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1.2 nW Neuromorphic Enhanced Wake-Up Radio

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Abstract—Low-cost devices with ultra-low power radio capabilities are a major challenge in smart devices, while a permanently-on receiver is required for smart communication. This paper proposes a wake-up radio with a neuromorphic pre-processing system both biased in weak inversion region. The system is able to receive a 2.4 GHz signal, demodulate it, and recognize bit patterns based on the spiking frequency of a neuron. Significant performance is obtained with 1.2 nW of total power consumption, which is at least three orders of magnitude less than the conventional RF envelope detectors. Further, spiking frequency responsiveness over input power suggests that the proposed system can distinguish different signals at 2.4 GHz. The proposed system achieves an energy efficiency of 1.2 pJ/bit with a minimum detectable signal of -27 dBm.

Index Terms—envelope detector, neuromorphic sensor, IoT devices, ultra-low power.

I. INTRODUCTION

The founding pillar of Internet of Things (IoT) concept is the availability of low-cost devices with ultra-low-power wireless communications capabilities [1]. A promising approach to dramatically reduce the power consumption is to use a permanently-on ultra-low-power receiver, a.k.a wake-up receiver (WuR). Whenever it detects a communication request, it wakes up the main radio of high performance from deep sleep to receive data. On-Off Keying (OOK) modulation is usually adopted with simple RF envelope detection to achieve low-power consumption. However, the minimum detectable signal by the receiver is limited by the quadratic nonlinearity of such detectors [2].

Furthermore, the approaching end of Moore’s law and the increasing power demands limit traditional computing, such as Von Neuman’s systems [3]. While Von Neuman architectures suffer from energetic and speed bottlenecks, neuromorphic systems come to achieve real-time performance and better power efficiency. In contrast to digital neuromorphic systems, analog solutions save significant power, thanks to their capability to faithfully mimic biological neural systems [4].

To explore the sensory processing in the brain, neuromorphic engineers have focused on mimicking the retina and cochlea [5]. However, a smart vision or audition in IoT requires an RF sensor system since IoT devices communicate through electromagnetic waves. With the increasing number of sensors and sensory systems in IoT, signal processing is becoming a problem due to the data complexity and the large number of devices. Thus, RF neuromorphic may drive a new generation of bio-inspired signal processing.

This paper aims to implement a novel RF architecture using neuromorphic sensing for IoT applications. The proposed method paves an innovative way for brain-inspired applications and hardware AI to explore new paradigms for neuromorphic sensors. This paper is organized as follows. Proposed system and transistor-level are described in Sec.II. Results of post-layout simulations are explored in Sec.III to demonstrate the spike-based signal processing. Finally, conclusions are drawn in Sec.IV.

II. PROPOSED RF NEUROMORPHIC SENSOR

The neuromorphic-enhanced WuR system level is illustrated in Fig. 1, while transistor-level description is available in Fig. 2. The proposed system is designed in the BiCMOS SiGe 55 nm technology from ST Microelectronics. It consists of a wake-up radio system with a neuromorphic pre-processing system (comprising a synapse and a neuron). The system detects the RF input signal (V_{RF}), demodulates it (V_{ED}), and converts it into an excitation current (I_{ex}) connected to an artificial fast-spiking neuron (FS eNeuron). The overall system can detect and identify bit patterns of a 2.4 GHz OOK-modulated signal. Moreover, the proposal can also observe the electromagnetic environment and seize important informations. In this case, it is able to recognize the RF input power based on the spiking frequency (f_{spike}) of eNeuron.

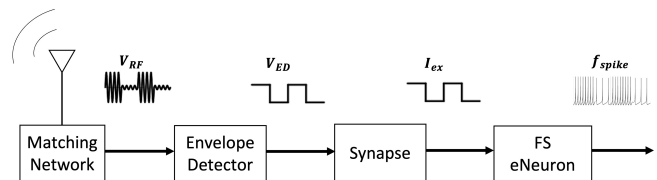


Fig. 1. Proposed RF neuromorphic sensor system composed of four stages: a matching network, an envelope detector, a synapse, and a fast-spiking eNeuron.

Figure 2(a) presents the envelope detector (M_{CG}) followed by a low-pass filter (C_{LP} , M_1). Excitation current I_{ex} is delivered by the synapse (Fig. 2(a)) to the FS eNeuron (Fig. 2(b)). A layout of the proposed RF neuromorphic sensor was designed in the BiCMOS SiGe 55 nm technology from ST Microelectronics. The proposed system occupies $9.8 \times 22 \mu\text{m}^2$ of silicon area and consumes 1.2 nW of power from a supply voltage ± 100 mV.

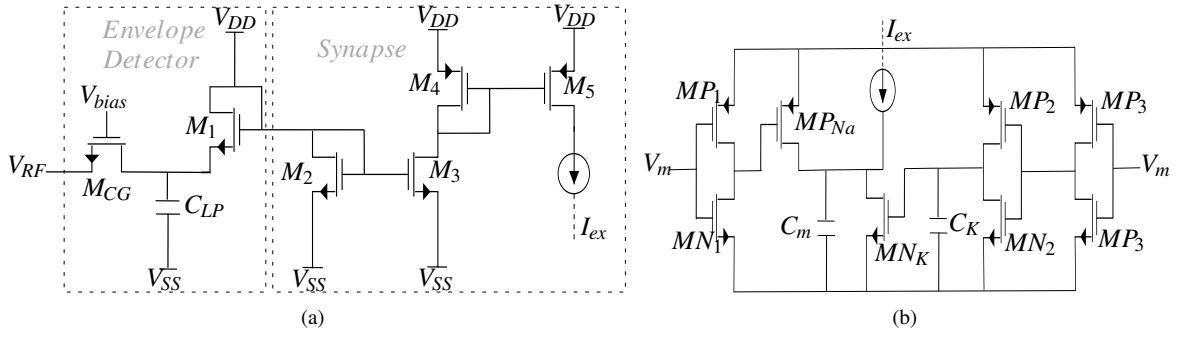


Fig. 2. Circuit level of the proposed system composed of a) an envelope detector and a synapse and b) an FS eNeuron ($V_{DD} = 100$ mV and $V_{SS} = -100$ mV).

III. RESULTS AND DISCUSSION

A 2.4 GHz OOK signal with different input powers (P_{RF} , in dBm) with 1 kbps data rate (DR) was connected to the system. The output at each stage of the system was observed for two bits levels '0' and '1'. When an FS eNeuron is excited by I_{ex} , its f_{spike} depends on the bit value and the input power. As the excitation current for bit '0' is the maximum current delivered by the system to the eNeuron ($I_{ex,bit0} = 540$ pA), its spiking frequency is considered the highest ($f_{spike,bit0} = 254$ kHz, constant for any P_{RF}). However, for bit '1', its spiking frequency varies proportionally with the excitation current in function of the input power, as shown in Fig. 3.

Assuming an uncertainty of 1 kHz spiking frequency between bit '0' (where $f_{spike,bit0} = 254$ kHz) and bit '1' in a window of 1 ms, the functionality of the system is validated until $P_{RF} = -27$ dBm where $f_{spike,bit1} = 253$ kHz. The system's performance is limited by the minimum detectable signal P_{mfs} of the envelope detector. Therefore, the system can distinguish signals at 2.4 GHz with input power levels between -27 dBm $< P_{RF} < 0$ dBm. The overall system consumes 1.2 nW for bit '0'. The power consumption P_{rms} stays at an average of 1.2 nW for bit '1' when P_{RF} is between -30 and -7 dBm.

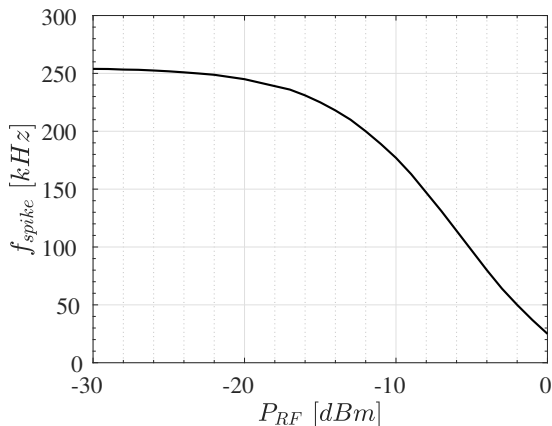


Fig. 3. Post-layout Simulations obtained for bit '1' for the spiking frequency f_{spike} in kHz in function of the input power P_{RF} .

State-of-the-art of envelope detector circuits target narrow-band matching for low-noise circuitry, which leads to a low $P_{mfs} \approx -50$ dBm for high DR [2]. Besides, a low P_{mfs} is demonstrated in spent of μ W-range power consumption. Proposed neuromorphic sensor system achieves a $P_{mfs} = -27$ dBm for only 1.2 nW of total power consumption. The system presents a remarkable improvement in energy efficiency ($E_{eff} = 1.2$ fJ/bit) due to the neuromorphic enhancement.

It can also be noticed that the spiking detection was evaluated for one bit in an observation window of 1 ms and for a DR = 1 kbps. If a higher DR is chosen, one may reduce the observation window to 0.1 ms (DR = 10 kbps) or 0.01 ms (DR = 100 kbps) with no power consumption drawback. It is not the case in the state-of-the-art where a low P_{rms} and an interesting P_{mfs} are achieved but only for a low DR [6].

IV. CONCLUSION

RF neuromorphic sensor system remains a challenging issue for smart IoT devices. This paper proposed a neuromorphic enhanced wake-up radio as an innovative way for brain-inspired applications. It can identify bit patterns of a 2.4 GHz OOK-modulated signal and seize important information from electromagnetic environment. Thus, the system is able to distinguish different input powers based on the spiking frequency of the neuron. It occupies $9.8 \times 22 \mu\text{m}^2$ of silicon core area and consumes only 1.2 nW of power from a supply voltage ± 100 mV. Lastly, the system achieves a significant energy efficiency of 1.2 pJ/bit with a minimum detectable signal of -27 dBm.

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