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Ultra-Low-Power IoT Communications: A novel address decoding approach for wake-up receivers

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***Abstract*—Providing energy-efficient Internet of Things (IoT) connectivity has attracted significant attention in fifth-generation (5G) wireless networks and beyond. A potential solution for realizing a long-lasting network of IoT devices is to equip each IoT device with a wake-up receiver (WuR) to have always-accessible devices instead of always-on devices. WuRs typically comprise a radio frequency demodulator, sequence decoder, and digital address decoder and are provided with a unique authentication address in the network. Although the literature on efficient demodulators is mature, it lacks research on fast, low-power, and reliable address decoders. As this module continuously monitors the received ambient energy for potential paging of the device, its contribution to WuR's power consumption is crucial. Motivated by this need, a low-power, reliable address decoder is developed in this paper. We further investigate the integration of WuR in low-power uplink/downlink communications and, using system-level energy analysis; we characterize operation regions in which WuR can contribute significantly to energy saving. The device-level energy analysis confirms the superior performance of our decoder. The results show that the proposed decoder significantly outperforms the state-of-the-art with power consumption of** 60 **nW, at cost of compromising negligible increase in decoding delay.**

***Index Terms*—5G/6G, IoT, wake-up receiver, low-power electronics, battery lifetime.**

I. Introduction

The Internet of Things (IoT) use cases, such as massive machine-type communications (mMTC) and ultra-reliable low-latency communications (URLLC), are one of the key drivers of fifth-generation (5G) wireless networks and beyond (6G) [1, 2]. A full realization of IoT can make substantial changes the life quality by providing an intelligent network covering every object in the daily life, such as in agriculture, surveillance, health care, body implants, home automation, etc [3, 4]. Each IoT node is typically equipped with sensors, microcontrollers, wireless transceivers, and energy sources such as batteries. The principal objective of most reporting IoT devices is to observe their surroundings and report/act upon their gatherings. Since most IoT devices are battery-powered, and once deployed, they are expected to live a long time without human intervention, battery lifetime has always been a key concern of IoT-enabled networks [5]. Hence, the IoT traffic demands support for low-energy consumption.

A. Energy-Efficient Cellular IoT

During the evolution of mobile networks towards 5G and beyond, the energy efficiency of large-scale IoT communications have been improved significantly [5–7]. The implemented methods and solutions to realize the energy-efficient IoT communications are summarized in [8, 9]. As per literature, these solutions can be categorized into evolutionary and revolutionary solutions [10]. The evolution began from LTE Release 12 by supporting low-cost communications over dedicated resources followed by in Release 13 [11] where LTE-MTC (LTE-M) and narrow-band IoT (NB-IoT) systems were introduced. NB-IoT is known as a revolutionary solution and reference signals and random access happen in time instead of frequency [7, 12]. Since in these systems the link budget is improved, the required energy to transmit a bit is reduced [13–15]. However, the access procedures requires listening to the control channel and exchanging signal for random access, synchronization, and resource reservation [6, 15], resulting in a challenge to realize the long-lasting battery limited devices activities [14, 16]. As per the state-of-the-art, extensive efforts are made to improve the energy efficiency of IoT devices such as discontinuous reception (DRX) [17], power-saving mode (PSM) [18], lightweight communications protocols [19, 20], low-power radio transceivers [19, 21], idle listening [22], and duty cycling [20, 23]. These methods imply an inherent trade-off between reachability and energy saving of the devices [24]. Motivated by addressing this challenge, the energy/reachability trade-off can be broken by leveraging device hibernation, and wake-up receivers (WuR) [24].

B. The WuR Approach

In WuR approach, the device is in hibernation mode unless it is paged by the base station (BS) or has a message to exchange. Since the battery is entirely intercepted as it is hibernating [25], no power is consumed except for monitoring whether the device is paged. To page a device, the network broadcasts a wake-up signal, including the device's unique address, to all devices. The device is equipped with an auxiliary WuR–consuming much less power than the primary device [26]–to receive and decode every wake-up signal and prompt the device if required [22, 27]. As a result, the power consumption of WuR lies in the μW domain, whereas the IoT device may consume several milliwatts [28, 29]. Therefore, reliable self-sufficient energy management is indispensable for achieving an eligible WuR capable of operating indefinitely without compromising the quality of service (QoS) [19]. A WuR contains a radio frequency (RF) receiver, a demodulator, a low noise baseband amplifier, and a digital address decoding unit. In this regard, ultra-low-power, noise-robust address decoders are presented to enhance WuR's power efficiency. For such ultra-low-power devices, harvesting energy from the environment