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Ultralow-Power Receivers

Overcoming battery limitations to facilitate self-powered operation

Fast forward to a world with 1 trillion wirelessly connected devices in which pervasive computing impacts every aspect of our lives. Now imagine that each of those devices operates on a battery that lasts an average of three years, which is very generous considering that most of today's Internet of Things (IoT) devices have batteries with much shorter lives. In that world, we would be changing 1 billion batteries per day just to maintain the network of devices. Setting aside for the moment the environmental impact of battery disposal at that scale, nobody wants to take on the battery maintenance problem. Today, this is what limits the mass adoption of IoT solutions. It is why factories have not installed monitors on their 10,000 assets and why shipping companies do not embed real-time tracking in every package label. When you examine the power consumption of IoT devices over their lifetime, most of the energy is used for wireless communication; of that electricity, a large amount is spent on network synchronization rather than transmitting data. This calls for better networking solutions to enable massive scales of devices and ultralow-power (ULP) radios to enable self-powered operation, eliminating the battery and, therefore, the maintenance problem.

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Quantifying Receiver Performance

We focus on four main specifications for receiver performance: active power, sensitivity, data rate, and signal-to-interference ratio (SIR), also called *adjacent channel rejection*. These generally trade off with one another, but there is no one figure of merit that captures their relative impact across all types of receivers, frequencies, modulations, and so on. To make it easier to observe trends and tradeoffs, we concentrate on ULP receivers, which we will, somewhat arbitrarily, define as having an active power <100 μW.

Active power is compared because you can always duty cycle a receiver to trade off the data rate with average power consumption. For example, if you turn off a receiver 50% of the time, the average power will be half the active power, and the average throughput will also be halved. In the limit, synchronization of the receiver and transmitter after they

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have been off for an extended period of time will add significant overhead and set a lower bound on the energy used for communication. It is worth noting that synchronization is more challenging as the number of devices scales, especially into the thousands. Sensitivity is a measure of the minimum required received signal strength to achieve a target bit error rate of, usually, 10^{-3} or a packet error rate of 10^{-2}. It can be limited by the gain of the receive path, the type of detector used for demodulation, and the amount of noise added by the receiver. It typically trades off with active power, the data rate, and bandwidth, but, as we will see for some ULP receivers, this is not always the case.

The data rate is often sacrificed for lower power and better sensitivity. For example, Bluetooth, Wi-Fi, and the narrowband IoT (NB-IoT) all support lower data rates in their standards via stronger error correction coding and data repetitions to extend their wireless range. Theoretically, the data rate trades off one to one with the received signal-to-noise ratio for a fixed bit error rate, according to the Shannon channel capacity theorem [1]. For this reason, we also compare the normalized sensitivity to a single data rate of 1 kb/s:

$$S_{\text{norm}} = S - 10\log(\textit{data rate}/1\,\text{kb/s}). \quad (1)$$

Finally, SIR has recently been considered in ULP receivers because the equipment often has energy detection receiver front ends that are known to be susceptible to interference. Especially considering deploying devices at massive scales and the increasingly crowded wireless spectrum, ULP receivers must be able to coexist with many different types of incumbent wireless signals.

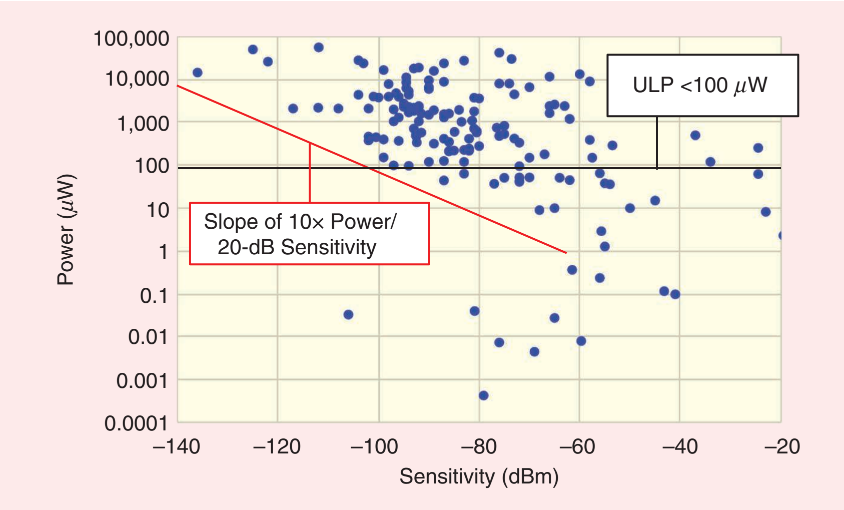

FIGURE 1: A survey of wireless receivers published in selected IEEE conferences and journals from 2005 to 2021 [2]. dBm: decibels referenced to 1 mW.

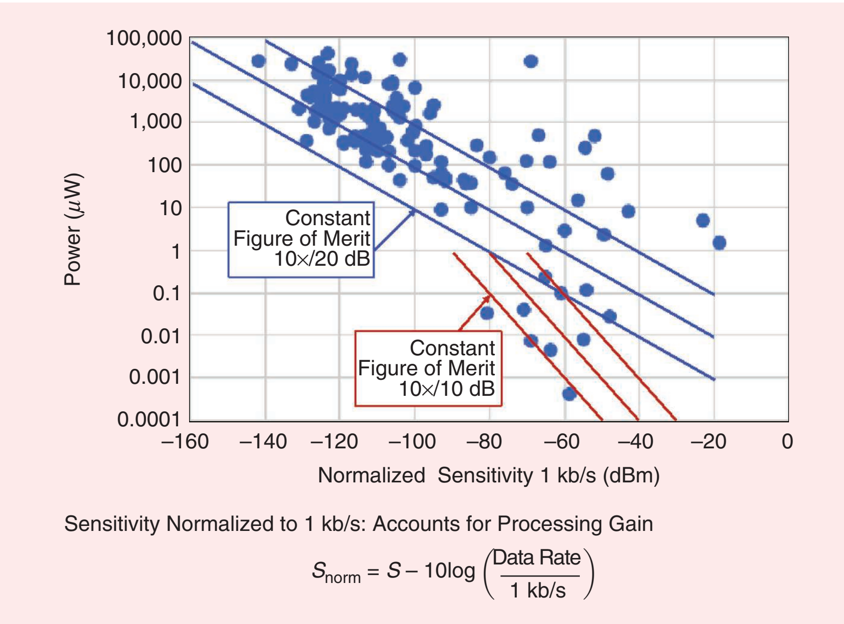

FIGURE 2: Sensitivity normalized using equation (1) and plotted with constant figure-of-merit lines for coherent and rectified-first receivers.

Power Versus Sensitivity

We compiled a survey of ULP receivers published in top-tier circuits journals and conferences [2]. Figure 1 shows the power-versus-sensitivity (range) tradeoff for the 191 receivers published at the time of writing. With the exception of nanowatt receivers, an empirical line with a slope of –1 decade power per 20 dB of sensitivity bounds the performance, which can be interpreted as a constant figure of merit. Conveniently, this implies that receiver power and range scale together, assuming a path loss coefficient of 2; e.g., a 10× increase in power results in a 10× increase in range. In Figure 2, the sensitivity is normalized to a 1-kb/s data rate using (1), which reduces the spread in points, particularly for nanowatt receivers since they have relatively low data rates. These normalized points are compared to two groups with a constant figure of merit: 10× power/20-dB sensitivity and 10× power/10-dB sensitivity. The latter is more commonly used for energy detection front ends [3].

ULP Receiver Architectures

Several receiver architectures have been published in the literature; however, most ULP receivers leverage some variation of a passive envelope detection radio-frequency (RF) front end, eliminating power-hungry RF blocks, such as low-noise amplifiers (LNAs) and RF local oscillators (LOs), as shown in Figure 3. Hybrid architectures have been demonstrated that, for example, add back an LNA for improved sensitivity and that include a passive mixer-first architecture incorporating an RF LO. The power of these RF components is >20 μW and often >100 μW; therefore, we are not considering them ULP. Exploring the architecture in Figure 3 further, passive transformers and matching networks are added in front of the envelope detector (ED) to reduce the noise bandwidth and improve the sensitivity by up to 20 dB, extending the wireless range [4]. This passive voltage boosting performs better with a high RF ED input impedance, which is easier to achieve at lower frequencies; therefore, <10-nW receivers tend to be subgigahertz (Figure 4). However, ULP receivers at <100 μW have been demonstrated across a wide range of frequencies, up to millimeter-wave bands.

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Following the transformer, a passive envelope detector is used for downconversion, which has a wide bandwidth; therefore, the amount of added noise can be high. This limits sensitivity to around –50 dB referenced to 1 mW. Baseband gain and filtering stages operate in the subthreshold, with a low bandwidth to keep the power minimal, resulting in a typical minimum detectable voltage in the 1–10-mV range. Finally, digital baseband processing typically consists of correlators to identify an on–off keying (OOK) wake-up sequence, cutting down on false detections and adding 5–15 dB of processing gain. Data rates for these receivers are less than 1 kb/s (Figure 5), limited by the speed and bandwidth of the subthreshold analog and digital baseband circuits.

Improving Selectivity

Many ULP receivers suffer from poor performance in the presence of in-band interferers. This is highlighted in Figure 6, which plots the SIR for all 191 receiver publications. Note that, for ULP receivers, the SIR is either poor or not reported. The ED-first architecture is inherently susceptible to interference because of its wideband response. Recently reported ED-first receivers have addressed this with Manchester encoding [5] and two-tone

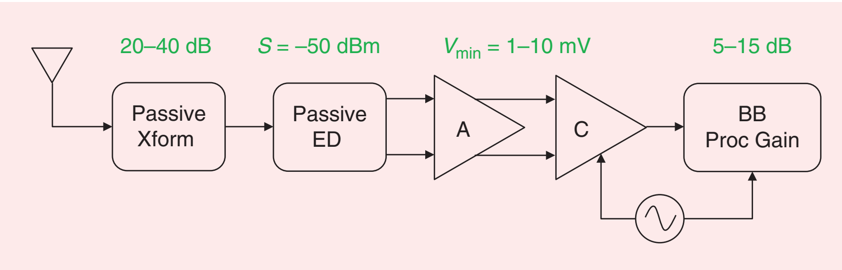

FIGURE 3: An energy detection receiver architecture with passive voltage boosting at RF and digital processing gain for improving sensitivity. Xform: transformer; ED: envelope detector; BB: baseband; Proc: processing.

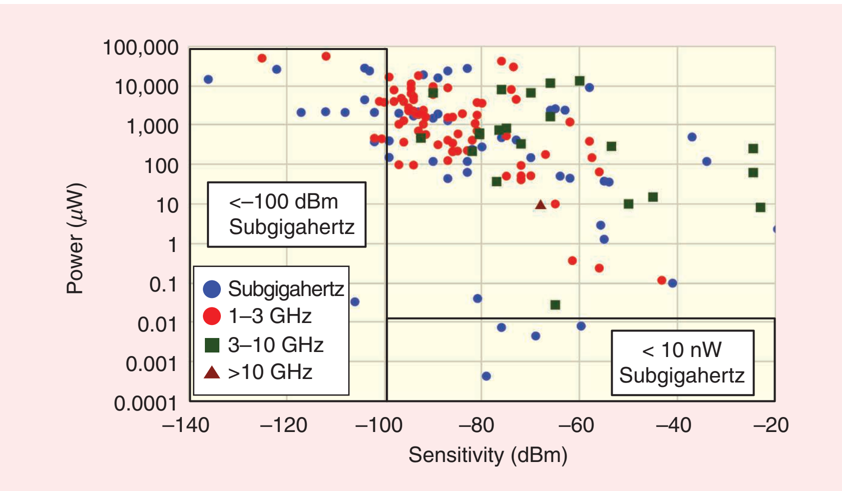

FIGURE 4: A comparison of power consumption and operating frequency.

The modulation scheme plays an important role in the required specifications of a receiver and hence its power consumption.

modulation [6]. Other solutions use a passive mixer-first approach to reduce the number of power-hungry RF components while adding some level of selectivity through down-conversion and high-Q baseband filtering [7] and frequency hopping [8]. Mixer-first solutions have demonstrated exceptional SIRs, with submilliwatt active power.

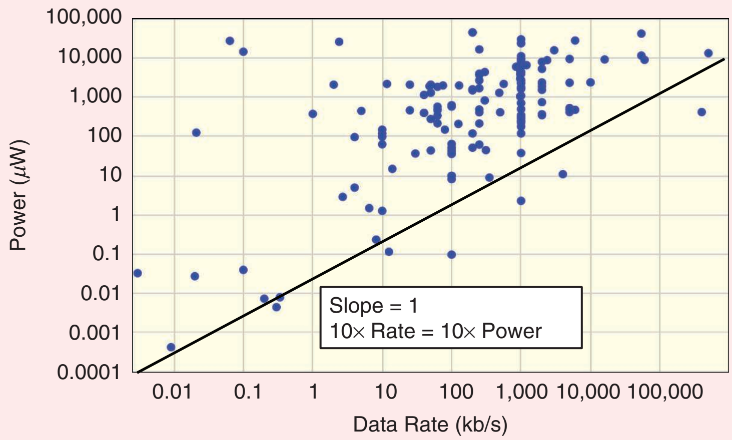

FIGURE 5: ULP receivers tend to be practically limited to peak data rates of 1 Mb/s, and the data rate trades with the active power as expected.

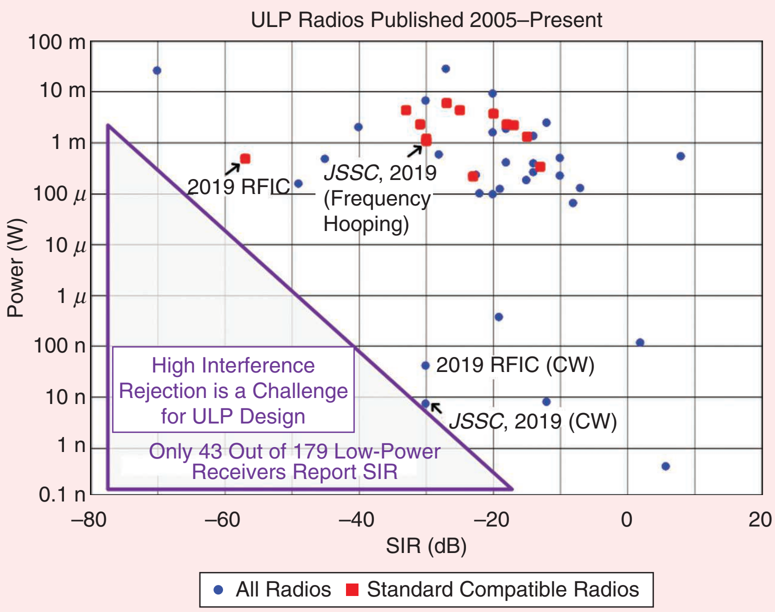

FIGURE 6: Interference is a challenge for ULP receivers, with many not reporting a measured SIR. RFIC: IEEE Radio Frequency IC Symposium; *JSSC: IEEE Journal of Solid-State Circuits; CW: continuous wave.*

ULP Receiver Adoption

The modulation scheme plays an important role in the required specifications of a receiver and hence its power consumption. Figure 7 shows that coherent communication [e.g., binary phase-shift keying, orthogonal frequency-division multiplexing (OFDM), and quadrature amplitude modulation] requires significantly higher power to demodulate. All modern wireless standards use some form of coherent modulation for better spectral efficiency. Noncoherent modulation, such as OOK, frequency-shift keying, and pulse position modulation, is used exclusively for ULP receivers. This creates a gap between standard-compliant radios and state-of-the-art ULP receivers.

Wireless standards are being modified to incorporate ULP receivers as wake-up radios to reduce the energy spent on synchronization. The IEEE working group for Wi-Fi created the 802.11ba task group to investigate adding a wideband OOK message to the 802.11 base standard. The OOK message is embedded in a standard Wi-Fi packet and can be generated with existing transmitters only after a firmware update. It can be demodulated with a ULP companion receiver that has an active power of <100 μW [9], [10]—more than 100× less power than a fully compliant Wi-Fi radio. A Bluetooth special interest group is also looking at adding a wake-up message to the next version of the standard. Hopefully, more details on this will become publicly available soon.

The 3rd Generation Partnership Project introduced a wake-up message for the NB-IoT in release 15 of the cellular standard. The NB-IoT uses OFDM with 12 subcarriers and quaternary phase-shift keying modulation, which inherently is not low power to demodulate. In release 15, NB-IoT paging events are preceded by a wake-up signal, which is a unique correlation-based OFDM Zadoff–Chu sequence that somewhat simplifies receiver implementation, resulting in lower power but not yet ULP [11]. The significant advantage of this is that it has the potential to be rolled out worldwide in all LTE cellular networks, with only software updates. These examples represent a shift in thinking inside wireless standard communities to address the power needs of the IoT, helping to realize the adoption of trillions of self-powered devices.

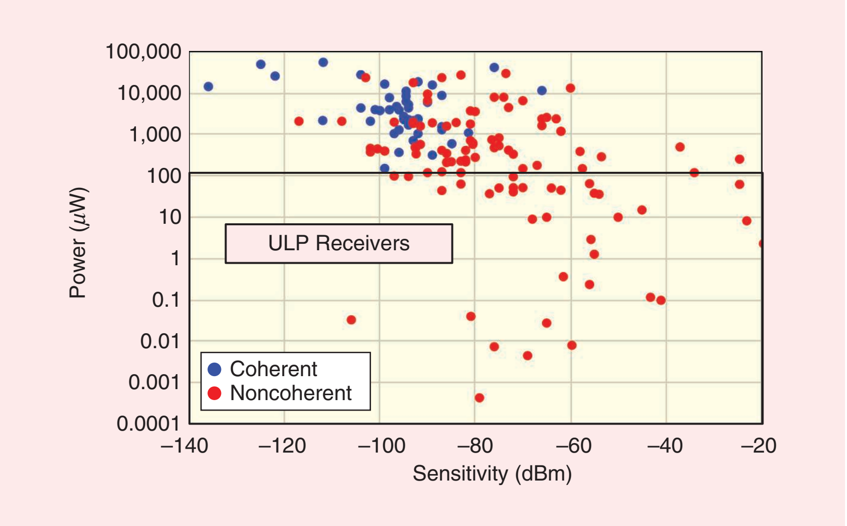

FIGURE 7: ULP receivers exclusively use noncoherent architectures with modulation formats such as OOK, pulse-position modulation, and frequency-shift keying.

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