An IEEE 802.11-enabled Wake-up Radio System: Design and Performance Evaluation

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Today, the vast majority of personal communication devices, such as laptops and smartphones, and logically Wi-Fi Access Points (APs), feature IEEE 802.11 chipsets. In turn, Wake-up Radio (WuR) systems are used to reduce the significant energy waste that wireless devices cause during their idle communication mode. In this letter, we introduce a novel WuR system that enables any IEEE 802.11-enabled device to be used as a WuR transmitter (WuTx) without requiring any hardware modification. The corresponding developed WuR receiver (WuRx) achieves a remarkably low power consumption of 10.8 μW and operates in the Wi-Fi 2.4GHz band. By means of thorough physical tests, we show that the proposed IEEE 802.11-based WuR system enables important energy-savings.

Introduction: As the sizes and the densities of wireless networks increase, energy-efficient communication becomes more crucial to achieve sustainability and scalability of these networks. Nowadays, a promising energy-saving approach for wireless communications is Wake-up Radio (WuR). In WuR systems, a wake-up radio receiver (WuRx) is attached to or implemented in a wireless device, and allows the device to remain asleep in a very low or no-power state until a communication is destined to the device. The device can be remotely activated by a wake-up radio transmitter (WuTx) sending a wake-up call (WuC) signal intended for the WuRx of the targeted device. The activated node then goes into full-power state, performs its function and returns to sleep.

This letter proposes a novel WuR system that enables any IEEE 802.11-enabled device to be used as a WuTx without requiring any hardware modification. The accompanying low-cost and ultra-low-power WuRx hardware that can be attached to any device (personal communication devices, sensors, actuators, etc.) for its remote wake-up is also presented.

Albeit there are WuR solutions proposed for Wireless Sensor Networks [1], only the proposal in [2] contemplates the use of an IEEE 802.11 transceiver as WuTx. The work in [2] employs Frame Length Modulation (FLM) to map different frame durations to WuC addresses. However, this design requires a sensitivity of up to -93 dBm. Such high value entails employing active circuit components such as signal amplifiers, and thus, increasing the WuRx power consumption up to 30 mW. A mW order of magnitude is not acceptable for state-of-the-art WuRx designs.

Wake on Wireless LAN (WoWLAN) by Intel [3] represents a software-based approach that allows the processor to be put in sleep mode, while keeping only the IEEE 802.11 interface active. Events such as receiving a special magic-packet or being disconnected from an access point (AP) provoke the interface to wake up the system. However, an IEEE 802.11 Network Interface Card (NIC) consumes around 500 mW when receiving.

Employing the Clear Channel Assessment (CCA) capability of an IEEE 802.15.4 sensor node as a low-power mechanism to detect 2.4 GHz signals has been proposed in [4]. However, the performance of such approach is limited since the receiver's sensitivity is degraded by 6 dB due to the different bandwidth used by the IEEE 802.11 WuC (20 MHz) and the CC2420-based IEEE 802.15.4 receiver (5 MHz). In addition, this mechanism does not support WuC addressing, which is crucial to prevent the energy waste caused by the overhearing, i.e., by receiving the communication intended for other devices.

IEEE 802.11-enabled WuR System: This section provides the design details of the WuRx and WuTx for the proposed IEEE 802.11-based WuR system.

IEEE 802.11-enabled WuRx Design

The WuRx for the IEEE 802.11-enabled WuR system is based on AS3933 chip [5] from Austria Microsystems. This integrated circuit is actually a 15 kHz to 150 kHz WuRx commonly used in short-range applications. Initial tests performed with the WuTx provided by the manufacturer, which transmits up to 1 W, showed a limited wake-up range of up to 5 m. The AS3933 WuRx chip features a kHz-level high-performance envelope detector and an address correlator, as well as the means to set a WuRx address through its Serial Peripheral Interface (SPI), while only requiring 8.1 μW for WuRx operation.

Our IEEE 802.11-enabled WuRx, shown in Fig. 1, is built by preceding an AS3933 integrated circuit with a 2.4 GHz antenna and the corresponding impedance matching stage. This shifts the WuR system's communication from magnetic to electric coupling and enables the system to use efficient microwave antennas, which require less transmission power and provide longer operational ranges. In Fig. 1, after impedance matching, the RF received signal is down-converted from the GHz to the kHz level by means of envelope detection (ED) and Low-Pass Filtered (LPF). The L-network consists of one inductance and two capacitors to match the 50 Ω output impedance of the antenna to the input impedance of the Schottky diode. Next, a secondary, internal envelope detector in the AS3933 extracts the node address modulated in the WuC. The data slicer block delimits data according to the bit-rate of the WuR system. If the final address correlator detects the device's address, an Interrupt ReQuest (IRQ) signal is generated to wake up the device's MicroController Unit (MCU) from its sleep mode. Our WuRx features a sensitivity of -52 dBm.

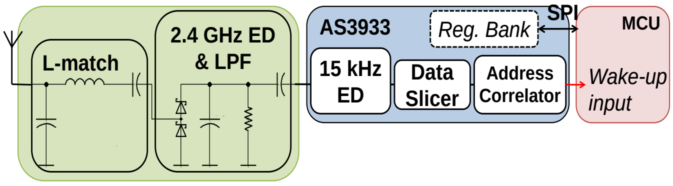

Fig. 1. IEEE 802.11-enabled WuRx design.

Note that, instead of using AS3933, the proposed IEEE 802.11-enabled WuRx can be implemented by means of any address correlator, that consists in a shift register and a parallel comparator.

The Wake-up Call (WuC) format

The WuC signal is modulated by On-Off Keying (OOK) and follows the format required by the AS3933 chip in our WuRx board. An initial carrier burst triggers the WuC-decoding procedure. Afterwards, a 14-bit `1010..` preamble delimits the bit-length at the WuRx. Finally, the 16-bit address of the intended WuRx is transmitted.

IEEE 802.11 WuTx

To generate the WuC format, we program a Linux user-level application implementing a so-called SubCarrier Modulation (SCM) strategy [6]. In SCM, as shown in Fig. 2, a high frequency signal is used to emulate a modulated lower frequency signal. In our case, the SCM strategy is employed by the use of 2.4 GHz Wi-Fi signals emulating the 15 kHz signals expected by the WuRx. The application in the WuTx employs Link Layer IEEE 802.11 broadcast data frames (only including preamble and MAC headers) to generate the desired signal. Unlike unicast frames, broadcast transmissions are not followed by an acknowledgment frame and, therefore, are suitable for the generation of a train of consecutive minimum-length frames. These broadcast frames are separated by 28 μs, which corresponds to the standard DCF Inter-Frame Space interval (DIFS). The time duration of the broadcast frames is 34 μs in the fastest IEEE 802.11g Modulation and Coding Scheme (MCS) of 54 Mbps. Note that broadcast frames must be sent at a basic rate, and that 54 Mbps is not usually included in the basic rate set. However, such basic rate set can be easily configured to include any standard rate. Alternating IEEE 802.11 frames and DIFS silence periods effectively emulates a carrier frequency of $(34\,\mu s + 28\,\mu s)^{-1} = 16.1$ kHz, the repetition of which is the basis for the generation of the binary '1' of the OOK scheme employed for WuCs. In turn, binary '0' is generated by means of a prolonged silence period.

For the generation of a neat train of IEEE 802.11 frames for the WuC, the MadWifi open source NIC driver is modified to disable the CCA mechanism to both prevent interfering sources in the channel from deferring the transmission of IEEE 802.11 frames, and also to be able to keep the 16.1 kHz frequency. Thus, as long as the NIC driver's source code is available, our development can be ported to any device that includes an

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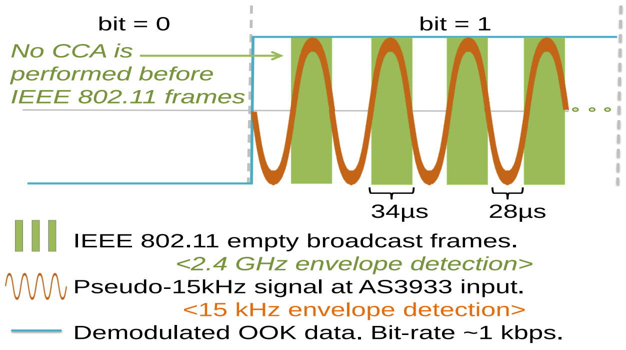

Fig. 2. SubCarrier Modulation: shaping a 15 kHz signal by 2.4 GHz.

IEEE 802.11-compliant transceiver such as tablets, smartphones, laptops or Wi-Fi APs, enabling their use as WuTx.

Performance Evaluation of the WuR system: In order to evaluate the performance of our IEEE 802.11-enabled WuR system, the latency, the power consumption and the operational range it features are measured.

Latency Analysis

For WuR systems, the total time required to wake up a node, i.e., the wake-up delay, is a distinctive metric. For the proposed IEEE 802.11-enabled WuR system, the duration of a WuC is measured to be 44.7 ms, as shown in Fig. 3. WuR communications typically feature ms-level latency values due to their low bit-rates; for example, a high-performance WuRx proposed in [7] features WuC duration of 40 ms to 110 ms. The WuC in Fig. 3 matches the WuC format required by the AS3933 previously described.

The data slicer in the WuRx is configured to operate at 0.9 kbps, which corresponds to a single-bit duration of 1.12 ms. After WuC detection, the WuRx generates a wake-up IRQ after a delay of 1.17 ms due to factors such as RF amplification settling time (250 μs) and the time required for a bit to enter the data slicer. Hence, a total wake-up latency of 45.87 ms (44.7 ms + 1.17 ms) is measured for a single wake-up event, a value which is among the best in the literature.

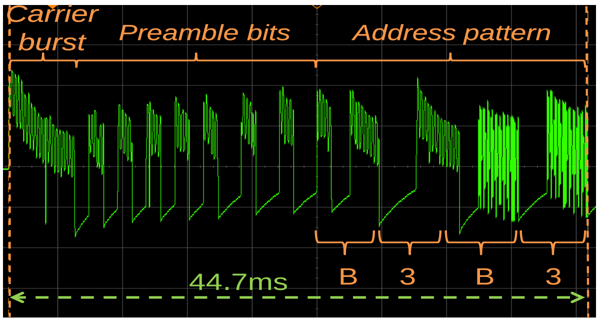

Fig. 3. A 2.4 GHz WuC containing a node address of 0xB3B3.

Power Consumption Analysis

The WuRx board is powered by a single CR2032 3V cell button battery. As MCU, a low-power MSP430F2350 from Texas Instruments is deployed in the WuRx board, which requires as low as 0.3 μW in its lowest power mode, i.e., in Low-Power Mode 4 (LPM4). The measurements showed that the total power consumed by the WuRx board is 10.8 μW in sleep mode and 24 μW in reception mode, i.e., during WuC decoding. Given a common capacity of 225 mAh for CR2032 batteries, our proposed WuRx board features between 3 and 7 years of lifetime, depending on how frequently the WuCs are generated, a significant battery lifetime for applications powered by low-profile batteries such as cell coin ones.

We consider an office environment where devices are in active state for 8 hours and in inactive state for 16 hours. Deploying WuRx allows setting devices in sleep state during their long inactive times, while still enabling data communication addressed to them. The DELL Optiplex 9010 desktop computer features 66 W, and 1 W in active and sleep states, respectively. The active power consumption values of two commercial wireless AP platforms, the Cisco WRT160N and Laguna GW2380, are measured to be 4.02 W and 1.9 W. The latter AP features a sleep mode, where the power consumption is 1 μW. Using this as a reference value for both APs, and in such an office environment scenario, attaching the proposed WuRx allows significant power savings per device of 64.32 Wh/day, 30.4 Wh/day and 320 Wh/day for the Cisco WRT160N, Laguna GW2380, and the DELL Optiplex 9010, respectively.

Operational Range Analysis

The wake-up range analysis is done with a test setup, where an IEEE 802.11 workstation operating as WuTx and a WuRx are placed at a height of 1 m. In our evaluations, the WuTx, i.e., the IEEE 802.11 NIC, is configured to transmit at +18 dBm using a +2 dBi gain antenna. The WuRx is progressively displaced away from the WuTx in steps of 2 m. 10 WuCs are transmitted per second, up to a maximum number of 100 WuCs. Fig. 4 shows the measured average delay the WuRx to detect the first valid WuC, averaged over up to 5 repetitions for each test point, for one outdoor campus environment with high interference and one interference-free indoor environment. Since the 2.4 GHz band hosts many wireless technologies, WuC are susceptible to interference from surrounding transmissions, which delays the wake-up of the WuRx. Beyond 40 m, WuC detection by the WuRx is not consistent. Average delays are found to be 0.9 s and 2.3 s for indoor and outdoor scenarios, respectively, which are acceptable values for many applications.

Conclusions and Future Work: The WuR system presented in this letter comprises a WuRx consuming as low as 10.8 μW and a WuTx that can be implemented on any IEEE 802.11-enabled device, such as a smartphone or tablet PC, without any hardware modification. The WuR system is demonstrate to enable drastic energy savings for realistic use cases. As future work, we contemplate using IEEE 802.11n aggregated frames for faster WuCs and forging the Duration/ID field of IEEE 802.11 frames to prevent surrounding Wi-Fi transmissions from interfering ongoing WuC.

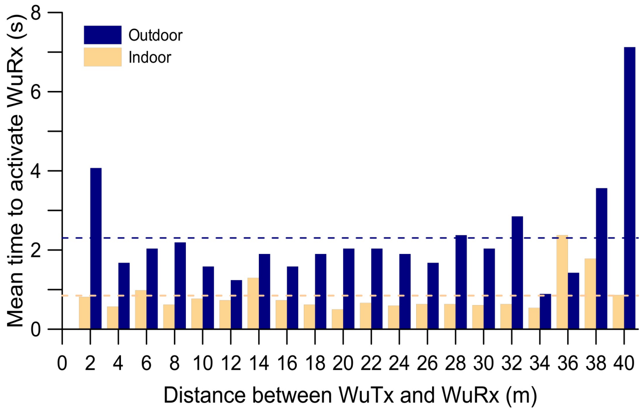

Fig. 4. Field operational ranges achieved by the proposed WuR system.

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