Poster: Going Beyond the Delegation Architecture of Low-power Wireless Communication

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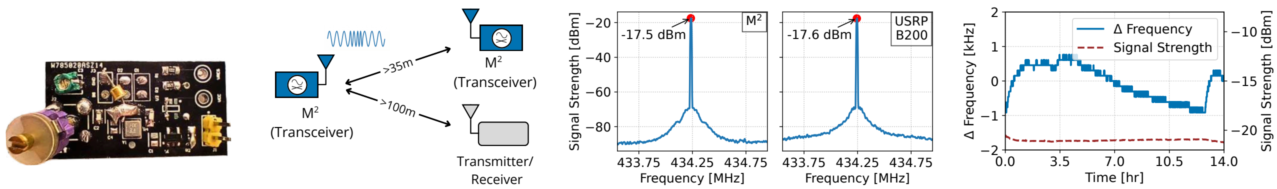

(a) M² Prototype (b) Overview of M² (c) Comparison with SDR (d) Long-term stability over 14 hours

Figure 1: (a), (b) M² generates stable microwave signals through an oscillator that breaks the power-stability tradeoff, enabling standalone transmitters and receivers. (c) The carrier signal generated by M² exhibits high spectral purity and is comparable to a commercial USRP SDR at the same output power. (d) M² achieves a 2.10 ppm **frequency stability at** 434.22 MHz **over** 14 hours**, with a maximum drift of only** 916 Hz **under** 105 µW.

Abstract

Generating a stable microwave carrier has traditionally required milliwatts of power, forcing low-power wireless communication to rely on a *delegation architecture* with a dedicated emitter device. This has resulted in a three-device topology that complicates real-world deployment. Returning to a true two-device topology under a microwatt power budget has therefore remained elusive. We introduce M², which breaks this power-stability tradeoff. The key contribution is a microwave oscillator that consumes only 105 µW of power while achieving 2.10 ppm frequency stability, enabled by coupling a tunnel diode with a high-Q SAW resonator. Beyond stable carrier generation, the tunnel diode's nonlinearity enables self-oscillating mixing for transmission and autodyning for reception, collapsing the transmitter and receiver into a single microwatt frontend. This stability is maintained over long durations and across variations in temperature, humidity, motion, and uncontrolled real-world environments, representing two orders of magnitude improvement over state-of-the-art tunnel diode oscillators. M² moves beyond the delegation architecture, enabling a new class of stable, standalone microwatt microwave (M^2) transceivers.

CCS Concepts

• **Hardware** → **Sensor devices and platforms**; **Wireless devices**; *Networking hardware*; • **Computer systems organization** → **Sensor networks**.

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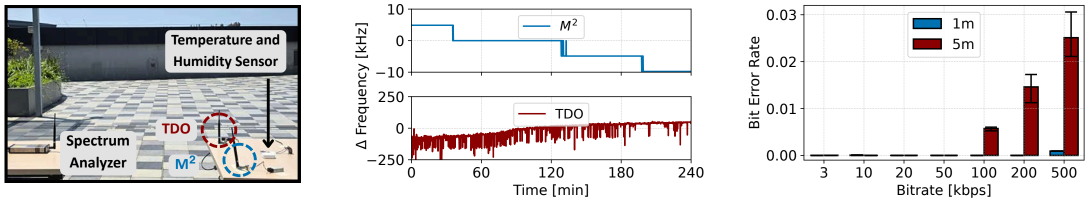
1 Introduction

Wireless communication is essential to embedded systems but it is also one of their most power-hungry operations [1, 2]. A major reason is carrier generation, which typically requires oscillators and signal-conditioning circuits consuming milliwatts of power. Over the past decade, the predominant strategy has been *delegation*, offloading carrier generation to an emitter device (ED) [1, 6, 7]. This gave rise to backscatter communication and Schottky diode-based receivers, enabling communication at very low device-side power.

Despite promising results in reducing power consumption, the delegation architecture suffers in real-world deployments. Its three-device topology (transmitter, receiver, and ED) complicates deployment and makes it impractical for many application scenarios. The holy grail is to return to a two-device architecture within a microwatt power budget, but this has been considered impossible because stable carrier generation is inherently power-consuming.

Conventional oscillators such as phase-locked loops provide stability but consume milliwatts [4, 7]. In contrast, tunnel diode oscillators (TDOs) operate at microwatt power but suffer significant frequency drift under bias and environmental changes. These couple a tunnel diode with an LC tank whose low quality-factor (Q) leads to poor stability. Prior efforts [3, 7] tackled stability through injection locking, but this falls back to a three-device topology. More recent works [4, 5] improved stability through shielding, bias



(a) Deployment on rooftop (b) Frequency drift on rooftop (c) BER with varying bitrate

Figure 2: (a), (b) M² exhibits only 15 kHz drift while the classical TDO drifts by hundreds of kHz in an outdoor deployment under uncontrolled temperature and humidity changes, confirming stability beyond controlled settings. (c) M² supports transmissions up to 500 kbps with near-zero BER at short range.

control, and noise reduction, but the fundamental low-Q limitation persists. This makes classical LC-tank TDOs too unstable for reliable wireless communication and practical transceiver design.

We introduce M², which breaks this power-stability tradeoff. By coupling a tunnel diode with a high-Q SAW resonator. M² generates a highly stable microwave carrier at microwatt power, as shown in Figures 1(c) and 1(d). M² also exhibits self-oscillating mixing (SoM) and autodyning, allowing the same device to serve as the basis for a complete transceiver (Figure 1(b)). Consuming only 105 µW, M² achieves few-ppm frequency stability and enables standalone transceivers without requiring an ED for generating a carrier signal.

2 Design

Unlike a classical LC-tank TDO [4, 5], M² employs a SAW resonator as the frequency-determining element. The SAW resonator confines energy in a mechanical standing wave on a piezoelectric substrate, with its resonant frequency set lithographically by electrode pitch rather than by discrete component values [8]. This yields a Q-factor exceeding 1000, which is an order of magnitude above any LC tank, directly suppressing frequency drift from temperature, bias voltage, and nearby motion. The tunnel diode serves solely as a negative-resistance element that sustains oscillation without influencing the frequency. The result is two orders of magnitude better stability than classical LC-tank based TDOs.

We implement M² on an FR-4 PCB, as shown in Figure 1(a). M² pairs a GE 1N3712 tunnel diode with a 433 MHz SAW resonator. The RF output is routed to an SMA connector for cabled characterization or an antenna for wireless communication. The total frontend power is below 105 µW, with the SAW resonator adding only 35 µW over the baseline 70 µW. A low-power MSP430 microcontroller consuming an additional 100 µW, generates a 2-FSK baseband signal for transmission which is mixed with the M² generated carrier.

The tunnel diode's nonlinearity enables transmission and reception without separate mixer stages. The SoM property [7] upconverts a baseband signal to sidebands at $f_c \pm f_{bb}$, while the SAW-anchored carrier (f_c) remains fixed. This decouples modulation from frequency stability and enables clean FDMA channel allocation. M² performs autodyning [3] by acting simultaneously as both the local oscillator and downconverter for ED-free reception. An incoming signal at $f_c \pm f_{IF}$ is downconverted to f_{IF} for demodulation.

3 Evaluation

Variability. We build three M² boards with 1N3712 and a fourth with a 3I306E tunnel diode, monitoring stability over 4 hours in a cabled setup. The frequency stability remains within 1.40–2.10 ppm for 1N3712 and 5.62 ppm for 3I306E, with an amplitude deviation of 0.069–0.708 dB. These results are consistent between different diode types and boards, with minor variations arising from parasitics and PCB fabrication, confirming that stability of M² holds and generalizes across tunnel diode variants.

Outdoors. We conduct experiments on a building rooftop under uncontrolled environmental changes in temperature and humidity to evaluate the stability of M². The frequency drift of M² stays below 15 kHz while a classical TDO drifts 250–310 kHz, as seen in Figures 2(a) and 2(b). Thus, this experiment confirms that the carrier generated by M² remains stable even in challenging outdoor environments and can support real-world deployments.

Bitrate. We instantiate a M² transmitter and conduct controlled experiments. It supports bitrates up to 500 kbps. Figure 2(c) shows that at 1 m, BER remains near zero up to 200 kbps and only 0.0009 at 500 kbps, indicating highly stable short-range links. Even at 5 m, BER stays under 0.017 at 200 kbps. This demonstrates that improved oscillator stability of M² directly translates to high reliability even at high bitrates, where classical LC-tank TDOs perform poorly [4].

Sensitivity. M² also enables reception through autodyning. We conduct experiments and find that M² reaches over 100 m indoor NLoS range with −75 dBm sensitivity, 5 dB better than prior work [3], and conversion loss of only 10.6–17.8 dB. This demonstrates the potential of M² for long-range and low-power reception.

4 Conclusion

We presented M², a stable microwatt oscillator that breaks the power-stability tradeoff by achieving 2.10 ppm stability at only 105 µW. M² exhibits self-oscillating mixing and autodyning, enabling a complete transceiver design for diverse applications.[1]

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[1] "Microwatt Microwave (M²) Oscillator: Going Beyond the Delegation Architecture of Low-power Wireless Communication" will be presented as a full paper in the main session of ACM MobiSys 2026.