Judo: Addressing the Energy Asymmetry of Wireless Embedded Systems through Tunnel Diode based Wireless Transmitters

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ABSTRACT

The radio transmitter is the most power-consuming component of a wireless embedded system. We present Judo, a radio transmitter that enables power balance between the wireless transmission, sensing, and processing tasks of a wireless embedded system. Judo transmitters leverage the fact that modern radio transceivers offer high receive sensitivity at low power. Therefore, even if a radio transmitter emits a weak signal, the link budget and transmission range will often remain high. With this key insight, we revisit the radio transmitter architecture by dramatically reducing the radiated power and hence the overall power draws. Specifically, Judo transmitters use a *tunnel diode oscillator* to integrate the stages of a radio transmitter into a single energy-efficient step. In this step, baseband signals are generated and mixed with peak power draws below 100 µW. However, tunnel diode oscillators sacrifice stability for low-power, which we sidestep by using injection-locking to stabilize the tunnel diode oscillator with an external carrier signal. Based on this novel architecture, we implement a transmitter that supports frequency-shift keying as a modulation scheme. Judo transmits to a receiver over distances exceeding 100 m at a bit rate of 100 kbps. Crucially, it does so with an emitter device providing the carrier signal, also located more than 100 m from the Judo transmitter. In terms of critical link metrics, Judo outperforms the radio transmitters commonly used in wireless embedded systems.

CCS CONCEPTS

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

KEYWORDS

Backscatter communication, Wireless transmitters, Wireless embedded systems, Internet of Things, Tunnel diodes

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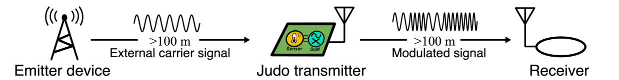


Figure 1: Judo can transmit at a bitrate greater than 100 kbps, peak power consumption of tunnel diode oscillator front-end under 100 µW, and a transmission range greater than 100 m (emitter device to Judo transmitter, and Judo transmitter to the receiver). In contrast to backscatter systems, Judo transmitters do not reflect carrier signals. Instead, the carrier signal stabilizes the noisy tunnel diode oscillator via the injection-locking phenomenon. Due to the tunnel diode oscillator's ability to injection-lock a weak signal, the emitter device may be located at a considerable distance from the Judo transmitter.

1 INTRODUCTION

Today, the components of a wireless embedded system (WES) consume vastly different amounts of power. Radio transmitters consume a few to tens of milliwatts [14, 42], the processing unit draws hundreds of microwatts [7], and the sensors require tens to hundreds of microwatts [8, 9]. Thus, the power asymmetry can be attributed to the radio transmitter [32, 39]. Consequently, in a WES powered by small batteries, radio transmitters dominate battery life. This forces frequent battery replacement, which is not feasible at a large scale. When a WES operates on ambient energy, possibly without batteries, it leads to short active time, and long delays between wake-up periods, limiting potential applications. Thus, the high-power draw of radio transmitters hinder the realization of a broader vision of ubiquitous WES.

A transmitter consists of digital and analog blocks. The digital block generates a low-frequency signal containing information, known as the baseband signal. The analog block generates a high-frequency carrier signal that is radiated from the antenna. The carrier signal is modulated by the baseband signal. Digital circuits consume just tens of microwatts due to their miniaturization following Moore's law. Analog components, however, do not benefit in the same way from scaling, remain energy-intensive, and result in power-consuming radio transmitter designs [21, 32, 51].

Backscatter enables a vision of ubiquitous WES by tackling the power asymmetry [39, 45]. It removes analog components from the radio transmitter, and the tasks are delegated to an external emitter device. As backscatter transmitters handle only the energy-efficient digital baseband and the antenna switching operations, they use little power (tens of microwatts) [26, 32, 41, 51, 56, 59]. This aligns the power consumption of the wireless transmissions with sensing and processing operations of WES.

Despite the promise of backscatter transmitters, there has not been large-scale adoption. There are several factors to be considered, including a lack of easily accessible radio frequency (RF) front-ends, challenges with the downlink reception [17, 22, 26, 47], and lack of system support to enable large-scale deployments [29]. However,

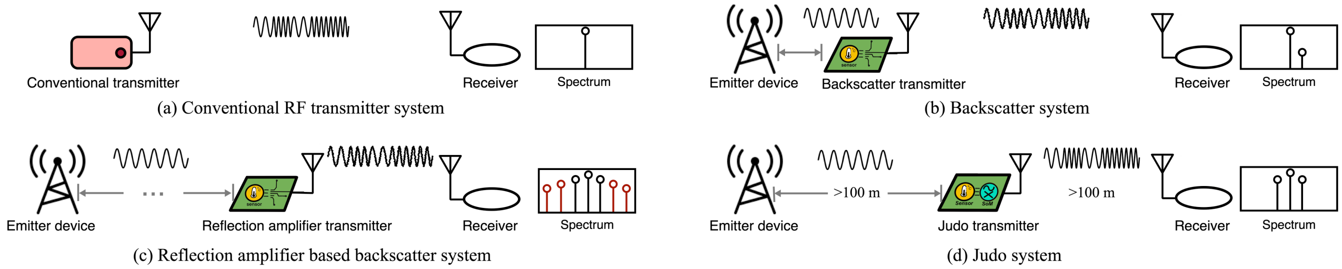


Figure 2: *Comparing Judo transmitter against transmitters commonly employed on WES.* Judo allows low-power transmissions while being spectral efficient. Unlike backscatter systems, Judo allows the emitter device and receiver to be placed at considerable distances from the Judo transmitter even at high bitrate (100 kbps). In contrast to reflection amplifiers based backscatter transmitters, it does not generate unwanted harmonics (harmonics are shown in red on the spectrum plot).

critical challenges include the limited transmission range and spectral efficiency of backscatter transmitters. Poor spectral efficiency prevents the formation of large networks. Furthermore, backscatter transmitters are strongly dependent on an external infrastructure. These constraints are due to the fundamental mechanism employed to mix the baseband signal with the external carrier signal. Despite decades of efforts [28, 39], this mechanism has remained unchanged. Judo rethinks it, and in this way, enables us to overcome the following limitations of backscatter transmitters.

Challenges. Backscatter transmitters require the proximity of the transmitters to an emitter device. First, the emitter device generates a RF carrier signal. Next, the transmitter's antenna is toggled using an RF switch in accordance with a *digital baseband signal*. This causes the reflected signal to be modulated with the baseband signal, but, this signal is significantly attenuated [3, 4, 58]. Consequently, to compensate for the losses, emitter devices radiate a strong signal [32, 51, 56]. Despite this, only when the backscatter transmitters are located in close proximity to an emitter device (a few meters), the transmission range will be practical (tens to hundreds of meters) [21, 30, 32, 66], particularly when backscatter transmitters operate at high bitrate. However, requiring a transmitter to be located very close to an emitter device is not practical in most deployments.

Poor spectral efficiency is also a problem that results from using digital baseband signals. It gives rise to unwanted harmonics, which are then widely spread across the spectrum [3, 51, 58]. In addition to causing interference, these harmonics also prevent transmitters from coexisting with other devices and forming a network.

Judo design. Judo rethinks the mechanism at the heart of the backscatter transmitters. Judo uses a tunnel diode oscillator (TDO) instead of an RF switch. TDO makes Judo transmitters fundamentally different from backscatter transmitters in that it does not reflect the carrier signal, but uses the carrier signal to injection lock a TDO. Moreover, a TDO allows us to mix a locally generated carrier signal with an analog baseband signal. This combination allows us to realize transmitter designs that overcome the challenges of backscatter transmitters previously described.

To contextualize the design of the Judo, we examine the architecture of transmitters employed in WES in Figure 3. Conventional transmitters perform a series of energy-expensive steps [15]. The carrier signal is generated by an RF oscillator. Next, with the use of an RF mixer, the carrier is modulated with the baseband signal (information). Finally, the resulting signal is amplified and radiated. Judo uses similar architecture, however, it integrates several of these stages into one energy-efficient step that use a TDO. Despite having borrowed its design from an energy-expensive conventional transmitter, Judo transmitters offers similar a power budget to a backscatter transmitter, but without inheriting its limitations.

Judo builds on recent work [55, 58], and implements a TDO that allows the generation of a high-frequency carrier signal (868 MHz) at tens of microwatts of power consumption. However, in doing so, Judo makes trade-offs: the TDO radiates a weak signal, which is orders of magnitude weaker than commonly employed transmitters. Furthermore, the TDO has poor stability, which means that its carrier signal frequency drifts due to changes in the ambient environment (temperature, humidity) and nearby motion [55].

Judo employs a number of design choices to counter these trade-offs. *First*, It employs a highly sensitive receiver. Together with improved propagation characteristics of the sub-GHz band, this allows Judo transmitters to support a high link budget and long transmission range. *Second*, to counter the instability of the TDO, Judo transmitters leverages the injection-locking phenomenon [16]. An emitter device generates an external carrier signal, then the TDO latches onto it, synchronizes itself, and thus helps to overcome the TDO's instability. As the TDO can latch onto a weak carrier signal (approximately −70 dBm for the tunnel diode employed in this work), it allows the emitter device to be located a significant distance away from the Judo transmitter, and still support a long transmission range (Judo transmitter to receiver). Judo supports this capability even in challenging radio environments.

Next, the carrier signal is modulated with the baseband signal. This is accomplished using an RF mixer. However, mixers are power-hungry due to the use of active analog components. Consequently, backscatter transmitters use the switching action of an antenna to mix the digital baseband signal with an external carrier signal. Nevertheless, they generate unwanted harmonics, and therefore require complex circuitry to eliminate them [30, 66]. We eschew conventional RF mixers, and instead use the nonlinearity of the tunnel diode to accomplish the task. This allows the analog baseband signal to be mixed with a locally generated carrier signal from the TDO. Hence, the TDO can be used as both a local oscillator (LO) and as an RF mixer, thus acting as a self-oscillating mixer (SoM). As we show in Figure 2, Judo prevents generation of unwanted harmonics that are common with backscatter transmitters.

On the basis of Judo, we design a transmitter with frequency-shift keying (FSK) as the modulation scheme. It supports high bit rates, and we have evaluated it as high as 100 kbps, and transmission range exceeding 100 m. Furthermore, it achieves these results while supporting a transmitter and emitter device distance that exceeds 100 m. The TDO front-end draws less than 100 µW of peak power. The results of the experiments and analysis presented in this study suggest that Judo offers distinct advantages over off-the-shelf radio transmitters and state-of-the-art backscatter transmitters.

Summary of results. We conduct extensive experiments, and offer the following key findings from our work:

- Signal strength of transmitted signal is improved by 100 - 10,000 times than that of conventional methods of backscattering external carrier signals. The weaker the external carrier signal, the higher the gain achieved by the Judo transmitter.
- Judo employs a novel mechanisms of mixing a baseband signal. When compared with tunnel diode reflection amplifier based backscatter tags [3, 4, 58], it allows significant reduction in spread of unwanted harmonics, as well as the use of an external carrier signal that is at least one order of magnitude weaker.

Summary of contributions. Following are our three contributions with the design of Judo: (1) We present and evaluate the self-oscillating mixer behaviour of the TDO. (2) Building on this behaviour, Judo presents a new architecture for low-power transmitters, that provides significant advantages over backscatter transmitters, especially in supporting long distances between the emitter device and transmitter. (3) We address the challenge of spread of unwanted harmonics in tunnel diode-based reflection amplifiers through a novel and power-efficient baseband mixing mechanism.

2 RELATED WORK

We provide background, and discuss works closely related to Judo.

Radio duty cycling (RDC). Most WES applications do not transmit often [60]. Taking advantage of this pattern, RDC mechanisms keep the transmitters inactive most of the time [18, 54]. However, the transmitters peak power consumption remains high. Therefore, when operating on batteries, it is difficult to send large amounts of information [44]. Judo transmitter consume orders of magnitude lower peak power, and complement existing RDC mechanism.

Communication on WESs. Near field communication (NFC) and Radio frequency identification (RFID) use radio signals to power the embedded device, as well as to communicate. Therefore, they allow battery-free devices, such as RFID tags and security cards. NFCs have a short range of a few centimeters [68]. RFIDs have a range of a few meters, but they require complex, expensive readers [56]. On battery-powered devices, we commonly employ power consuming LoRa, ZigBee, and Bluetooth transceivers. They have a power consumption in the range of milliwatts [32, 51]. LoRa trades-off bitrate for a longer range and can operate up to distances of few kilometers. On the other hand, ZigBee and BLE transceivers transmit at higher bitrates, but only to ranges of tens of meters. By comparison, Judo addresses a gap that is left unaddressed by these technologies (Refer Section 6). Judo supports a range that is comparable to ZigBee and Bluetooth at a significantly lower power consumption.

Visible light backscatter. Several systems leverage light's ubiquitous nature, and transmit through the reflection and absorption of ambient light [27, 38, 62, 63]. However, they are limited to low bitrates and a short range which requires a receiver to be located in line of sight to the transmitter. Judo overcomes these limitations and achieves a better transmission range and energy per bit metric.

Reflection amplifier. Reflection amplifiers are employed in several backscatter systems. A reflection amplifier replaces the standard RF switch in the tag, allowing the carrier signal to be backscattered with a gain. As a result, losses that are typically associated with backscatter mixing processes can be reduced. Negative-resistance elements such as transistors or tunnel diodes are used in reflection amplifiers. Amato et al. created a tunnel diode-based reflection amplifier that operates in the 5.8 GHz band with a gain of 34 dB while consuming 45 μW [3–6]. Adeyeye et al. designed a repeater using tunnel diode reflection amplifier with a gain as high as 50 dB and consuming 40 μWs in the 5.8 GHz frequency band [2]. Varshney et al. [58] designed a tunnel diode-based reflection amplifier operating in the 868 MHz band with a reflection gain of 35 dB and and a peak biasing power of 57 μW. Kimionis designed a transistor-based reflector in the 900 MHz frequency band with a reflection gain of 10.2 dB and a peak power consumption of 325 μW [33].

Reflection amplifiers use and enhance the backscatter mechanism. Using the antenna's switching action, the digital baseband signal is mixed with an external carrier signal. However, the reflection gain amplifies unwanted harmonics as well. With tunnel diode reflection amplifiers, these harmonics cover a significant part of the unlicensed spectrum [3, 55, 58]. As a result, it would be difficult to deploy these systems or allow them to coexist with other wireless devices. Judo employs a different mechanism and thus does not generate unwanted harmonics. Furthermore, our experiments demonstrate that we can utilize an external carrier signal that is at least ten times weaker than reflection amplifier-based transmitters.

Self-oscillating mixer (SoM). The discovery of a single circuit able to perform both signal generation and mixing dates back to 1915. Armstrong demonstrated several functions, such as local oscillation and frequency conversion, in a single circuit for audion reception [10]. Efforts have been made to integrate SoM with an antenna to enable compact designs [61, 64]. When a single device generates and mixes carrier signals, cost, complexity, and power consumption are reduced. Judo is the first to demonstrate the feasibility of low-power transmission using tunnel diode SoMs.

Eliminating harmonics on backscatter transmitters. A backscatter transmitter modulate information by changing the antenna state with a digital baseband signal. This leads to the harmonic problem and leaves out-of-band interference. As a result, there has been efforts to design mechanisms to mitigate this challenge. Several systems vary the antenna state in discrete or near-continuous states to approximate a mixing operation with analog baseband signal [30, 34, 51, 65]. Nevertheless, this mechanism adds extra complexity to the backscatter transmitter. Moreover, these designs require a strong carrier signal since they do not reflect or absorb carrier signals with a gain. Judo transmitters overcome these limitation by allowing the mixing of the carrier signal with an analog baseband signal without requiring complex circuitry. Furthermore, Judo transmitters can operate with very weak carrier signals and perform a significant gain.

Injection locking. Oscillators have an inherent property of injection locking. This phenomenon allows oscillator circuits to couple and synchronize with each other. It has been employed to improve the power efficiency of several critical modules including frequency divider [40], phase-locked loop [36], clock and data recovery [35] and oscillator [15]. In addition, the injection locking technique has also been shown effective in synchronizing wireless devices that use heterogeneous oscillators [16, 43]. Similarly, by injecting the low-precision TDO with a high-precision external carrier signal, we improve transmission reliability in Judo transmitter.

Commercial mixers. RF mixers can be purchased commercially off-the-shelf. Combining these RF mixers with an external high-frequency oscillator allows us to perform the task at the core of the Judo transmitter. Their mixing performance is superior to TDOs, as they employ high-precision components and designs. Nevertheless, these oscillators and RF mixers are power-hungry and expensive. Their power consumption can easily reach several milliwatts. Additionally, they usually require a strong carrier signal to operate. We can reduce cost, power consumption, and complexity by trading off power consumption and performance and utilizing the SoM behaviour of the TDO. We can overcome the trade-offs in TDO performance by injecting an external carrier signal.

3 SYSTEM DESIGN

Judo includes one or more transmitters, an emitter device, and a receiver. This system operates as follows: First, we generate a carrier signal through an emitter device. Next, the Judo transmitter uses an external signal to stabilize its internal TDO. Then, the locally generated carrier signal from the TDO is mixed with an analog baseband signal. The resulting signal is radiated out and received.

Emitter device. Due to superior signal propagation characteristics, Judo operates in the sub GHz frequency band. In order to generate the carrier signal, we build on LoRea [56] and re-purpose a commodity transceiver (TI CC1310). To conduct controlled experiments, we use a software defined radio (SDR) (USRP B210 [24]).

Receiver. We employ a transceiver (TI CC1310). It supports a narrow bandwidth, thus enabling high receive sensitivity. Furthermore, it allows for easy configuration of the reception parameters. We use a low-cost launchpad with an onboard amplifier.

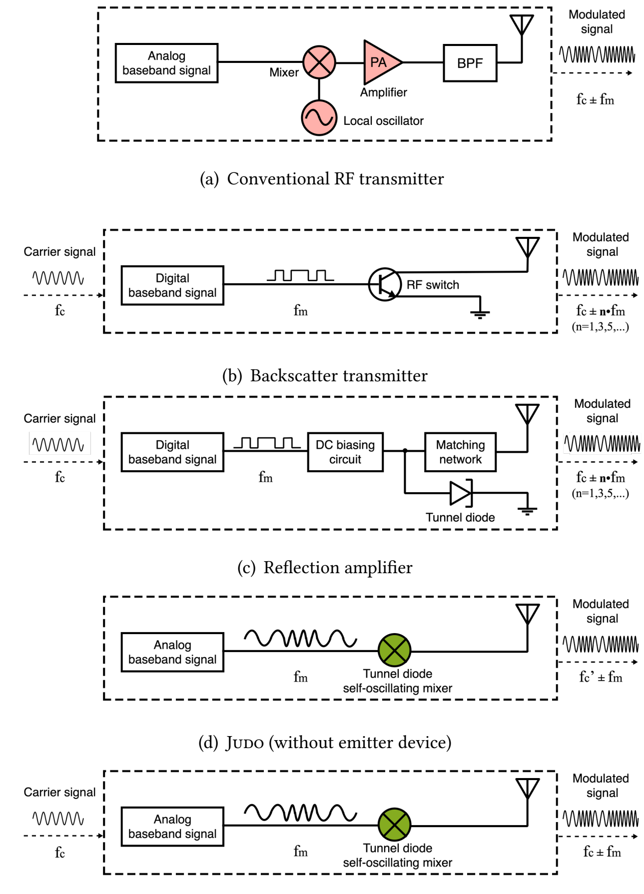
Judo transmitter. This is the main contribution of the work, and we describe its design in detail next.

4 JUDO TRANSMITTER

We describe the design of the Judo transmitter, and put it in context to transmitter architectures that are commonly used in WES.

Overview of transmitters. In Figure 3, we show the transmitter architectures that are commonly employed in WES. Let us first consider a conventional transmitter; The RF oscillator produces a high-frequency carrier signal. The carrier signal is then modulated with a baseband signal using an RF mixer. Finally, the resulting signal is amplified and radiated out via an antenna. Unfortunately, all of these steps are power consuming [15]. Conventional transmitters consume tens of milliwatts of peak power consumption.

A backscatter transmitter avoids the energy-intensive steps of a conventional transmitter. Instead, the tasks are delegated to emitter devices and receivers. An externally powered emitter device generates the carrier signal. Afterwards, the backscatter transmitter performs digital baseband operations and accordingly toggles the antenna between reflection and absorption states. Consequently, the carrier signal is reflected and modulated with the baseband signal. Backscatter transmitters consume little power which is in the order of tens to hundreds of microwatts [30, 32, 56, 66]. However, the use of digital baseband signals leads to generation of unwanted



(a) Conventional RF transmitter

(b) Backscatter transmitter

(c) Reflection amplifier

(d) Judo (without emitter device)

(e) Judo (injection-locked)

Figure 3: ***Comparison of transmitter architectures used in WES*** **(a) shows a conventional transmitter that consists of energy-expensive local oscillator, mixer, and amplifier components (shown in red). (b) and (c) show transmitters designed using a RF switch and tunnel diodes for backscatter communication. Backscatter transmitters reflect an external carrier signal and produce odd harmonics on the spectrum. They mix digital baseband signals using the switching property. Finally, (d) and (e) present the two different modes of Judo transmitter. They mix an analog baseband signal using the non-linearity of tunnel diode. An external carrier signal lends stability to the TDO.**

harmonics. Eliminating these harmonics requires the introduction of complex harmonics elimination mechanisms [30, 51, 66]. In addition, the losses inherent in the backscatter mechanism cause backscatter transmitters to achieve a practical transmission range and bitrate only when the backscatter transmitter is co-located with an emitter device generating a strong carrier signal.

Reflection amplifiers equipped transmitters overcome the constraint of requiring a backscatter transmitter to be co-located with the emitter device to achieve practical range and bitrate [3, 6, 58]. The reflection amplifier is designed using transistors [33] or tunnel diodes [3, 5, 6, 55, 58], and it replaces the standard RF switch. Therefore, they can reflect external carrier signals with gain as high as 34 dB [3]. Hence, the backscatter transmitter and the emitter device can be placed at great distances apart from each other. To perform the mixing, they still use a digital baseband signal and the switching action of the antenna. However, in combination with high gains, this causes severe harmonics spread on the spectrum.

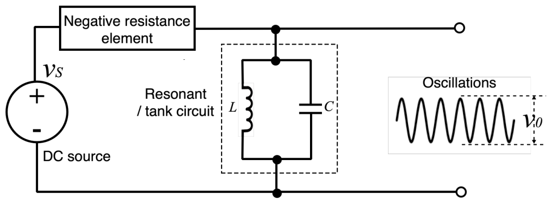


Figure 4: ***Oscillator designed using a negative resistance element.*** **When a negative resistance element is coupled with a resonant circuit, sustained oscillations result. The frequency of the oscillations is governed by the characteristics of the resonant circuit and the negative resistance element.**

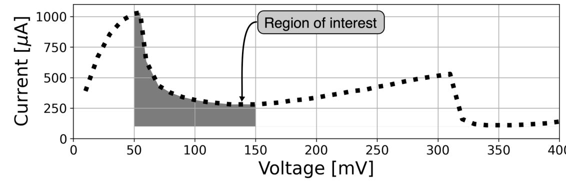


Figure 5: ***Characteristics of a tunnel diode GE 1N 3712 (IV).*** **Tunnel diodes show region of negative resistance, which occurs at low bias voltages and currents. The shaded area of the IV curve represents the region that leads to oscillations in the tunnel diode oscillator.**

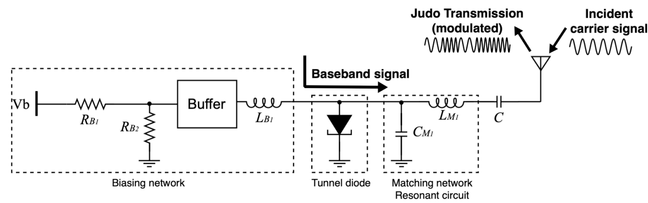


Figure 6: ***Judo transmitter schematic.*** **The TDO is a critical component of the transmitter. Locally, the TDO generates a high frequency carrier signal within the 868 MHz frequency band. An external carrier signal provides stability to the TDO. Finally, the self-oscillating mixer property enables mixing of the analog baseband signal with the locally generated carrier signal under 100 µWs.**

Judo overview. Judo borrows design elements from all three transmitter architectures described earlier. Building on backscatter transmitters, a tunnel diode is used in place of an RF switch. In terms of power consumption is similar to the backscatter transmitters; it also requires an emitter device to provide an external carrier signal. However, Judo transmitter's architecture is closest to a conventional transmitter. Like a conventional transmitter, Judo locally generates a carrier signal and modulates it with an analog baseband signal. However, it performs these tasks with only tens of microwatts of power consumption.

Judo transmitter uses a TDO to combine stages of a conventional transmitter into a single energy-inexpensive step, with the TDO acting as a SoM. The TDO generates a weak carrier signal at the 868 MHz frequency band. Using the non-linearity of the tunnel diode, the analog baseband signal modulates the locally generated carrier signal. Thus, no dedicated RF mixers are required. However, there is a trade-off made in terms of the stability versus low-power consumption of TDO [55, 58]. To counteract TDO's instability, Judo transmitters use the injection locking phenomenon. Here, an external carrier signal lends stability to the TDO. Furthermore, as the TDO is capable of injection locking very weak signals, it allows the emitter device to be kept at a significant distance away from the Judo transmitter. Finally, the ability of TDO to mix the analog baseband signal prevents the generation of unwanted harmonics.

4.1 Carrier Signal Generation

Radio transmitters generate a carrier signal at a high frequency, which must be stable and precise. Thus, the radio transmitter employs energy-intensive precision oscillators. They also amplify the carrier signal. Because of these steps, the carrier signal generation operation is the most energy-intensive for the transmitter.

Judo build on the key idea that receiver sensitivity is improving. Receivers for long-range wireless standards [51, 52] achieve sensitivity levels that are far below standards such as Bluetooth and WiFi. Highly sensitive receivers allow a high link budget and thus a high transmission range even when a transmitter is radiating a weak signal. This insight enables us to rethink the transmitter architecture. As a result, the Judo transmitter architecture focuses on emitting weak signals. More importantly, Judo transmitters exclude the architecture's power-consuming amplification stage.

Low-power carrier signal generation. We use an RF oscillator with a circuit configuration similar to that in Figure 4. It consists of a negative resistance element coupled to a resonant circuit. When this circuit is biased with a DC voltage, it oscillates, and some of the energy from the DC source is converted into AC signals. The frequency of oscillations depends on the resonant circuit and the characteristics of the negative resistance element. In addition, the negative resistance element dictates the power consumption. Thus, we can generate carrier signals at a low-power consumption by reducing the power consumed by the negative resistance element. The tunnel diode [48] is a great candidate for such element. It exhibits region of negative resistance (RNR) at tens of microwatts of power consumption.

Tunnel diodes. Tunnel diodes were discovered more than half a century ago [23], and they were the first semiconductor devices to demonstrate quantum tunnelling. Tunnel diodes have several remarkable properties, but perhaps the most notable one is their ability to exhibit RNR [48]. *What does this mean?* Consider biasing a tunnel diode with a DC voltage and varying the bias voltage (V). This relationship between the current (I) passing through a tunnel diode and the bias voltage (V) is nonlinear. It shows negative differential resistance in certain parts of the (IV) curve. In Figure 5, we display the RNR for the tunnel diode (GE 1N3712 [1]) used in this work. It only consumes tens of microwatts of power to bias the tunnel diode to the RNR. The non-linearity of the IV curve, specifically the RNR, allows for novel applications. The tunnel diode can be used in the design of logic elements, switching circuits, and RF components, such as oscillators and amplifiers [48], and in enhancing backscatter transmitters [6, 55, 58].

Tunnel diode oscillator. We design an oscillator using a GE 1N3712 [1] tunnel diode. We show this particular tunnel diode's IV characteristics in Figure 5. It exhibits negative resistance characteristics under 100 µW of power consumption. The oscillator design consists of the tunnel diode connected to a matching network and a DC biasing circuit. In conjunction with the intrinsic properties of a tunnel diode, the matching network determines the oscillating frequency. We show the schematic of the Judo transmitter in Figure 6. The biasing circuit keeps the tunnel diode in the RNR. We connect the TDO to a spectrum analyzer and capture the signal transmitted by the TDO. Figure 7 shows the spectrum of the TDO; the carrier signal is generated in the 868 MHz band and has an average radiated signal strength of −19 dBm (12.5 µW).

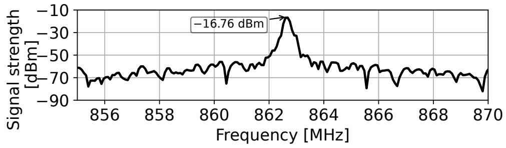


Figure 7: *Tunnel diode oscillator spectrum.* The tunnel diode oscillator generates a carrier signal in the 868 MHz frequency band. The strength of the carrier signal (on average) is −19 dBm. In this plot, since no injecting carrier signal is present, TDO is noisy and the carrier signal has a broad peak.

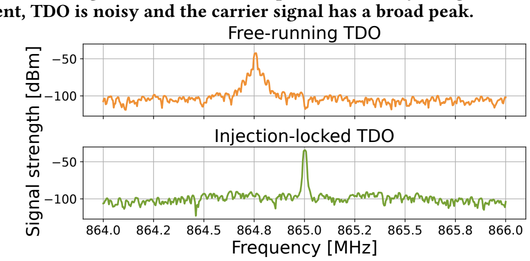


Figure 8: *Injection locking a tunnel diode oscillator.* A free-running TDO produces a noisy signal with a broad peak of the carrier signal. The stability is improved by injection locking the TDO to an external carrier signal. Therefore, we observe a sharper peak of the carrier signal generated by the TDO.

4.2 Stability Challenges with the TDO

TDO trades-offs stability for low-power consumption. As a result, the TDO has higher phase noise [58], and the frequency of the TDO drifts over time [55]. In addition, changes in the environment, such as fluctuations in temperature or humidity [55], or nearby motion, can also impact the TDO's stability and frequency.

It is undesirable to design transmitters with a noisy TDO. Therefore, it is necessary to mitigate noisy behaviour without increasing power consumption. The approach we take is to use the injection-locking phenomenon demonstrated by the TDO, which occurs when two oscillators are coupled and made to oscillate simultaneously. They can be synchronised by injection locking if their resonant frequencies are close together. This is a well-known phenomenon that provides stability for noisy oscillators. In Judo system, the TDO injection locks onto an external and stable carrier signal.

With the help of an experiment, we show the injection locking of the TDO. We use an SDR (USRP B210) as an emitter device, keeping it approximately 5 m from the TDO-equipped transmitter. We then generate a 3 dBm carrier signal with a frequency close to the resonant frequency of the TDO. A spectrum analyzer observes the signal, and it is located about 1 m from the TDO. Figure 8 shows the results. Because of the noisy nature of the free-running TDO, the carrier signal shows a broad peak. Furthermore, when the carrier signal generated by the external emitter device injects into the TDO, the peak of the carrier signal becomes sharper because the external signal contributes to the stability of the TDO.

Injection-locked TDOs are resilient to environmental dynamics and changes. Our experiments investigate this aspect. We use a similar setup as in the previous experiment.

Frequency drift with time. The TDO's frequency drifts by tens of kHz over time [58]. This study investigates whether injection locking can mitigate these frequency drifts. We set up a TDO in a free-running mode without injecting a external carrier signal. We collect the spectrum log for approximately 1 h. The experiment is then repeated with the TDO injection locked to an external carrier signal. Figure 9(a) shows the results of the experiment. Similar to earlier work, the resonant frequency of a free-running TDO drifts over time. However, injection-locking enables us to maintain the TDO at a stable frequency throughout the experiment.

Frequency drift with nearby motion. TDOs are sensitive to motion in their vicinity. We investigate whether injection locking helps in this situation. We keep the TDO in a room and let a person walk around the room. In the first experiment, we leave the transmitter in free-running mode. In the second experiment, we injection lock the TDO using an externally generated carrier signal. Figure 9(b) shows the results of this experiment. A large deviation (about 200 kHz) is observed from the base frequency of the TDO. In contrast, we do not detect deviations when the TDO is injection-locked to an external carrier signal.

Frequency drift with temperature. Changes in ambient conditions, such as temperature and humidity, can affect the TDO frequency [55]. Therefore, we first investigate whether injection locking enhances the stability of the TDO under temperature variations. An infrared lamp is placed at a distance of approximately 10 cm from the TDO, a non-contact thermometer measures the temperature of the tunnel diode at the beginning and end of the session. Similar to previous experiments, the test is conducted in both TDO free-running and injection-locked modes. Figure 9(c) shows that temperature causes significant variations in the frequency of a free-running TDO. In contrast, we do not observe these deviations when the TDO is in injection-locked mode.

Frequency drift with humidity. Next, we conduct experiments to investigate the stability of the TDO under different humidity conditions. The TDO and humidifier are kept together inside a box, and the humidity is monitored using a wireless sensor. Figure 9(d) shows the results of the experiment. When the TDO is in free-running mode, the frequency drifts downward (about 200 kHz) as environmental humidity rises. However, the frequency maintains the same level when the TDO is injection-locked with an external carrier signal. This shows that injection-locked TDOs are resilient to changes in environmental conditions.

Frequency drift with interference. TDOs are also affected by the presence of interfering wireless signals. We have seen that in the presence of external signals in the same band or a nearby band, the TDO frequency may drift towards external signals. At a high level, the TDO attempts to latch onto external interference. Nevertheless, when the TDO is injection-locked to an external carrier signal, it is much less susceptible to these external interference. In addition, since the Judo transmitter does not produce unwanted harmonics during the mixing procedure, the adjacent frequency bands to the channel with the carrier signal and mixed signals are still available for transmission to other wireless devices.

Injection locking and carrier signal strength. The strength of the incident signal is one key factor in determining the oscillator injection locking state. The minimum signal strength depends on the frequency difference between the oscillator resonant frequency and the external carrier signal. This minimum signal strength is proportional to the minimum injection current I_{inj}, which is determined by the following equation [16, 46]:

$$I_{inj} \approx 2QI_{osc}\frac{|\omega_0 - \omega_c|}{\omega_0} \quad (1)$$

where ω_0 is TDO resonant frequency, and Q is the circuit Q factor, ω_c is the carrier frequency, and I_{osc} is the oscillator output current.

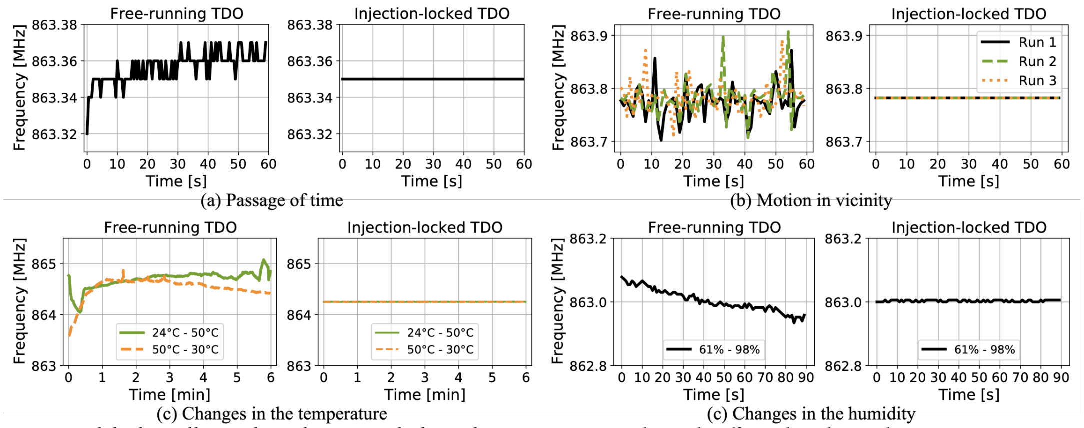


Figure 9: *Stabilizing tunnel diode oscillators through injection locking phenomenon.* Due to the trade-offs made to lower the power consumption of the TDO, it is unstable and prone to environmental changes (humidity, temperature). By injecting an external carrier signal into the TDO, the stability of the TDO is enhanced.

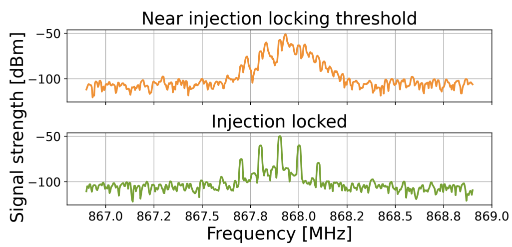


Figure 10: *Injection-locking stability.* The instability of the TDO (distorted signal) is observed at the threshold of the injection locking state.

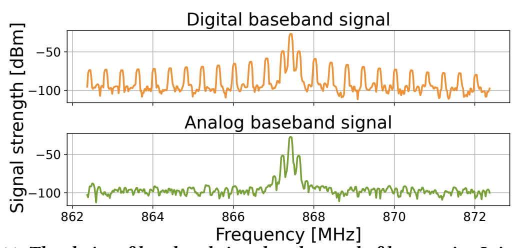


Figure 11: *The choice of baseband signal and spread of harmonics.* It is possible to eliminate unwanted harmonics generated during the mixing process using an analog baseband signal instead of a digital baseband signal.

In the case when the incident signal frequency is closer to the resonant frequency of the TDO, the TDO requires a weaker signal to achieve its locking state. Experimentally, we observe that for a carrier frequency in close proximity to the TDO resonant frequency, the weakest but still sufficient carrier signal strength is about −70 dBm. The TDO is pulled from its resonant frequency when the input carrier signal strength is just below the injection lock level, which can be seen in Figure 10. As a result, the TDO is pushed to one edge of the lock range and reaches a quasi-lock state.

4.3 Tunnel Diode Oscillator as a Mixer

To transmit information, the carrier signal needs to be modulated with a baseband signal. This is done using an RF mixer. They are usually three-port devices; two ports take the carrier signal and the baseband signal as inputs, and the third port outputs the resulting signal of the mixing operation. However, RF mixers consume significant power because they rely heavily on active analog components. Thus, the backscatter transmitters avoid RF mixers. Instead, they combine an external carrier signal with a digital baseband signal using the switching action of the antenna. It is a lossy method, and it also leads to unwanted harmonics generation.

Judo introduces a new RF-mixing technique for low-power transmitters. It allows for the use of an *analog baseband signal*. Furthermore, the transmitted signal is orders of magnitude stronger than the reflections from conventional backscatter mechanisms. Judo takes advantage of the tunnel diode's nonlinear properties. It enables the use of TDOs as self-oscillating mixerself-oscillating mixers (SoMs), i.e., TDOs can generate carrier signals and are also used for the mixing operations, which avoids the need for dedicated RF mixer circuitry. Unlike conventional mixers, the TDO mixer has two ports. An analog baseband signal is fed into the first port, and the result of mixing of the signal is radiated out from the second port. Because of the low-power nature of the tunnel diode, the TDO exhibits peak power consumption of under 100 μW for this task.

Mixing of the baseband signal. The analog baseband signal is mixed with the locally generated carrier signal by feeding it into the same biasing port of the TDO. We illustrate this in Figure 6. The backscatter system and tunnel diode-based reflection amplifier differ from this mechanism. In these systems, through the switching of the RF switch or tunnel diode, the digital baseband signal is mixed. This produces unwanted harmonics. Backscatter tags become complex because harmonic cancellation mechanisms are required [30, 51, 66]. In addition, to the best of our knowledge, there is no mechanism for eliminating harmonics generated by tunnel diode-based reflection amplifiers [3, 4, 55, 58]. Because of the reflection gain, harmonics pose a significant challenge.

Digital baseband signal harmonics challenge. Conventional backscatter architectures utilize RF switches for mixing operations. Specifically, the mixing operation is achieved by controlling the switch with the information-bearing baseband signal. Since RF switches are digital, the baseband signal is constrained to the square waveform. The use of a digital (square) baseband signal in the mixing process results in undesired harmonics. We can understand this better by looking at the Fourier series of the square waveform:

$$square(t) = \frac{4}{\pi}\sum_{n=1}^{\infty}\frac{1}{n}sin(n \cdot 2\pi f t), \quad \text{where } n = 1, 3, 5... \qquad (2)$$

In the case of a square wave, it is possible to write it as a sum of sinusoidal components. These sinusoidal waveforms, located at the harmonics of the fundamental frequency, create unwanted

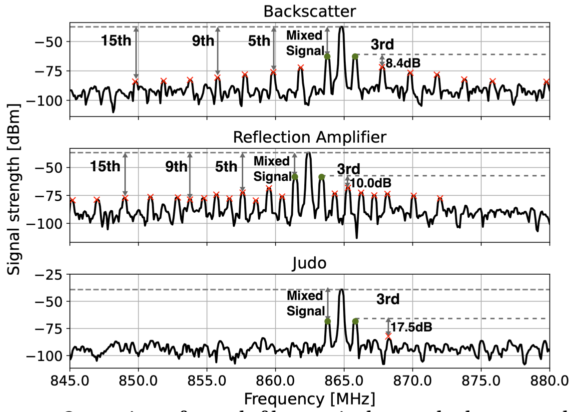


Figure 12: ***Comparison of spread of harmonics between backscatter and Judo transmitter.*** **Judo transmitter does not generate unwanted harmonics because it allows the mixing of the analog baseband signal.**

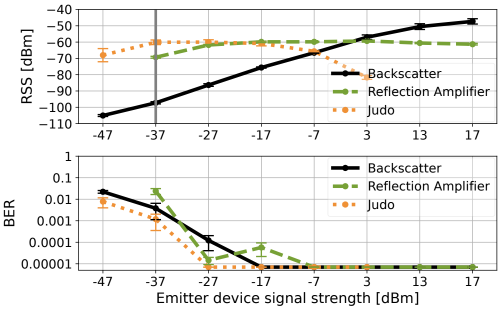


Figure 13: ***Signal strength and link reliability comparison between transmitters.*** **This is done by varying the carrier strength of emitter device. Judo significantly outperforms the backscatter transmission when the carrier is weak.**

Data rate	Subcarrier offset (MHz)	Frequency deviation (kHz)
3 kbps	1	15
100 kbps	1	50

Table 1: Parameters of the baseband signal used in Judo transmitters

harmonic components in the spectrum. By enabling direct mixing of the analog baseband signal, Judo transmitters prevent these unwanted sinusoidal signals from being mixed. To illustrate this aspect, we connect a TDO to a spectrum analyzer, mix a digital and analog waveform, and capture the spectrum plot. Figure 11 shows the results of the experiment. We observe a significant spread of harmonics on the spectrum when we mix a digital baseband signal, which disappears when mixing an analog baseband signal.

4.4 Comparing Judo to Other Transmitters

In this section, we compare the spread of harmonics, the received signal strength, and link reliability of the Judo transmitter, a reflection amplifier-based backscatter transmitter [58] and a backscatter transmitter based on standard RF-switch [56].

Setup. We conducted the experiment indoors: we configure the USRP B210 SDR to generate carrier signals ranging from −47 dBm to 17 dBm in strength. These represent the span of signal strength supported by the particular SDR. We place the emitter device and receiver (TI CC1310) equidistant from the Judo transmitter (1 m). Furthermore, we configure the Judo transmitter to low bitrate (3 kbps).

Investigating spread of harmonics. We compare the frequency spread of the harmonics for the different transmitters. We generate a carrier signal with a strength of −7 dBm in the 865 MHz band. The reflection amplifier enhances the backscatter mechanism. Therefore, the tag with a reflection amplifier also reflects the carrier signal. Meanwhile, the Judo transmitter uses an external carrier signal to stabilize the TDO. We capture the spectrum using the Keithley 2810 RF spectrum analyzer as shown in Figure 12. In this figure, red crosses indicate undesirable harmonics. On the spectrum of the backscatter transmitter and reflection amplifier based backscatter transmitter, these unwanted harmonics are seen up to 15th order. In contrast, we only see the mixed signal plus its mirror image when looking at the Judo transmitter spectrum. The third harmonic is close to the noise level, which is 17.5 dB lower than that of the mixed signal. Because of the direct mixing of the analog baseband signal, the transmitter avoids generating unwanted harmonics.

Investigating link metrics. We evaluate the link metrics among different transmitters. Specifically, we vary the signal strength of the SDR. Figure 13 shows the results of the experiment. On the received signal strength plot, the grey vertical line at −37 dBm represents the lowest carrier signal strength that maintained stable injection locking of the TDO. The Judo transmitter outperforms the backscatter transmitter when the carrier signal is weak (below −7 dBm). When the carrier signal is as weak as −37 dBm, the Judo transmissions are ten thousand times stronger than the backscatter transmissions. The Judo transmitter even outperforms the reflection amplifier based backscatter transmitter for the weakest carrier signal strengths. However, the backscatter transmitters outperform the Judo transmitter and reflection amplifier transmitter when the carrier signal is strong. Because the stronger carrier signal causes the bias voltage to shift, affecting the reflection gain. In addition, we observe a better BER for the Judo transmitter when compared to other transmitters due to its superior SNR.

4.5 Baseband Generation

In the next step, we modulate the locally generated carrier signal from the TDO with a baseband signal. We generate narrow bandwidth transmissions to enable a large transmission range. This allows highly sensitive radio transceivers for reception and results in a high link budget. As a modulation scheme, we use 2-FSK. We mix the baseband signal with a 1 MHz intermediate frequency to reduce interference from the carrier signal to the Judo transmissions [56]. Table 1 shows the parameters that we employ for the modulation scheme. Because we use the Texas Instruments CC1310 device as a receiver, following its specifications, we structure the packet as follows: 4 B preamble consisting of a fixed sequence of alternating 1 and 0 bits, 4 B of the synchronization word, 1 B indicating packet type, 1 B to identify the node, 1 B for the sequence number, and 29 B as the payload. To receive corrupt packets without having them dropped, we deliberately avoid the checksum byte.

Judo transmitter employs a narrow bandwidth 2-FSK baseband signal. The following question remain: Can Judo transmitters support wide bandwidth baseband signals?

Baseband signal frequency and the mixing ability. We investigate the impact of the baseband signal frequency on the ability of the tunnel diode SoM to perform the mixing operation. In this experiment, we vary the baseband signal frequency from 100 kHz to 10 MHz. This frequency range corresponds to the function generator used to generate the baseband signals. We measure the strength

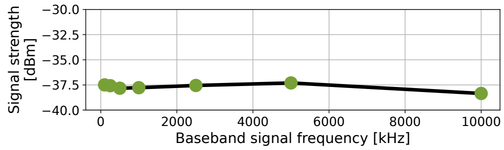


Figure 14: *Impact of baseband signal frequency.* Varying of the baseband signal frequency does not significantly affect the mixed signal strength.

of the mixed signal on a spectrum analyzer. The results are shown in Figure 14. We find that we could mix a baseband signal with a frequency as high as 10 MHz. The strength of the mixed signal remains stable and does not vary with frequency. In our experiments, we were able to mix signals with a wide frequency range, indicating that we may be able to employ baseband signals of wide bandwidth, and employing complex modulation schemes.

4.6 Putting It All Together

Judo transmitters work as follows: An external carrier signal stabilizes the TDO. Next, the TDO generates a carrier signal. It is mixed with an analog baseband signal. Finally, the resulting signal is radiated out of the antenna. Next, we describe implementation.

Implementation. We implement the transmitter with commercial off-the-shelf components on a PCB designed using FR4 substrates. The Judo transmitter contains the TDO front-end and the baseband generation circuit. The TDO uses a tunnel diode GE 1N3712 [1]. A Texas Instruments MSP430FR5969 microcontroller [53] generates the baseband signal. The baseband signal is obtained by toggling the microcontroller's general-purpose input/output port (GPIO). The digital signal is then converted to analog domain using a low-pass filter (RC) designed with passive components. We note that we mix a very weak baseband signal (few microwatts) with the TDO; consequently, little power is expedited in the passive components. The Judo transmitter uses a VERT900 antenna with 3 dBi gain [25].

4.7 Power Consumption

We measure the power consumption using a Keysight E36313A power supply [19]. To calculate the power consumption of the TDO frontend, we vary the bias voltage and measure the current flowing through it. We estimate that the TDO performs the carrier signal generation and mixing process at a power consumption of approximately 48 µW. This aligns well with other systems that use tunnel diodes in backscatter transmitters [2, 4].

The baseband generator is implemented on a microcontroller (MSP430FR5969). When it operates at the lowest supported voltage (1.8 V), the peak power consumption is estimated to be under 200 µW. However, because there are various low-power and sleep states, the average power consumption of the microcontroller remains well below this figure. One could also design a custom chip to generate baseband signals at a low-power consumption of only tens of microwatts [32, 66]. Thus, even conservatively, we expect the overall power consumption of transmitter to be below 100 µW.

5 EVALUATION

We evaluate our system in various scenarios and environments. The main findings are as follows:

- We transmit to distances as high as tens of meters even when the emitter device and edge device (receiver) are co-located, i.e., the monostatic configuration. This represents the most challenging scenario for the Judo transmitters due to the high self-interference from the carrier signal to weak Judo transmissions.
- Judo transmits through several floors of a building. Besides, it achieves significant transmission range (≥ 100m) outdoors even when the transmitter is located at 100 m distance from a emitter device generating a carrier signal of strength 25 dBm.

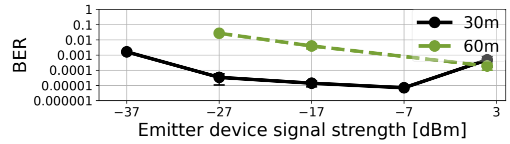


Figure 15: *Link reliability in the monostatic configuration* We evaluate the link metrics with the Judo transmitter configured to low-bitrate (3 kbps). We vary the strength of the carrier signal. Link quality, as expected, worsens with the distance of Judo transmitter from the emitter device.

Setup. We use the following configuration: We use SDR, USRP B210, as the emitter device and TI launchpad CC1310 as a receiver (edge device). The Judo transmitter, emitter device, and the receiver are equipped with 3 dBi omnidirectional antennas. We then position these devices at a distance of about one meter from the ground in order to reduce the impact of the ground reflections.

We configure the Judo transmitter at two different bitrates (3 kbps, and 100 kbps). Link metrics are estimated by transmitting packets of length 32 B with random payloads. Each run of our experiments transmits a fixed number of packets (2000). We disable CRC check at the receiver and do not send checksum bytes. It allows the reception of packets with corrupt bits, which would be otherwise dropped by the receiver. In order to calculate the bit error rate (BER), we only consider the successfully received packets and compare them with the baseline sequence. We do not consider the packets that not received for the estimation of link metrics.

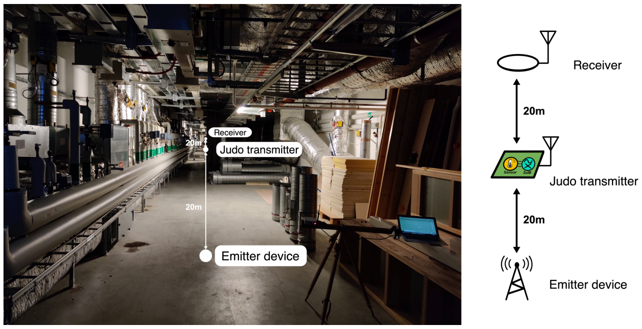
5.1 Monostatic Configuration

We evaluate the transmission range and link metrics in a monostatic configuration. The emitter device and the receiver are co-located (approximately 1 m in separation). This is challenging for the receiver because the carrier signal interferes with the receiver. Furthermore, the commodity receiver (CC1310) lacks the self interference cancellation mechanisms of monostatic RFID readers.

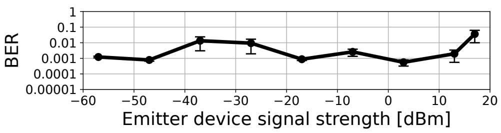
Setup. The setup is similar to the previously described. We investigate the maximum transmission range and link metrics by varying the distance of the Judo transmitter from the emitter/receiver device. Our experiments are conducted in the corridors of a university building. We vary the carrier signal strength of the emitter device between −37 dBm and 2 dBm. These emitter device strengths ensure that the self-interference from the carrier signal does not overwhelm the weak transmissions of the Judo transmitter.

Low bitrate. We keep the Judo transmitter at a distance of 30 m and 60 m from the location of the emitter/receiver. The distances represent the midway point and maximum length of the corridor where the experiment is conducted. Figure 15 shows the result of the experiment. In general, we observe that the BER is low, well below 10^{-2}. We observe an increase in BER at greater distances due to the deteriorating link quality (SNR).

High bitrate. We conduct this experiment using a Judo transmitter set to a higher bitrate (100 kbps). It is possible to transmit to a



(a) Indoor environment



(b) Link quality (Indoors, bistatic)

Figure 16: *Link quality (Indoors, bistatic).* Even in a multi-path rich and challenging radio environment, Judo transmitters maintain high link quality. However, the link metrics deteriorate at higher carrier signal strengths due to significant self-interference from carrier signal to Judo transmissions.

distance of 30 m with a 10^{-1} BER. It is significantly higher than the low bit rate at similar distances. Firstly, it is due to the high self-interference from the carrier signal. The receiver uses a filter with a wider bandwidth to support higher bitrates, which affects its ability to attenuate the external carrier signal. Secondly, the receiver's sensitivity drops with higher bitrates. These factors both impact the SNR and affect the BER. In the previous experiment involving low bitrate, we observed, on average, the minimum signal strength of received packets to be −114 dBm. However, at a high bitrate, this level drops to −82 dBm. This is because of the lower rejection of the interference from the carrier signal at a higher bitrate.

Insights. Monostatic configuration suffers from considerable self-interference from the external carrier signal. Even in this challenging configuration, we show that the Judo transmitter can support a range of tens of meters. Our system outperforms typical RFIDs, which use monostatic configurations as well. The fact that we are able to do this, considering that we do not use any self-interference cancellation circuitry, is remarkable. In addition, we can increase the transmission range and reliability by using coding schemes and self-interference cancellation mechanisms at the receiver [31].

5.2 Bistatic Configuration

We examine the transmission range in the bistatic configuration where the receiver, emitter device, and Judo transmitter are separated by a distance of tens of meters from each other. In comparison with monostatic configuration, we should expect a significant increase in the transmission range, since the receiver will be less susceptible to self-interference owing to the path loss suffered by the carrier signal [32, 56].

Setup. The setup and methodology is similar to earlier experiments. In comparison to a low bitrate configuration, a high bitrate configuration limits transmission range because of high self-interference, and a low receiver sensitivity. Due to space constraint, we only present the results with high bitrate configuration (100 kbps).

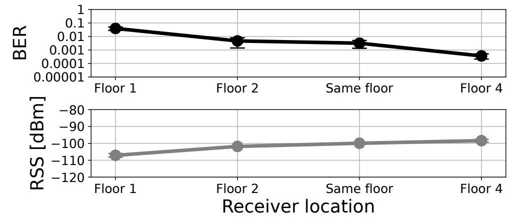


Figure 17: *Link quality (Indoors, bistatic).* Even with a weak carrier signal, Judo transmitters offer long-range capabilities. When reflecting a carrier signal, the Judo transmitter is able to transmit to multiple floors.

Indoor environment. The first experiment is conducted in the basement of the university building. It consists of a variety of metallic equipment, air vents, and other objects, as shown in Figure 16(a). Judo transmitter is placed line-of-sight (LoS) and evenly apart from both the emitter device and receiver to cover the basement floor. Distance between emitter device and Judo transmitter is 20 m. The carrier signal strength generated from the emitter device is varied between −57 dBm and 17 dBm. These values represent the range that are supported by the specific SDR.

Figure 16(b) demonstrates the results of the experiment. We observe reasonably low BER even under diverse carrier signal strengths. However, we do notice a significant variation in the BER as we alter the carrier signal strength. This may be due to the multi-path rich environment or due to the self-interference from the carrier signal to the Judo transmissions.

We conduct the next experiment with the Judo transmitter kept non-line-of-sight (NLoS). We place the Judo transmitter on the third floor of the university building. We then place the receiver on the same floor and adjacent floors. The emitter device (SDR) is positioned at a distance of 15 m from the Judo transmitter, which is also the maximum length of the corridor. We generate a weak carrier signal of strength −17 dBm, which is the lowest carrier signal strength that we found was necessary for a stable injection locking of the TDO on the Judo transmitter at the particular Judo transmitter and emitter device separation.

Figure 17 shows the results obtained from the experiment. We could transmit to multiple floors of the university building and that the BER is well below 10^{-3}. On the first floor, i.e., two floors below the location where the Judo transmitter is situated, the link reliability significantly decreases. This is because the received signal strength of the received packets approaches the noise floor of the receiver. We observe that on an average the minimum signal strength of the successfully received packet is −109.7 dBm.

Outdoor environment. Finally, we experiment outdoors. The stability of the TDO is significantly compromised outdoors. This is due to the changes in the ambient environment, such temperature humidity and wind. There is also interference from other wireless transmitters. The experiments are conducted on the university campus, with a building on one side of the setup and a forest on the other side. The USRP B210 is equipped with an external power amplifier. We generate a carrier signal at 868 MHz with the strength of 25 dBm, which is the maximum signal strength achievable with the SDR and amplifier combination. From the emitter device, we place the Judo transmitter approximately 90 m and 150 m away. 150 m is the maximum distance to achieve stable injection locking of the TDO. The Judo transmitter and emitter device are in an

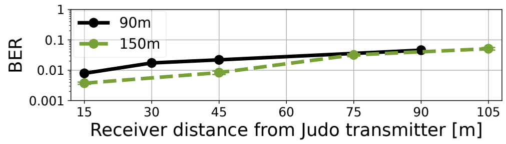


Figure 18: ***Link quality (Outdoors, bistatic).*** **The distance between the Judo transmitter and emitter device, and the Judo transmitter and receiver, can be over 100 m. As compared to backscatter systems, the transmission range is less dependent on the carrier signal strength.**

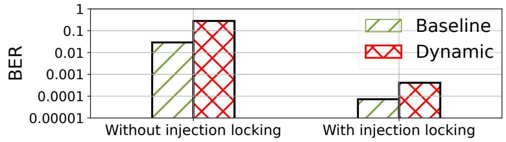


Figure 19: ***Link reliability of Judo transmitter in the dynamic environment.*** **When we operate in the without emitter device mode, we observe a significant increase in the number of lost packets and BER. Injection locking the TDO enables us to improve its stability, and consequently, the reliability.**

NLoS setup and blocked by a building. We position the receiver at a distance of 15 m to 105 m from the Judo transmitter in LoS.

Figure 18 represents the results of the experiment. Despite being located at a considerable distance from the emitter device, we are able to transmit to distances of tens of meters to hundreds of meter away from the Judo transmitter. We find that on average the minimum signal strength of received packets is −108 dBm.

Insights. We observe that Judo can achieve a large transmission range despite significantly weak carrier signals at the transmitter. For example, for a bitrate of 100 kbps, we can support a transmission range of 105 m even when the emitter device is over 100 m apart from the Judo transmitter. This allows the possibility of significantly increasing the reach of the emitter device. A strong emitter device could be kept at significant distances from the Judo transmitter. Thus, there is greater flexibility in positioning the emitter device than in conventional backscatter systems.

Another observation is that when compared to a conventional backscatter system, the transmission range is less impacted by the distance between the emitter device and Judo transmitter. This is because transmissions from Judo transmitter are not reflected carrier signals. Instead, the carrier signal injection locks the Judo transmitter, and lends stability. Based on these two observations, we purposefully keep the carrier signal strength to a minimum level to enable a stable injection locking of the Judo transmitter.

In all of these experiments, we could not compare the Judo transmitter with a conventional backscatter system, such as LoRea [56]. These systems have a short range of a few meters under weak carrier signal strengths. However, due to the enhanced ability of Judo transmitters under similar conditions, we can reach tens of meters of transmission range and transmit across multiple floors in the building. Additionally, the link reliability of Judo transmitter is similar to that of related backscatter systems [21, 56, 58, 66, 67].

5.3 Dynamic Environment

We investigate the ability of Judo transmitters in dynamic environments, i.e. when there are motions in its vicinity. These experiments are conducted with a person walking in the same room as the Judo transmitter. It is a challenging scenario since in absence of external carrier signal the frequency of TDO drifts with nearby motions.

Setup. The experiments are conducted in the offices of the university building. The transmission rate is 3 kbps, which means that

Radio Technology	Bitrate (bps)	Tx power (dBm)	Energy consumption (mW)
BLE (nRF52840) [50]	125K, 500K 1M, 2M	-40/0/8	11.5/14.4/49.2
BLE (cc2625) [13]	125K, 500K 1M	0/5	21.9/28.8
BLE (ATM2202) [42]	1M	0	7.2
ZigBee (nRF52840)	250K	0	19.2
SigFox (ATA8520E) [11]	100	14	95.4
LoRa (SX1276) [49]	0.293, 3.125 9.375	7/13/17/20	66.0/95.7/287.1/396.0
LRM-FSK (CC1310) [12]	3K, 100K	10	48.2
Judo	3K, 50K 100K, 500K	-19	0.1

Table 2: ***Transmission parameters of Judo against commercial transmitters.***

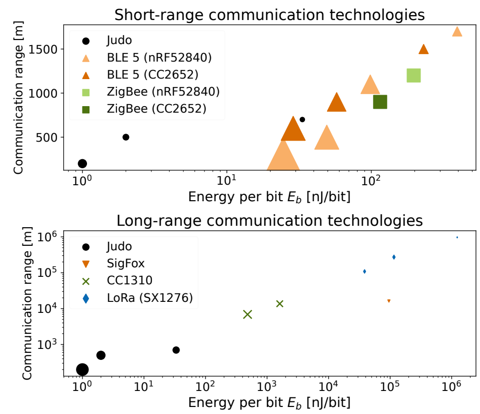


Figure 20: ***Comparing Judo against commercial transmitters.*** **The marker size represents the bitrate (min.** 0.293 bps**, max.** 1 Mbps**).**

we are able to transmit on-air for a longer period of time and are vulnerable to environmental changes. We conduct several runs of the experiment, transmitting a fixed number of packets (1000). The receiver is located approximately 10 m from the Judo transmitter (kept NLoS and separated by several walls). We generate the carrier signal from the SDR located about 8 m away from the transmitter (NLoS and separated by several walls). In order to assess the reliability of the link, we calculate the BER based on the received packets, and we also track the number of missed packets.

Judo (without emitter device). We conduct the experiment without an external carrier signal. Thus, the TDO is not injection-locked. Consequently, if there is motions in TDO vicinity, the TDO frequency is impacted. We run the Judo transmitter in a room without motion for the baseline calculation. After that, a person walks within the room a fixed number of times. Figure 19 shows the results of the experiment. In comparison to the baseline, we observe a marked drop in the reliability of the link. Our experiments logs show that significantly fewer packets are received within the same time period. There is frequency instability in the TDO caused by nearby motions. It is evident from the experiment that TDO instability must be addressed to enable operation in dynamic environments.

Judo (with emitter device). The experiment methodology and setup remain the same as in the earlier experiment. However, this experiment is conducted with the TDO on the Judo transmitter injection-locked to an external carrier signal. The SDR is configured to generate an external carrier signal of 3 dBm strength. Figure 19 shows the link reliability in comparison to Judo transmitter without being injection-locked. We can improve the ability of the Judo transmitter to function in dynamic environments by injection locking the Judo transmitter to an external carrier signal.

Insights. TDO’s stability is a concern. However, we can overcome this concern by utilising the injection locking phenomenon.

6 DISCUSSION

Commercial transmitters. A wide range of radio transmitters exists for WES. They support wireless standards like BLE, Zigbee, LoRa, and Sigfox. Therefore, we can ask: *How does Judo transmitters compare with them ?* Our peak power consumption is several orders of magnitude lower. However, we cannot say that Judo transmitters perform better than commercial transmitters when considering essential parameters such as bitrate, transmission power, current draw, and energy per bit. Thus, we analyzed to compare Judo transmitters against commercially available transmitters.

We show the transmitters used for comparison in Table 2. First, we populated the values in the table from the specifications mentioned in the datasheet. Then, we calculate the transmission range (in free space), energy per bit for each transmitter. Finally, we compare Judo to long-range and short-range radio transmitters and show the results in Figure 20. The results indicate that Judo transmitters perform well against commercial short-range transmitters. The reason for this is the high receiver sensitivity and the use of sub-GHz frequencies. On the other hand, Judo transmitters are less advantageous than long-range transmitters. Nonetheless, Judo transmitter's lower power consumption is beneficial and allows operations on small batteries, or energy-harvested from environment.

Availability of tunnel diodes. The tunnel diode was invented in 1957. The recent years has seen a decline in tunnel diode usage, and there are few manufacturers produce them. Consequently, it is difficult to procure tunnel diodes, and they are not available off-the-shelf. Nonetheless, tunnel diodes have a long shelf life [23], and we have used tunnel diodes produced several decades ago. Recent research results demonstrate that tunnel diodes offer great promise for the design of low-power transmission mechanisms [2, 4, 6, 58, 58]. These efforts re-motivate the mass production of tunnel diodes.

Phase noise and receiver sensitivity. We implement the design of TDO that was presented in TunnelScatter [58]. It trades off higher phase noise for low-power consumption. Nevertheless, by injecting a weak external carrier signal into the TDO, we can significantly improve TDO stability. Modern radio transceivers can tolerate interference in the same and adjacent bands through phenomena such as the capture effect and filters present in the transceiver. Consequently, as we had seen in the Section 5.1 and Section 5.2, when the external carrier is weak, we can reach the receiver's lowest sensitivity level (as indicated in the datasheet). However, we notice a significant drop in sensitivity levels when the carrier signal is strong. This is because of interference from the carrier signal.

Enhancing link reliability. Judo achieves low-power consumption by adopting several design choices, and among them, the most important is to radiate a weak signal. Yet, Judo does not employ coding mechanisms which adversely affects the reliability of the link. With techniques such as DSSS and FEC, we can improve the reliability of the link. Indeed, Varshney et al. demonstrated using these techniques to enhance the reliability of the FSK backscatter transmissions [57]. The system may also use emerging developments in machine learning and other methods to recover corrupt bits and improve link reliability further [37].

Judo without emitter device. Experimental results show the Judo transmitter can receive transmissions without requiring the carrier emitter device. As we introduced in Section 4, the TDO without an external carrier signal is unstable and can be affected by changes in the environment like motions or temperature. As a result, this configuration can only be applicable in specific scenarios where conditions remain very static with little or no dynamics in the environment. We may consider indoor scenarios, such as inside homes with a minimal amount of motion in the environment. To illustrate this aspect, we conducted an experiment where we placed a Judo transmitter without an emitter device in one of the floors of the university building. We could transmit to all the four floors of the building, as we show in the Figure 21. However, we do notice a drift in the frequency of the TDO which required reconfiguration of the reception frequency of the receiver.

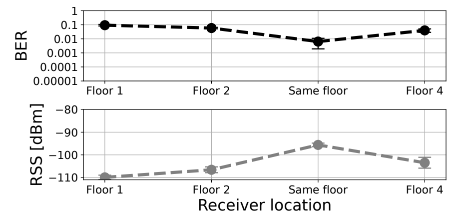


Figure 21: ***Link quality without emitter device (Indoors, bistatic).*** **Even without an external carrier signal, we can transmit to several floors of a building.It was necessary to configure the receiver frequency regularly to counter drift.**

Future research directions. We had seen earlier in Figure 13, Judo outperforms backscatter transmitters at weak carrier signal strengths, and vice-versa. For the Judo transmitter to operate under diverse carrier signal strengths, a backscatter module may also be required in the Judo transmitter. Depending on the carrier signal strengths, it may switch between Judo and backscatter transmitter. We leave designing such hybrid transmitters to future efforts.

Ensworth et al. discuss the architecture of a low-power receiver that uses a diode and an external carrier signal to down-convert a BLE transmission and recover the baseband signal [20]. However, this design suffers from poor sensitivity of the diodes. Tunnel diodes may overcome some of these limitations.

Availability. The source code and design files of Judo transmitter would be made available here: https://github.com/weiserlab/JUDO

7 CONCLUSION

We have presented, Judo, a low-power architecture that allows transmissions even in challenging radio environments. It achieves a transmission range exceeding 100 m and at peak power consumption below 100 µW. The key contribution made with Judo is to demonstrate the self-oscillating mixer behaviour of the TDO. It enables the Judo transmitter and emitter device to be located far apart (≥ 100 m). Additionally, the novel baseband mixing mechanism helps Judo transmitter avoid generating unwanted harmonics.

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