Enabling Transiently-Powered Communication via Backscattering Energy State Information

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Abstract. The growing interest in ultra-low-power wireless sensors powered directly by energy harvesters has revealed one of the major drawbacks of such battery-less devices, which is engaging communication between nodes, without wasting energy due to unavailable receivers. Backscatter communication enables low-power communication by eliminating energy-hungry hardware components and can communicate if IoT devices are ready to receive even at zero-energy onboard. In this paper, we present the design of a backscatter radio mechanism that is used as a feedback channel to transmit the energy state information almost for free. Simulation results demonstrate the effectiveness of our approach designed according to the novel approach of "transient computing".

1 Introduction

Powering the Internet of Things using batteries brings about fundamental drawbacks such as high maintenance cost for replacing the batteries and limited miniaturization of the hardware [1]. Fortunately, with the growth of energy harvesting circuitries [2] and ultra-low-power microcontrollers [3], zero-power wireless communication mechanisms [4] and sensors [5], we are now able to build tiny sensing devices that can operate by relying only on ambient energy, without the need for batteries [5-9]. These batteryless devices enable a new application space such as body implants and wearables [10, 11], and even deployments in extreme locations [12].

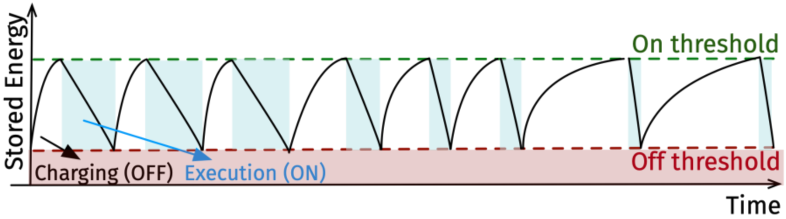


Fig. 1. The operation of the transiently-powered device is composed of interleaved charge-compute-die cycles, that lead to an intermittent execution.

The architecture of a typical batteryless device consists of an energy harvester block that stores the ambient energy from several sources (e.g., solar [2], [5], radio-frequency

(RF) [6], [13]) into an energy buffer, i.e., typically a capacitor. The stored energy in the capacitor is used to power the ultra-low-power microcontroller as well as other system components such as sensors and communication circuitry. Since the energy is harvested in marginal amounts, and the availability of the ambient energy sources is sporadic and stochastic, batteryless devices are powered transiently and in turn, operate intermittently utilizing charge-compute-die cycles. As depicted in Fig.1, if the energy stored in the capacitor is above an operation threshold, a batteryless device can compute, sense, and communicate. As the device consumes the energy stored in the capacitor and the energy level drops below a threshold value, the device dies due to a power failure. This leads to the loss of the volatile state of the device, i.e., the contents of the stack, program counter, registers, and memory. The device starts operating again when the capacitor is charged and the voltage level is above the operating threshold.

1.1 The state-of-the-art

The marginal energy budgets and intermittent operation of transiently-powered batteryless devices bring about several research challenges within the context of computation and communication.

Intermittent Computing. The intermittent operation of the transiently-powered devices prevents existing software designed for continuously-powered computers from being run correctly due to frequent power failures and loss of the computational state. In particular, power failures might hinder the forward progress of computation and lead to memory inconsistencies. The researchers proposed instrumenting existing programs with *checkpoints* to save the device state (e.g., registers, contents of the volatile memory) in non-volatile memory typically implemented as FRAM [14, 15], so that upon a power failure the device state can be restored from the latest checkpoint and the computation can be progressed with a consistent memory content [16–19]. Another approach is to rewrite existing programs using *task-based* programming models [20, 21], that offers an efficient alternative to checkpoints but require a non-trivial code transformation.

Zero-Power Communication. Backscatter communication, implemented by traditional RFID tags, enables almost *zero-power* wireless communication by eliminating the energy-hungry hardware components of active radios, e.g. power-hungry mixers that generate carrier waves. This makes it a perfect choice for batteryless devices considering their marginal energy budgets. In traditional backscatter, tags transmit by modulating the reflections of RF signals generated by a dedicated reader, that requires several orders of magnitude less energy than transmission with active radios [22]. Most of the traditional backscatter networks [23, 24] allow *one-way (unidirectional)* communication, i.e., only between a batteryless device and a dedicated master device (e.g., an RFID reader). This pushes the decoding of the received weak backscattered signal, which requires complex digital signal processing techniques, to the RFID reader side and simplifies the design, and reduces the energy requirements of the batteryless devices. Recent works demonstrated *bidirectional* communication among batteryless devices without the need for a dedicated RFID reader [4, 25–27].

This is enabled by decoding the received signal using only low-power analog operations such as envelope detectors that require components like diodes, capacitors, operational amplifiers and comparators.

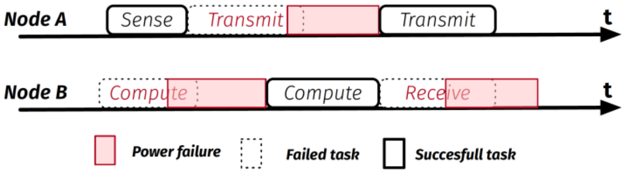


Fig. 2. Two transiently-powered devices miss packets during communication due to unpredictable power failures. A coordination mechanism is required to ensure packet delivery.

1.2 The Problem Statement and Contributions

Despite the aforementioned progress achieved in the intermittent computing and zero-power communication for batteryless devices, *intermittent communication* remains untouched. In prior work, the batteryless devices are powered continuously by dedicated energy sources (e.g., the carrier wave generators or RFID readers) during communication. Therefore, these studies overlooked the intermittent operation of batteryless devices. However, when sporadic energy sources power these devices, the transmission or reception of the packets can be interrupted due to arbitrary power failures (see Fig. 2). For successful communication, the stored energy on both sides of the channel should be sufficient to perform packet transmission and reception. Otherwise, the energy consumed for data transmission is lost, and the data transmission fails.

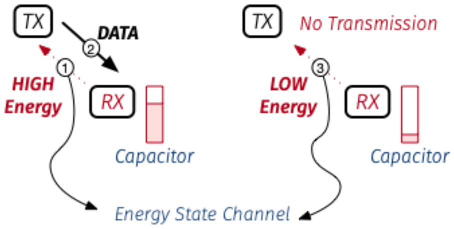


Fig. 3. To ensure packet delivery, the transmitter device (depicted as TX) receives the energy status of the potential receiver (depicted as RX) via the backscatter channel almost for free. If the receiver's energy status is high, the data transmission can be performed via an active radio; otherwise, the data transmission is postponed until the receiver has sufficient energy.

This requires a notion of coordination between the transmitter and receiver so that the transmitter device knows beforehand the receiver device's availability before transmitting its data. Therefore, the batteryless devices need to obtain state information from their neighbors to understand if they have sufficient energy and, in turn, if they will be able to receive the transmitted data. In this paper, we propose to use backscatter communication as a feedback channel to transmit the energy state information almost for free (see Fig. 3). Based on the backscatter radio design proposed in [27], we use a duty cycling protocol for mismatching the antenna to indicate different energy levels using an ultra low power, low frequency oscillator. By using the energy state, any transiently-powered transmitter device can start data transmission by means of an active radio. We believe that our work proposes the first attempt to introduce the fundamental hardware support and the building block of future transiently-powered networking protocols.

2 Systems Design

In this scenario, the challenge is to encode the information of the energy status using the backscatter radio channel and the lowest power-hungry components and circuits. The proposed system is developed upon the circuit design presented in [27]. The core of the system can be divided into two main sections: the receiver (RX) and the transmitter (TX). Besides, we propose to implement a low frequency, low power oscillator to modulate a backscatter signal to share the energy status information.

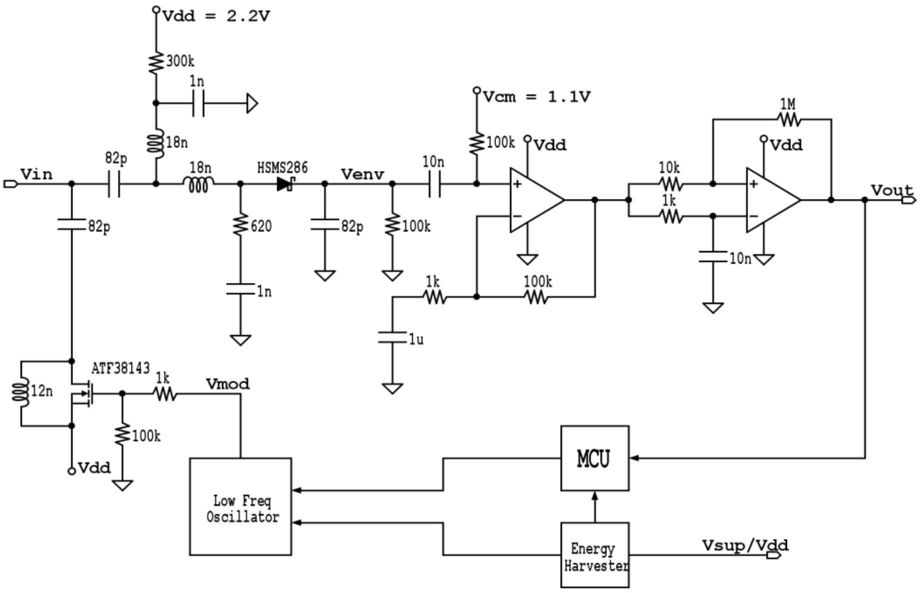


Fig. 4. Backscatter transceiver schematic derived from [27]. To notice the input RF signal (Vin), the output digital signal (Vout), the envelope detector output signal (Venv), and the oscillator modulation (Vmod). The energy harvester, the low-frequency oscillator, and the MCU are linked so that the low-frequency oscillator can encode the information about the energy status.

2.1 Receiver RX

The backscatter receiver aims to demodulate the signal coming from a neighbor backscatter node. For this purpose, an RF mixer circuit is usually designed to shift the backscatter signal in the baseband. Thanks to the accuracy of the demodulator, the RF mixer, and the reference RF oscillator, it is possible to achieve a complex modulation scheme. However, even though it is possible to reach a relatively high data-rate, all these circuits are power-hungry.

For simpler modulations and lower data-rate, such as ON-OFF keying, the system can be built upon a much simpler circuit. Indeed, the backscatter receiver presented in [27] is specially designed as a demodulator exploiting an envelope detector to operate the frequency shift in a clever, low power and cheap circuit. The main actor is a biased Schottky diode envelope detector which is finely matched with the RF input and the antenna (see Fig. 4).

The remaining circuitry aims to optimize the voltage swing of the low frequency demodulated signal using a high pass filtering amplifier stage and a comparator for the final digital output.

2.2 Transmitter TX

The backscatter transmitter produces a modulated RF signal by the reflection of the incident RF power, as discussed, allowing for zero-power communication for the end-nodes. The fundamental operation is a mismatch of the antenna exploiting RF switches and different match impedances.

As a proof of concept for a simple implementation backscatter transceiver, a single MOSFET can be utilized (see Fig. 4). The MOSFET is operated as a switch to achieve the required ON-OFF keying modulation. When the switch is open, the antenna is matched, and the envelope detector can operate the demodulation. When the switch is closed, the antenna is mismatched, and the circuit operates the reflection.

The modulation is given by the low power, low-frequency oscillator. Properly driving the MOSFET could require a relatively high peak current. A tradeoff is needed to comply with the low power oscillator output and a fast switching of the device. If needed, a driving buffer can be placed between the oscillator and the switch.

A second solution can be to use an analog switch (e.g., the ADG904 presented in [27]), which is easier to match with the RF circuit.

2.3 Low-frequency oscillator

In this paper, we propose to modulate the energy status information of a generic end-node. To achieve this result in the harsh condition discussed above, we must comply with low power requirements, especially in the charging phase (see Fig. 1). We propose to drive the RF switch with a low frequency, ultra-low power oscillator. The low-frequency oscillator can be tuned at a specific frequency identifying and differentiating multiple end-nodes. Moreover, we propose a duty cycling protocol for the oscillator to encode the information regarding the energy status and to ensure all the nodes to get in touch. The duty cycling period should be relatively long, several milliseconds.

For instance, while the node is in a charging transient and/or the energy is too low to compute specific tasks, such as receiving information from the neighboring nodes, the oscillator is placed at a fixed duty cycle e.g. 100% (i.e. the oscillator is always on). On the other hand, while the node is in an active transient the duty cycle can be easily changed by the MCU accordingly to the energy status and availability, for instance, to advise the neighboring nodes that the energy is close to the lower threshold and the communication could be interrupted.

This energy status information can be decoded on the receiver side when the end-node has enough energy to perform the computing action (discharge transient see Fig. 1). After that, it can decide to transmit the sensible and relevant information, avoiding the problem of packet loss mentioned above.

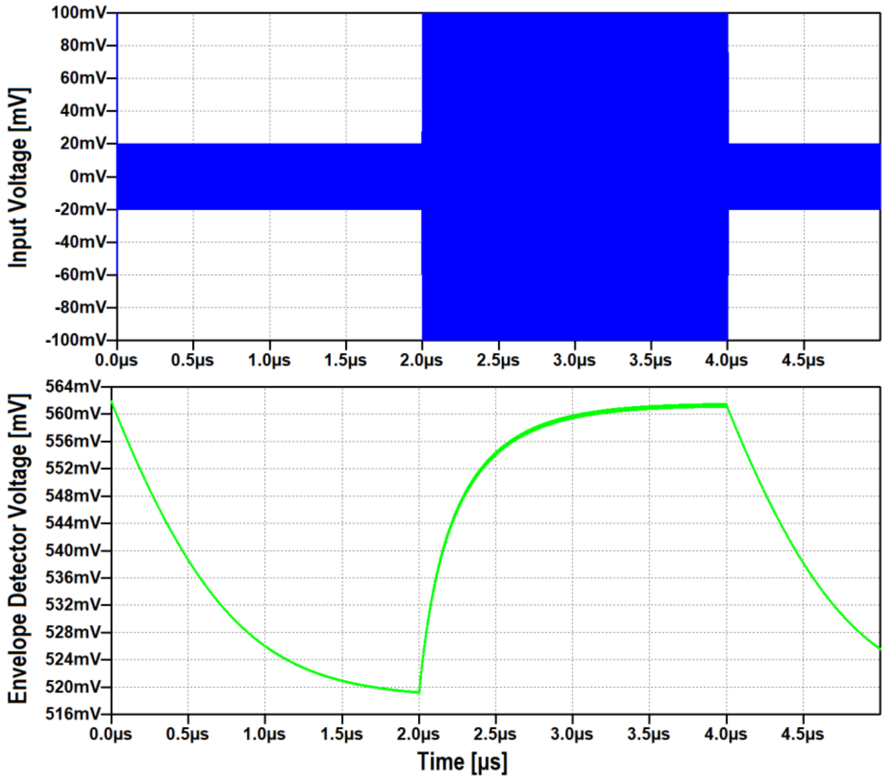
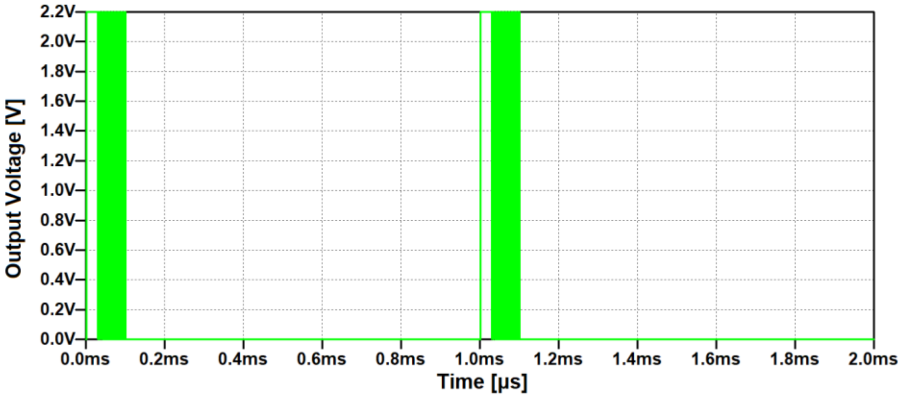


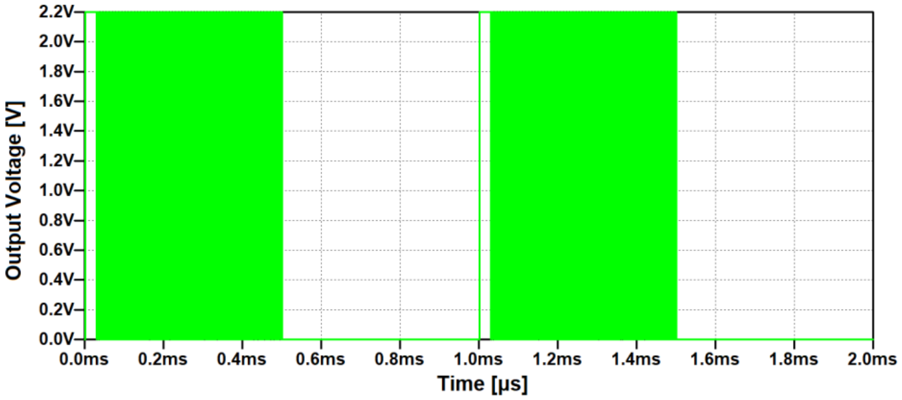
Fig. 5. Simulation results on the receiver (Input Voltage) and envelope detector (Envelope Detector Voltage) while a 250kHz ON-OFF keying waveform is applied at the circuit input (Vin in the schematic, see Fig. 3) and the MOSFET is always off.

3 Results

To validate our proposal, we carried out some simulations, using LTSpice, on the electronic circuit depicted in figure Fig. 4. A first simulation, while the transmitter is off and a modulated RF signal is applied at the input, is performed to show the behavior of the envelope detector output. Figure Fig. 5 presents the results of this simulation. The input RF signal is simulated with an amplitude varying between 20mV and 100mV, a carrier frequency of 868MHz, and a modulation frequency of 250kHz, while the output of the envelope detector is about 5mV. In the figure, it is visible that the signal needs to be amplified before the comparator and digitalization stage.



(a)



(b)

Fig. 6. Simulation results on the duty cycle protocol (a) 10% and (b) 50% of the period of 1ms. The input signal is a 250kHz ON-OFF keying modulated. The digital output voltage Vout contains information on the duty cycle and on the ON-OFF keying modulation frequency.

We performed a second simulation to show the behavior of the duty cycling protocol at the digital output of the receiver (Vout in the schematic, see Fig. 3). In Figure Fig. 6 (a), a 10% duty cycle is applied, while in Figure Fig. 6 (b), a duty cycle of 50% is used. Still, it is visible the ON-OFF keying modulation frequency, which is set to 250kHz. This should be recognized by the receiver to identify the specific modulation frequency of the transmitting node. Finally, it is visible that the ON-OFF keying modulation appears at the digital output only after a settling time of roughly 25µs.

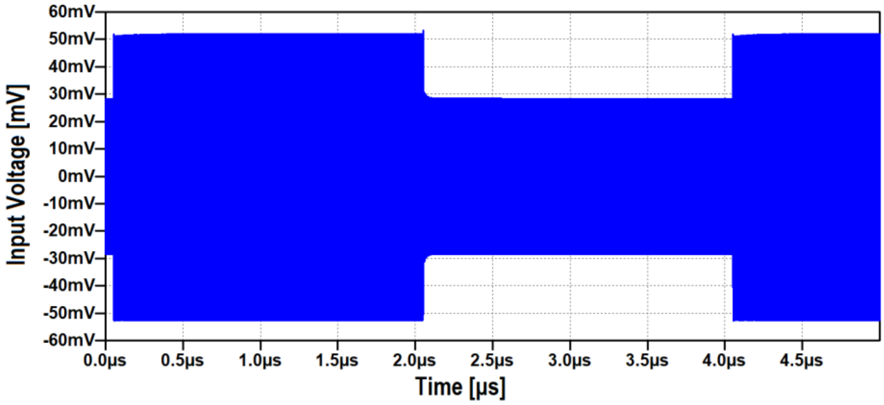


Fig. 7. Simulation results on the 250kHz ON-OFF keying modulation produced by the MOSFET. The RF source voltage is 100mV.

Figure Fig. 7 presents the results of the preliminary simulation of the transceiver behavior. We fixed the input RF source to 100mV and 868MHz, the ON-OFF keying modulation of the MOSFET at a frequency of 250kHz, and a duty cycle of 50% (the duty cycle of the ON-OFF keying modulation). In the figure, the input voltage of the circuit shows the mismatching operation of the switch. Indeed, while the switch is in the off state the voltage is a half of the RF source and about 50mV, while, when the switch is in the on state, the mismatch operation appears and the voltage decreases above 25mV, accordingly with matching rules.

4 Conclusions

We presented a backscatter communication circuit to improve the overall energy efficiency in a network of wireless sensors powered only by the ambient energy. The backscatter circuit is used mainly as a feedback channel to transmit the energy state information almost for free, while data communication is engaged using conventional low-power radios. Based on the proposed backscatter radio design, we use different duty cycle levels for mismatching the antenna to indicate different energy levels using an ultra low power, low frequency oscillator. Simulation results demonstrate that the transmitters can always be updated about the availability of the receiving nodes.

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