Unified Receivers for True SWIPT for IoT

Yasser Qaragoez, Eleni Demarchou, Zulqarnain Bin Ashraf, Constantinos Psomas, Dominique Schreurs, Sofie Pollin, Besma Smida, Natasha Devroye, and Ioannis Krikidis

Abstract

The sustainable development of the Internet of Things hinges on communication solutions that are battery-less, minimal in hardware complexity, and capable of operating near the optimal tradeoff between data and power reception. Traditionally, the balance between downlink data and power transfer has been explored through various forms of splitting and conventional communication methods. In this article, we introduce two novel approaches that enable simultaneous and unified receivers, capable of rectifying power and demodulating information from the same received signal using identical analog low-power hardware. We demonstrate how information can be encoded in both amplitude and frequency, and how hardware-induced non-idealities can be mitigated or even leveraged. Our goal is to bring these unified receivers to the forefront of the IoT community's attention, and outline several open problems that warrant further investigation.

Introduction

Ambient Internet of Things (IoT) devices are batteryless devices with near-zero energy consumption, ultra-low complexity, and ultra-low power consumption. Ambient backscattering is often seen as a viable technology, which relies on passive reflection and modulation of an incident radio frequency (RF) signal that is not modulated. Such designs enable (passive) uplink communication but fail to provide downlink information transfer to the node. When downlink power transfer is also added, the design of ambient IoT nodes with bidirectional communication and guaranteed wireless power supply becomes feasible. In this article, we make the case for unified receivers, which are receivers capable of Simultaneous Wireless Information and Power Transfer (SWIPT) using an integrated receiver architecture. We show how unified receivers can be designed and used without significantly compromising complexity, information rate, or wireless power transfer (WPT) efficiency.

Most research on SWIPT assumes that it is not possible to fully integrate the wireless information and power transfer functionalities effectively. While time or power-splitting of received signals is not optimal [1], it is a common assumption in state-of-the-art SWIPT. Any split architecture reduces the efficiency, as resources are not shared, and increases the cost, as the hardware is duplicated after the split. In addition, active mixers used in conventional information receivers for down-conversion consume much power.

We believe such separation-based architectures are commonly assumed not only because they map onto separate and basic building blocks we understand (power harvesting, or downlink digital information transfer), but also because we have not yet thoroughly studied or understood truly integrated receiver implementations which for example avoid the usage of a power-hungry mixer, and allow for the same hardware to achieve power transfer and data transfer simultaneously. Despite recent interest in Wireless Information and Power Transmission, key challenges for both practical implementations and theoretical understanding of the unified receiver remain.

WPT is often accomplished through a rectifier. When contemplating using a rectifier as a communications receiver, one is immediately confronted with the fact that it complicates the phase information content of the signal and generally adds significant distortion to the signal. In addition, wireless information transfer (WIT) and WPT have very different power sensitivity (e.g., –10 dBm for energy harvesters versus –60 dBm for information receivers) [2]. As such, it is widely assumed that it is not possible to perform both WPT and WIT operations on the same received signal using one antenna [2–5].

In this article, we throw this assumption out, and present two new unified SWIPT receiver architectures that are low-power and enable simultaneous WIT and WPT. First, we argue that a rectifier, although acting as a very non-linear envelope detector given the high input power, can act as an information receiver for information embedded in the amplitude of the power signal. For this type of receiver, we show that memory effects and non-linear amplitude distortion can be overcome, making the integrated WIT and WPT receiver not only feasible but also efficient. Second, we focus on the second order inter-modulation products created by the rectifier, and show how they can also be exploited to achieve frequency and phase modulation without a mixer. The system can be designed to achieve high WPT and low bit error rate (BER) WIT when exploiting the high signal-to-noise ratio (SNR) regime and keeping the non-linear distortions low. We illustrate the concepts behind two simple communication methods which use these receiver

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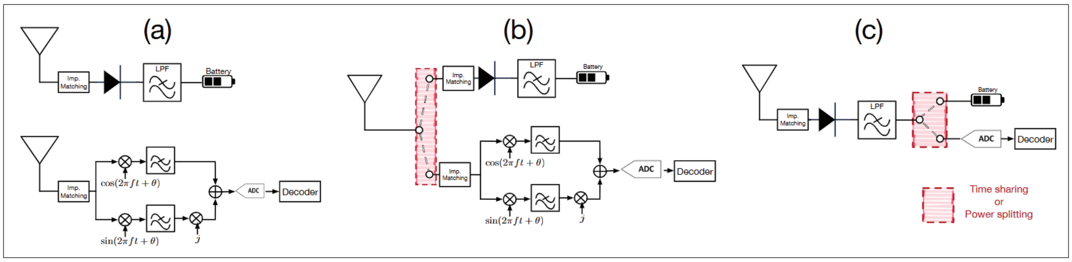


FIGURE 1. Existing architectures [6] for SWIPT: a) separated; b) co-located; and c) integrated.

architectures: amplitude shift keying (ASK) and frequency shift keying (FSK).

The rest of the article is organised as follows. First, we discuss existing SWIPT receiver architectures and clearly identify how the unified receiver differs from approaches typically assumed. We then discuss two feasible and low-cost unified receiver architectures, focusing on amplitude and memory effects first, and inter-modulation distortions second. We conclude with an outlook to open research questions related to the fascinating and under-studied field of unified receivers.

SWIPT Receiver Implementations

Most Prior SWIPT Receiver Implementations Assume Some Splitting

Existing work on SWIPT from the information-theoretic and circuit implementation communities mainly separate power and information transfer in one of three ways:

Separate receivers: Both WIT and WPT circuits are included as two separated receivers with separate antennas as illustrated in Fig. 1a [2, 4, 5]. This scheme allows for energy harvesting and information decoding independently and concurrently. To extract information from the received signal, this implementation uses the power-hungry oscillator-based down-converter circuit — leading to traditional communication models such as additive white Gaussian noise (AWGN) channel models. Having two circuits is expensive in terms of area, and using a traditional power hungry mixer for down-conversion is not well suited to low-power IoT devices.

Separation after antenna: The *co-located* configuration lets WIT and WPT share the same antenna as illustrated in Fig. 1b. This receiver splits the signal immediately upon reception and there are two separated circuits for energy harvesting and information detection. To coordinate WIT and WPT at the receiver, time-switching and power-splitting were proposed [2]. It has been recognized that power-splitting achieves better tradeoffs between WIT and WPT [7]. However, as in the previous separated receivers, this implementation uses active mixers for down-conversion of the information signal which consumes much power.

Separation after rectifier: This configuration, known as an *integrated* receiver, represents the first attempt to integrate both WIT and WPT circuits — to reduce the overall power consumption [8]. The implementation of RF-to-baseband conversion for information decoding is integrated with energy harvesting through the rectifier, as illustrated in Fig. 1c. This circuit splits the signal immediately after the Low-Pass Filter (LPF) using a power-splitter to optimize the trade-off between WPT and WIT. Note that the integrated configuration outperforms the co-located configuration in the energy harvesting regime only [8]. However, the investigation of the performance of such receiver is not trivial due to the absence of an expression for the achievable rate. More recently, in [1], a new framework is developed to facilitate investigation of the achievable performance. They investigated both power-splitting and time-switching scenarios and saw that power-splitting always outperformed time-sharing.

Truly Unified SWIPT Receiver Architectures and their Models

We present two unified receiver implementations that do not split signals or make use of any mixers, leading to very high efficiency, low-cost implementations well suited to ambient IoT devices.

Diplexer-based unified receiver: A diplexer is a passive device that implements frequency-domain multiplexing. It is a three port reciprocal device in which two ports (e.g., A and B) are multiplexed onto a third port (e.g., C). The signals on ports A and B are in disjoint frequency bands and hence can co-exist on port C without interfering with each other. We make use of a diplexer to separate low and high frequency components and to use one port for either WIT or WPT, and the other port for the other functionality, simultaneously. We name this the diplexer-based unified receiver, and it is motivated by

1. A desire to reduce the power consumption of the devices by avoiding the use of *a local oscillator*
2. Noticing that because of the diplexer's reciprocity, it may be used to separate the two signals in port C into low pass and high pass components on ports A and B as depicted in Fig. 2a [6].

The down-convertor is substituted by dual diode. Indeed, the high-frequency component that should have been removed in traditional receivers can be transformed into direct current using a diode/rectifier. As a result, this receiver architecture consumes less power by avoiding active components. This first circuit does not include a power-splitter like in [8]: the low-pass band-pass diplexer allows the *dual and continuous use of the same signal for both WPT and WIT* by effectively using the high-frequency signals that are discarded by the LPF in the *integrated* receiver in Fig. 1c. Note that this diplexer-based unified circuit is versatile: we can switch the battery and analog-to-digital converter (ADC) output ports to obtain either a sustainable (prioritizing the extraction of energy by linking the battery to the low-pass output of the diplexer because the power sensitivity for energy harvesting, e.g. –10 dBm, is higher than the power sensitivity for information transmis-

The down-convertor is substituted by dual diode. Indeed, the high-frequency component that should have been removed in traditional receivers can be transformed into direct current using a diode/rectifier.

Architecture	Advantages	Disadvantages
Separated (Fig. 1a)	–Well-understood performance limits for both WPT and WIT –Standardized hardware implementations	–Very high duplication of hardware –High power consumption in WIT receiver caused by large number of active components (low noise amplifier, mixer)
Co-located (Fig. 1b)	–High performance for both WPT and WIT –Sharing of antenna	–High duplication of hardware –High power consumption in WIT receiver
Integrated (Fig. 1c)	–Simple hardware for both WPT and WIT that is shared –Easy control via duty cycle or power splitting ratio –WPT performance understood	–Energy is divided between WPT and WIT –WIT performance compromised because mixer and low noise amplifiers are removed –WPT performance compromised because of WIT waveform constraints when doing power splitting
Unified Receiver (Fig. 2)	–Simple hardware for both WPT and WIT that is shared –Codesign of topology and waveform for WPT and WIT –More design parameters to tune WIT-WPT trade-off space –No a priori splitting but unified reception harvesting power while doing the information processing steps	–New models needed for analyzing non-linear WIT and trade-off with WPT –Non-standardized implementation –Very large design space (WIT versus WPT versus processing power cost versus hardware cost)

TABLE 1. Comparison of SWIPT Receiver Architectures. A unified receiver is the most integrated form, as there the waveform and hardware for WIT and WPT are jointly codesigned. Non-linearities and memory effects are not avoided, but exploited, improving both WIT and WPT efficiency. Non-linearities are e.g. exploited to give new degrees of freedom for a biased-FSK waveform that has benefits both in WPT and WIT.

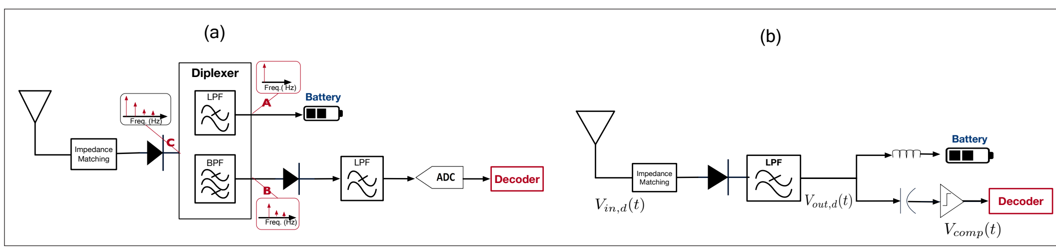


FIGURE 2. Truly unified receivers: a) diplexer-based receiver, and b) waveform-based LPF receiver.

sions) or green (prioritizing the communication receiver by linking it to the low-pass output of the diplexer to extract maximal signal amplitude and avoid a second rectifier) operation.

Waveform-based LPF unified receiver: The second implementation is based on an even simpler circuit consisting of only one diode/rectifier and an RC-based LPF — see Fig. 2b. This second implementation has been co-designed with the idea of transmitting multi-tone signals (multiple sinusoids rather than a single one) to maximize power conversion efficiency through optimising peak-to-average power ratios (PAPR), as discussed in [9, 10]. A high PAPR ratio causes greater distortion in the SWIPT signal. Contrary to previous works, where all the tones of transmit waveform have equal power, this implementation requires that the power of the side tones be proportional to that of the center tone — which we call a biased-FSK waveform. Introducing this bias in the three-tone FSK reduces its PAPR from 6 to 5.3, ensuring the signal remains within a more favorable region of the diode's nonlinear transfer characteristic. As a result, the total harmonic distortion (THD) was reduced by 6%, the BER at low SNRs improved by a factor of five, and the power conversion efficiency remained comparable.

Leveraging the frequency-dependent transfer function of the rectifier, this circuit may be designed to attain different attenuation levels for information transfer: high attenuations are paired with a non-coherent comparator-based decoding scheme suited to low power operation, while low attenuations are paired with a coherent (requiring higher power) fast Fourier transform (FFT) based decoding technique which allows for better noise resilience for the information transfer.

Note that this second circuit also does not include a power-splitter like in [8]: it allows the *dual and continuous use of the same signal for both WPT and WIT* by effectively designing the multi-tone waveforms. The key idea is that the non-linearity of the diode can be exploited in two ways: it can harvest power, but it can also bring amplitude, phase or frequency information to baseband. The baseband signal can then be sampled directly and processed in an information decoder. The use of a multi-tone waveforms gives rise to low-frequency inter-modulation distortions that can be seen as a baseband envelope signal carrying information.

Trade-off analysis and comparison with integrated architecture: in prior work [6], using a lower bound on capacity and a simple linear diode model, we found that the diplexer-based design achieves near-maximal harvested power at close-to-maximal data rates, outperforming the integrated approach (Fig. 1c). The integrated receiver relies on power-splitting, forcing a trade-off between BER and energy harvesting, while ASK, FSK, and Phase Shift Keying (PSK) modulations vary in complexity and efficiency. As shown in Fig. 3, repetition coding lowers the BER but reduces the raw data rate. By contrast, the unified receiver (Fig. 2a) largely overcomes these trade-offs, achieving near-maximal BER and harvested energy.

We now present two communication schemes that use the diplexer-based and waveform-based LPF receiver architectures as both down-converters and energy harvesting circuits: an ASK method, and a FSK method. Unified WPT receivers suffer from the non-linear distortion and low-pass filtering of the rectifier. To mitigate information distortion in SWIPT, biased ASK (to be described) and phase modulation waveforms were developed, as described in [11] and [12], respectively. A recent study, referenced in [13], introduces a multitone PSK modulation approach (which we will not focus on here). This method demonstrates a reduction in voltage ripple at the diode output compared to ASK. Contrary to amplitude variation-based modulation schemes (PSK and ASK) a third alternative was presented in [14]: a multitone FSK scheme which we will outline here. This FSK scheme appears promising in terms of energy harvesting capabilities. These waveforms (i.e., biased-ASK or biased-FSK) are compatible with those used by conventional, more advanced receivers. Furthermore, existing RF transmitters are capable of generating such waveforms, enabling integration with current infrastructure.

Information Transfer Exploiting Memory Effects: Biased ASK

Following the analysis in [12], a simple diode-LPF rectifier or a diplexer-based design can be used as an integrated receiver for ASK modulation.

Encoder: The transmitter generates and sends the signal $A_k \sin(2\pi ft)$, where f is the carrier frequency and A_k is the signal's amplitude as defined by the k-th ASK modulation symbol, $k \in \{1, ..., M\}$ and M corresponds to the number of symbols. As shown in the example of Fig. 4a, the binary data is mapped into an ASK modulation with two symbols; specifically of amplitudes 0.5 and 1 V. Note that we used biased ASK to enable both information receiving and energy harvesting using the same rectifier [11]. Various trade-offs between power transfer and BER can be produced by varying the amplitude levels of biased ASK, A_k.

Decoder: At the receiver, the diode functions as an envelope detector, removing the high frequency carrier component from the amplitude-modulated passband signal. In the high-receiver power regime, however, a significant amplitude distortion is introduced by the voltage-dependent junction capacitor and resistor of the diode, as well as a memory effect caused by the capacitance of the LPF. The memory induced by the capacitor's characteristics turns out to be an important aspect to take into account [15], particularly at higher symbol rates. As the rectifier's circuit is excited by an ASK modulation, the capacitor will charge or discharge accordingly, depending on its current charge and the input symbol. Specifically, if the input symbol is of a higher amplitude, then the capacitor will be charged and reach a higher voltage level. On the other hand, if the symbol is of a lower amplitude, the capacitor will be discharged towards a lower level. A symbol at the input of the rectifier can determine a specific output voltage level in the capacitor, referred to as the symbol's steady state. For this to be achieved, it is required to have a constant amplitude for a specific time, which depends on the actual components of the circuit (capacitance, resistances). As such, at higher symbol rates, the capacitor may not reach steady state and the sequence of symbols will determine the capacitor output levels.

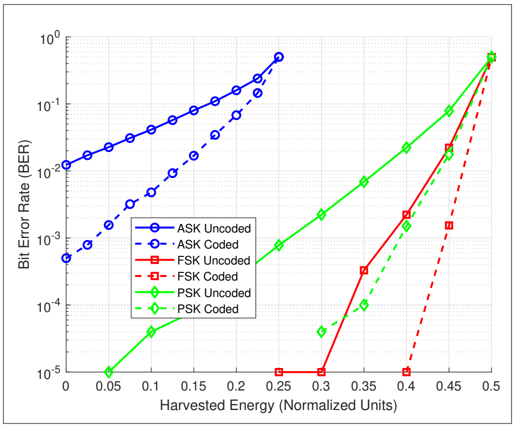
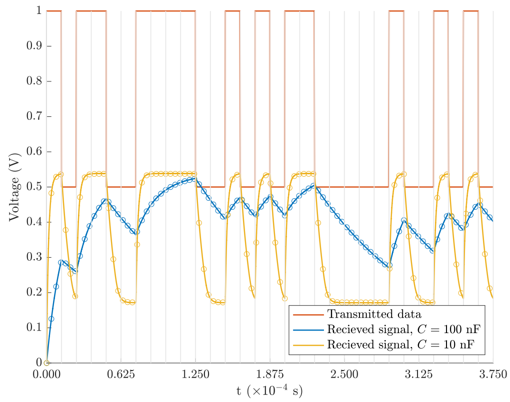


FIGURE 3. BER vs. normalized harvested energy for ASK, FSK, and PSK, comparing uncoded and repetition-coded schemes at E_b/N_0 = 10 dB.

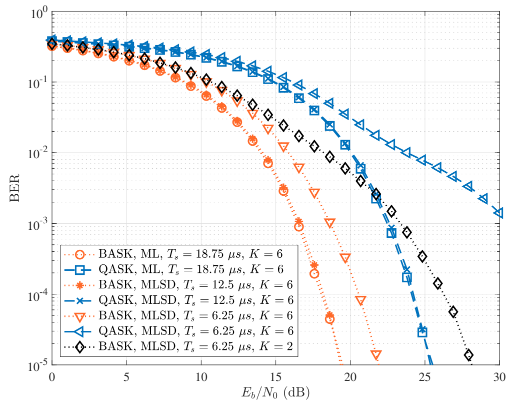
The rectifier's output can be sampled according to the symbol's period and a suitable detector can be employed for the symbols' detection. Moreover, based on the circuit characteristics, if the symbol period is long enough, the symbols can be accurately sampled at their corresponding steady state values and detected through a symbol-by-symbol maximum likelihood (ML) detection. Conversely, if the symbol period is small, the input ASK symbols will not drive the capacitor to their corresponding steady states. As a result, the symbols are sampled during the charging or f discharging periods of the capacitor at different voltage levels. An example is depicted in Fig. 4a, where the input of two (or more) consecutive symbols of the same voltage amplitude charge/discharge the capacitor at different levels and thus their sampled outputs are distinct. Note that, the transitions between these periods depend on the circuit's components. In particular, these components affect the time needed to reach the steady state, define the charging/discharging periods, and subsequently determine the memory effects. This is clearly depicted in Fig. 4a, where the impact of memory at sampling instances is more severe with a larger capacitor. In this case, a symbol-by-symbol ML detection can be applied as long as the sampled values of distinct symbols are fluctuating over non-overlapping ranges; in other words, a decision rule can be formed based on these ranges. On the other hand, higher data rates that result into overlapping ranges for distinct symbols, imply the existence of inter-symbol interference which makes the symbol-by-symbol ML detection inefficient. A more appropriate approach is the use of an ML sequence detector (MLSD) in which the detector makes decisions on the symbols in a time window, which corresponds to a sequence of voltage transitions of the capacitor [15]; as expected, performance improves with the length K, of the sequence. This is also revealed in Fig. 4b, where the BER for both ML and MLSD is shown for binary and quadrature ASK (BASK, QASK) modulations. Observe that, for higher order modulations, the impact of memory is more critical due to the smaller Euclidean distances between the symbols. Similarly, for higher data rates the charging/discharging time periods are restricted due to the smaller symbol

A symbol at the input of the rectifier can determine a specific output voltage level in the capacitor, referred to as the symbol's steady state.

High attenuation at large frequency shifts enables non-coherent decoding (suited to low power decoding at lower data rates and higher BER), while low attenuation at small frequency shifts supports coherent decoding (suited to higher data rates and better BER).



(a) Output voltage with ADS (markers) and analysis (lines).



(b) BER over additive white Gaussian noise.

FIGURE 4. Memory effect (a) and performance evaluation (b) of the integrated receiver; Unless otherwise stated: f = 800 MHz, T_s = 12.5μ s, C = 10 nF, R_L = 1 $k\,\Omega$.

period T_s. As a result, the application of MLSD is necessary in these cases to combat the increased intersymbol interference.

The authors of [15] analyzed the memory induced by the capacitor in the case of high data-rate (short symbol time). To keep the derivation tractable, they used a simple *linear* piece-wise model for the diode and derived a closed form expression of the channel transition function relating symbols at the input and output of the detector in the case of a single sinusoid input signal and amplitude modulation. They did this by solving the underlying differential equation dictating the circuit behavior, including non-linearities. Note that the piece-wise model proposes two linear forward-biased and reverse-biased diode characterisation — giving two linear differential equations. They show that the numerical evaluation of their analytical expressions almost match those of the ADS circuit software output.

Information Transfer Exploiting Non-Linearity: FSK

We now look at FSK modulation rather than ASK modulation through the rectified-based unified receiver architectures. Adapting FSK modulation for SWIPT applications can further simplify the hardware to the waveform-based LPF of Fig. 2b by utilizing more creativity in the waveform and receiver processing design, resulting in energy harvesting efficiency and downlink signal quality. The rectifier can be used beyond an envelope detector as done for ASK modulation: by designing our transmit waveforms to be multi-sine signals, the rectifier may be used as a downconversion device that yields baseband frequency and phase information that depends on the frequency difference Δf between multiple sines.

In [14], a three-tone FSK signal was introduced with a frequency spacing Δf between the tones. The side tones were selected to have equal amplitude and to be proportional to the amplitude of the central tone. This approach, known as Biased-FSK modulation, linearizes the envelope signal in WIT while maintaining the power conversion efficiency of WPT as in equal-amplitude multitone FSK. In [14], it is shown that the rectifier's frequency-dependent transfer function can be exploited to reduce the energy requirements at the node through selective attenuation strategies. By designing the frequency spacing and LPF design in the rectifier of Fig. 2b, we can control the attenuation level of the receiver. High attenuation at large frequency shifts enables non-coherent decoding (suited to low power decoding at lower data rates and higher BER), while low attenuation at small frequency shifts supports coherent decoding (suited to higher data rates and better BER).

Encoder: Figure 5a illustrates the operation of the FSK schemes: binary data "001111100110101" is fed into the Biased-FSK modulator (1 + cos(2πΔft + ϕ_0)), as described in [14], to generate a continuous-phase FSK signal. The binary data is transmitted at a rate of 100 kbps, with the modulation frequency (Δf) alternating between 100 kHz for binary "1" and 200 kHz for binary "0." The modulated baseband signal is then up-converted to an RF frequency of 2.63 GHz. This up-converted signal, denoted as ($V_{\mathrm{in,d}}(t)$, is applied to the input of a diode. The diode, in conjunction with the LPF, down-converts $V_{\mathrm{in,d}}(t)$ from the RF domain back to baseband, generating the output signal $V_{\mathrm{out,d}}$. The $V_{\mathrm{out,d}}$ signal comprises a DC component of 0.12 V and a sinusoidal signal with peak-to-peak voltages of 0.278 V, alternating between the two frequencies of (Δf). The DC voltage can be utilized for energy harvesting, while the AC signal can be demodulated to retrieve the binary data.

Decoder: FSK demodulation can be achieved using either a coherent or non-coherent approach, each providing different trade-offs in terms of data rates, power consumption, and BER. Coherent detection requires phase synchronization with a reference signal, which, while more complex, offers greater robustness in noisy environments. Synchronization is achieved by cross-correlating the received signal ($V_{\mathrm{in,d}}(t)$ with a reference signal containing a Barker code. Subsequently, the synchronized received signal is detected by mixing with two cosine signals[1] at frequencies of (Δf) (100 kHz and 200 kHz). The non-linearity and memory effects in the received signal can degrade the accuracy of product detectors. The signal is then passed through LPFs to isolate the 100 kHz and 200 kHz components corresponding to "1" and "0." The filtered signals are compared against a threshold to determine the original binary data. The frequen-

[1] This does use a power-hungry mixer which may not be ideal for all ambient IoT devices, but we present it as a possibility if there is extra power available to be traded off for better rates and noise resilience than the non-coherent approach.

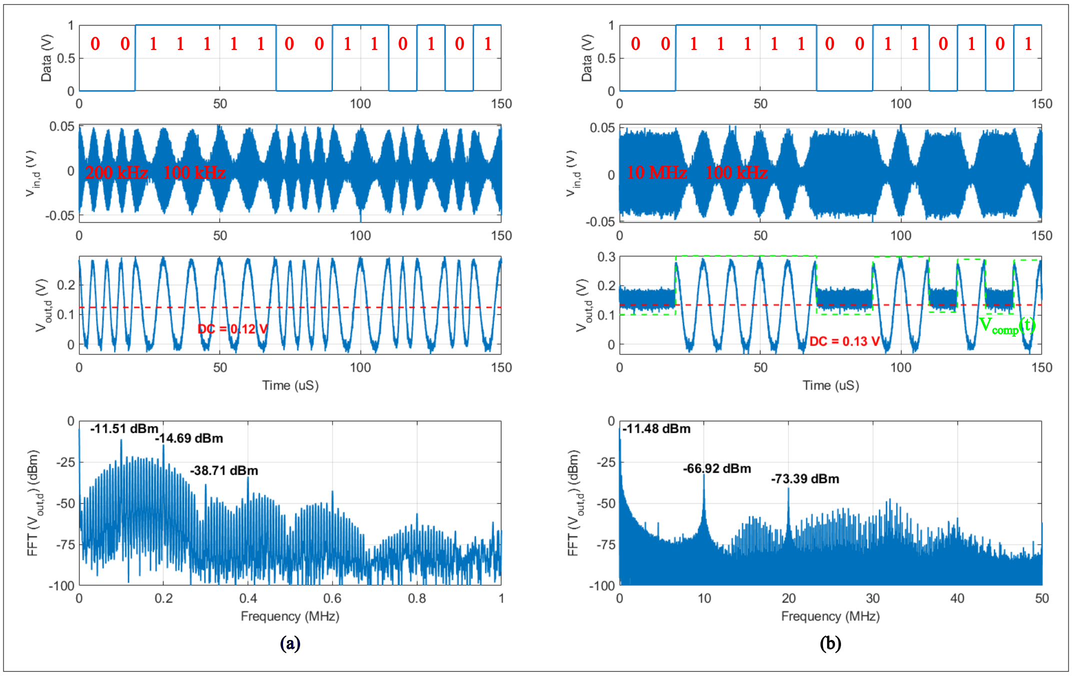


FIGURE 5. Measured biased FSK signals are processed by the rectifier. The upper plots the RF signal ($V_{in,d}(t)$) before the rectifier, and the lower plots show the baseband signal at the output of the rectifier ($V_{out,d}(t)$). Importantly, both output signals have a non-zero mean output voltage even when measured over low time periods, and independently of the information being transmitted, which is good for energy harvesting. The left figure illustrates a scenario with Δf_1 = 100 kHz and Δf_2 = 200 kHz, while the right scenario has a much larger Δf_2 = 10 MHz. The latter results in an attenuation of the amplitude of the high-frequency baseband signal, because of the LPF behaviour of the circuit. The second scenario gives a higher mean output voltage, and at the same times makes it possible to implement a simpler decoder, as the information can be deocded both from the frequency and amplitude of the baseband signal.

FSK demodulation can be achieved using either a coherent or non-coherent approach, each providing different trade-offs in terms of data rates, power consumption, and BER.

cy spectrum of the diode's output (FFT(($V_{out,d}$))) shows the received FSK signal at 100 kHz and 200 kHz and their harmonic distortions. The power levels of FSK signal at 100 kHz and 200 kHz are −11.51 dBm and −14.69 dBm, respectively.

Alternatively, for true low-power operation, one can use a non-coherent detector as follows. Non-coherent detection does not require phase synchronization, making it simpler and more suitable for low-complexity systems. The received FSK signal is passed through two band-pass filters, each tuned to one of the frequencies in (Δf). After filtering, the signals are fed into envelope detectors, which convert the filtered signals into a form that can be easily compared using what we call a "comparator based detector." The outputs from the envelope detectors are then compared against reference thresholds to determine the binary "0" or "1." While non-coherent detection is simpler and more robust to phase variations with faster signal acquisition, it generally offers lower accuracy, lower data rates, and poorer performance in noisy environments. The choice between coherent and non-coherent detection typically depends on the power constraints of the SWIPT system.

Figure 5b illustrates comparator-based non-coherent detection, where the modulation frequency shifts between 100 kHz and 10 MHz, leading to a decrease in signal amplitude from 0.370 V to 66 mV due to LPF attenuation at higher frequencies. Nonetheless, the output maintained an average voltage of 0.13 V. The frequency spectrum of the diode's output (FFT(($V_{out,d}$)) under these conditions shows power levels of −11.51 dBm at 100 kHz and −66.92 dBm at 10 MHz.

Power consumption analysis: the proposed SWIPT system minimizes power usage by eliminating high-consumption components such as amplifiers and mixers. Instead, it employs a low-power diode front end and comparators operating in the nanowatt-to-microwatt range, corresponding to a few hundred microjoules (μJ) of energy consumption per second. These components are well suited for FSK signals in the kHz-to-MHz range. While more complex demodulation methods (e.g., FFT-based processing) are possible, they rely on low-clock-rate digital logic, incurring minimal additional power consumption. In contrast, some commercial low-power receivers — such as the Nordic Semiconductor nRF series — draw at least 2 mA in receive mode, translating to roughly 6 mJ of energy per second at a 3 V supply, which is significantly higher than the proposed architecture's nanowatt-to-microwatt consumption.

Open Problems and Future Directions

As we can see, the proposed receiver architectures, combined with novel ASK and FSK signaling, offer a promising path toward truly unified wireless information and power transfer (WIT and WPT). They are especially relevant for IoT devices that rely on batteries, enabling simultaneous wireless power delivery and downlink data transfer. Yet, several open problems remain. We highlight some examples:

Accurate modeling of the non-linearities and memory effects in unified receivers: the diode's non-linearity — essential for all WPT circuits — both harvests power and brings amplitude, phase, or frequency information into baseband, potentially replacing mixers and local oscillators. Current approaches approximate diode behavior with Taylor expansions and consider only lower-order terms. To capture voltage-dependent junction capacitance, temperature changes, and parasitic elements, more comprehensive higher-order models may be needed. These could clarify how best to compensate for or exploit non-linearities using techniques like pre-distortion, equalization, or novel communication scheme designs. In some cases, solving underlying differential equations might yield deeper insights.

Fundamental limits and trade-offs: traditional research largely separates WIT and WPT, using linear waveforms optimized for energy harvesting and capacity. In contrast, unified receivers pass signals through a non-linear channel for both power extraction and data reception, demanding new methods to encode, decode, and evaluate capacity under constraints like input power and constellation size. Multi-sine models for ASK, FSK, and PSK can help uncover achievable data rates, while also highlighting new WPT-WIT trade-offs.

Circuit and communication co-design to optimize WPT and WIT trade-offs. Parameters such as circuit tuning, modulation constellations, and data rates directly affect WPT and WIT performance. While certain non-idealities (e.g., memory) may complicate reception, others (e.g., avoiding mixers) could reduce complexity. Bias-based schemes, such as biased-ASK and biased-FSK, have demonstrated promise, but a systematic design framework remains an open challenge.

Effects of fading. Wireless information and power transfer occurs over fading channels, which can exacerbate memory effects in non-linear circuits. Fading alters the signal's amplitude, phase, and harmonic content, potentially reducing power conversion efficiency and data integrity. Under severe multipath, rectifier non-linearities may introduce additional distortions, complicating demodulation. Additionally, device mobility changes link conditions, demanding adaptive strategies for optimal performance. Mitigation techniques such as adaptive biasing, parameter tuning, and machine learning-based decision-making could enhance system resilience under fading. Overall, addressing — or even leveraging — fading for improved data and power transfer remains an open challenge for future research.

WPT over terahertz (THz) bands. When looking towards designing WPT systems for operation over the THz band, it is important to note that conventional Schottky diodes exhibit poor energy efficiency performance. Recent research advocates that resonant tunnelling diodes (RTDs) are more suitable since they have much smaller transient times. However, RTD-based rectifiers exhibit non-monotonic input-output behavior where a higher transmit power does not always result in more harvested energy. This imposes the need for new, intelligent system designs which account for these circuit characteristics.

Conclusions

This work presents two concrete unified receiver architectures that enable harvesting of power and information from the same waveforms, without splitting, using the same analog hardware. The biased-ASK modulation can be seen as a non-linear envelope detector, and it has been shown that the non-linearity and memory effects introduced by this unified receiver can be mitigated effectively. To improve the trade-off between information and power transfer for this architecture, it is important to co-design the biased-ASK waveform well with the hardware, balancing distortion and efficiency before the signals go to the battery or information decoder. A second unified receiver shows another design opportunity, relying on intermodulation products and FSK, resulting in very different design trade-offs and degrees of freedom to optimize the power and information transfer. For example, the biased-FSK waveform introduced results in a constant power transfer, which might be desirable for some applications. In addition, combining the frequency selectivity of the rectifier's LPF, a very simple FSK decoder could be built. Although no detailed analysis of the two co-designs is given in this article, the two examples illustrate that the co-design of SWIPT waveforms and unified receivers possibly brings many more unexplored opportunities. We conclude this article with a list of open problems and future directions to emphasize this point.

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