requirements.

5. Ethics, Safety, and Societal Impact

This project is motivated by technologies used in implantable and wearable biomedical systems, but the ECE 445 prototype is a research and educational device rather than a medical device. No testing will be performed on human participants or implanted animals. The receiver coil will be evaluated using non-biological loads and, if useful, a tissue-equivalent phantom. This limitation avoids creating the impression that a classroom prototype has been clinically validated.

The IEEE Code of Ethics places public safety, health, and welfare at the center of engineering practice and also requires engineers to be honest and realistic about the capabilities and limitations of their work [7]. We will follow these principles by reporting measured performance rather than claiming medical efficacy, by clearly labeling the system as a prototype, and by documenting test conditions and uncertainty. We will also acknowledge and cite the NanoVNA open-source project rather than presenting its architecture as original work [6].

RF exposure and heating are the principal safety concerns. ICNIRP publishes human-exposure guidance for RF electromagnetic fields from 100 kHz to 300 GHz [5]. FCC guidance also states that wireless-power-transfer equipment above 9 kHz is subject to Part 15 and/or Part 18 authorization requirements and RF-exposure limits [8]. For this course prototype, RF output will be limited to 1 W or less, operation will occur on a bench with current-limited supplies, and the system will include a hardware power-disconnect mechanism. The device will not be worn or operated against a person during testing.

The nominal 13.56 MHz frequency is within an FCC-designated ISM band centered at 13.56 MHz with a ± 7 kHz band tolerance for unrestricted ISM operation [4]. Because the prototype tuning sweep intentionally extends outside this narrow band for laboratory characterization, the system will be treated as low-power test equipment and will not be operated as a consumer transmitter or intentionally radiating product. Final deployment of a medical or wireless-power product would require a separate regulatory and electromagnetic-compatibility assessment beyond the scope of ECE 445.

Societally, adaptive wireless power links may contribute to smaller and more reliable implantable systems by reducing dependence on wired connections or frequent battery replacement. However, medical technologies can create risks if prototype performance is overstated. The project therefore emphasizes quantitative verification, conservative power limits, transparent limitations, and bench-only validation.

6. Project Scope and Stretch Goals

The required project scope is the closed-loop tuning system, not the construction of a complete standalone VNA. The baseline final demonstration will use the laboratory VNA as the measurement reference if necessary. This separation reduces schedule risk: the MCU, RF source, driver, matching network, coil link, feedback algorithm, and automatic retuning can be completed and verified even if the custom measurement front end is not finished.

- Stretch Goal 1: Replace the laboratory VNA with a custom single-port reflection/impedance measurement circuit.
- Stretch Goal 2: Implement embedded complex S11 extraction, calibration, and digital signal processing based on concepts used by NanoVNA.
- Stretch Goal 3: Add electronically switchable matching capacitors or another tunable matching element so the controller can optimize both excitation frequency and impedance match.
- Stretch Goal 4: Add a PC visualization tool that plots sweep response, selected resonance, and retuning events in real time.

7. References

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