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Design and Implementation of a Wake-up Radio Receiver for Fast 250 kbps Bit Rate

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***Abstract*—Wake-up Radio (WuR) systems have appeared as a solution for reducing power consumption. As IEEE 802.11 is the preferred radio technology, IEEE 802.11 task group TGba focuses on the IEEE 802.11-based WuR standardization. We present an implementation of a Wake-up Receiver (WuRx), based on off-the-shelf components, using a microcontroller unit for decodification at the fastest bit rate of 250 kbps allowed by TGba. The proof-of-concept that has been developed, does not aim at presenting an optimized power consumption solution for WuRx, but at enabling a comparative evaluation for several reception cases based on latency and power utilization. The evaluation of the performance shows the WuRx robustness in presence of frame receptions different from the expected for WuR operation or addressed to other WuRx in the surrounding area. The paper also presents the convenience of implementing a mechanism for avoiding consecutive erroneous WuRx identification matchings within the same WuR procedure.**

***Index Terms*—Wake-up Radio, low-power, WLAN, IEEE 802.11, IEEE 802.11ba**

I. Introduction

The number of Internet of Things devices has increased in the last years. This kind of devices shows power consumption restrictions, as they are mainly powered by batteries or energy harvesting. Thus, it is necessary to use low-power equipments and reduce energy consumption. The main challenge is in reception, due to the fact that the reception instant is unknown in advance, being the receiver forced to be always-on. The solution commonly adopted by battery powered devices has been the so called duty cycle. Using this mechanism, the receiver goes to the sleep state, and wakes up periodically for the duty cycle that has been defined. This allows power reduction, though adding transmission delay, synchronization overhead and energy waste due to idle sensing and the use of low-precision clocks. More recently, the concept of Wake-up Radio (WuR) has appeared as an alternative to duty cycle [1]. Employing a WuR system, two radio interfaces per device are used. There is a primary transceiver for main data communication in the energy-saving state, and a secondary receiver for switching the primary transceiver from the energy-saving state to the active state. The secondary receiver consists of a low-power consumption receiver that is always-on. It is called Wake-up Receiver (WuRx) and wakes the primary transceiver up upon reception of a Wake-up Call (WuC) signal sent by a Wake-up Transmitter (WuTx) (Fig. 1). As for the WuTx, the standard radio transmitter of the node is used as WuTx in most of the WuR systems [2].

IEEE 802.11 is the radio technology preferred, with the highest adoption rate, and is used in almost all consumer

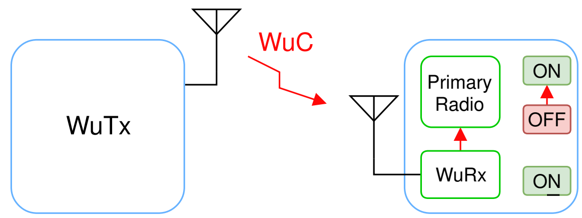

Fig. 1. WuR system.

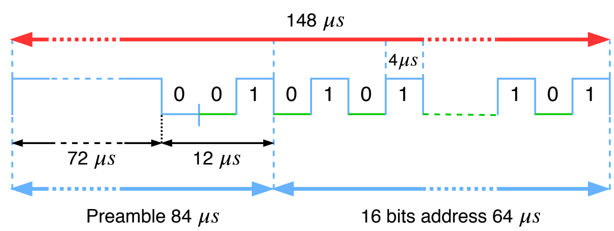

Fig. 2. Wake-up Call.

electronic devices. There have been several WuR systems proposals based on IEEE 802.11, and published in the literature. Legacy IEEE 802.11 PHY Protocol Data Units (PPDU) of different lengths are used in [3] for WuC generation and coding of WuRx address. A WuC using On–Off Keying (OOK) is presented in [4], stating that *on* periods are created by the transmission of subsequent legacy IEEE 802.11 broadcast PPDUs of minimum length, and *off* periods by silence intervals. These proposals have in common the usage of a WuC built of a set of legacy IEEE 802.11 PPDU transmissions, thus increasing the WuC duration and reducing the achievable bit rate. Since December 2016, IEEE 802.11 task group TGba is working on PHY and MAC specifications [5]. IEEE 802.11ba will define the IEEE 802.11 specification for WuR operation, with a high bit rate of 250 kbps, using a single PPDU for WuC transmission. This WuR PPDU consists of a preamble (enabling WuR frame transmissions to be sensed by any legacy IEEE 802.11a/g/n/ac device) and a payload field, in which OOK modulation with Manchester coding is being employed, with symbol duration of 4 μs for 250 kbps bit rate mode.With this in mind, a WuR system is proposed in [6], where the WuC is generated through a single IEEE 802.11 PPDU coded with an amplitude-based digital modulation exploiting the properties of OFDM PHY and achieving 250 kbps.

In this paper, we present an implementation of a WuRx module using off-the-shelf components with a microcontroller unit (MCU) for OOK modulation based WuC, decoding at the

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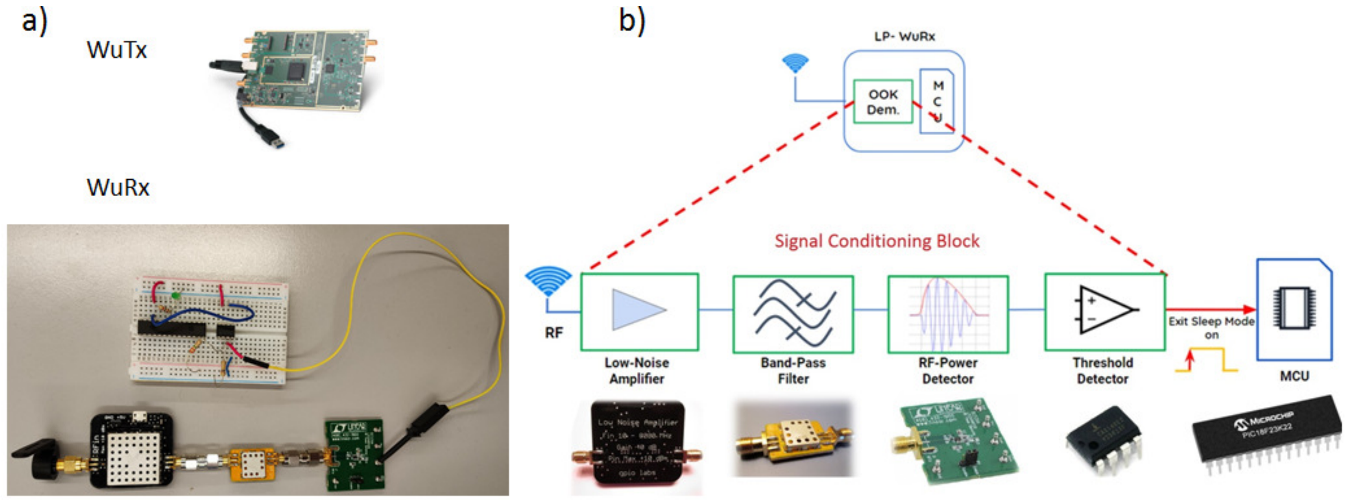

Fig. 3. a) Implemented testbed, b) WuRx implementation.

fastest bit rate of 250 kbps allowed by TGba (Section II). A proof-of-concept has been built including a WuC transmitter for WuRx performance evaluation (Section III). Both, latency and power consumption for the procedure of waking the primary interface up have been analyzed, and compared with the reception of WuC with incorrect preamble or addressed to a different WuRx device. The optimization of the power consumption of the WuRx is not the aim of this paper, but the possibility of implementing a WuRx using off-the-shelf components, capable of decoding correctly at a high bit rate of 250 kbps, and identifying incorrect preambles and WuC addressed to a different node. Finally, Section IV summarizes the conclusions of the paper.

II. WuRx frame decoding

In this section, we present the WuRx module implementation for WuC decoding through OOK modulation and the fastest bit rate of 250 kbps allowed by TGba (one OFDM symbol of 4 μs per encoded bit). The WuC, shown in Fig. 2, consists of one PPDU with preamble and payload field, being the later composed of OOK symbols with 4 μs of duration. The preamble consists of a long pulse of 72 μs and a short pulse of 4 μs, separated by an interpreamble space of 8 μs. The long pulse is determined according to the legacy short IEEE 802.11 preamble for compatibility reasons. The 8 μs interpreamble space is obtained by two symbols with bit value of *zero*, and the 4 μs pulse by one symbol with bit value of *one*, building a 12 μs sequence. The whole preamble sequence enables to distinguish between the WuC and legacy IEEE 802.11 PPDUs, and it is later justified in this section. Then, a Wake-up identifier (ID) of 16 encoded bits is included in the payload field, thus identifying the WuRx device to wake up. Fig. 3 shows the testbed with the WuTx (USRP B200 platform) and the WuRx. The WuRx implementation is based on off-the-shelf components. Our WuRx consists of a signal conditioning block and a MCU. The former is composed of a low-noise amplifier (LNA) amplifying the received signal (35 – 40 dB gain from 100 MHz to 8 GHz), followed by a band pass filter (BPF) for filtering the amplified signal in the 2.4 GHz band, and an off-the-shelf RF-Power detector (LTC5508 [7] with operating range of 300 MHz to 7 GHz) for converting the signal to a DC voltage. A threshold detector block is then included, the output of which is delivered to the interruption pin of the MCU. The MCU is in the sleep mode and exits it upon signal detection over a threshold through the interruption pin. Then, it decodes the WuC that has been received by detecting low and high input voltage levels for bit values of *zero* and *one*, respectively. Hence, the RF-Power detector is one of the main WuRx components, as it demodulates the WuC by converting the incoming signal to DC. An incoming RF signal of -24 dBm is converted to 250 mV at the RF-Power detector output. This value is used as threshold in the threshold detector block, to distinguish low and high signal values. The threshold detector block is a comparator, implemented with a typical operational amplifier circuit with CA3140 [8]. Based on incoming voltage levels from RF-Power detector, it provides at its output the low and high voltage values that are required to the interruption pin of the MCU. The bandwidth characteristics are not restrictive at this point, as the signal is now in baseband. Under these conditions, an operating range of 2 m for reliable WuC detection was obtained. Microchip PIC18LF23K22 [9] has been chosen as MCU, due to its low-power consumption features and fast wake-up time. This MCU enables the sleep mode, with minimum consumption (current of 34 nA at 1.8 V). In sleep mode, its CPU core is disabled, while maintaining active an interrupt channel able to wake the MCU up, and move quickly to the full active mode upon WuC detection. In Table I the main component parameters are shown.

The MCU needs to be fast enough in order to sample the input WuC signal as fast as 4 μs per symbol, i.e., 250 kbps. This MCU has eight clock frequencies, enabling to select a value between 31 kHz and 16 MHz. This provides a stable reference source without using any external crystal or clock circuit. Using the 16 MHz clock, the instruction cycle lasts 0.25 μs (4 clock cycles per instruction). After sampling each WuC bit, the MCU has to follow the Wake-up

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TABLE I
MAIN COMPONENT PARAMETERS.

Component	Parameters	
LNA	Gain[1]	31 dB
	Noise factor	2.8 dB
	Supply voltage	5 V
	Supply current[1]	200 mA
BPF	Center frequency	2.45 GHz
	Bandwidth[1]	150 MHz
	Insertion loss	2 dB
LTC5508	Supply voltage	4 V
	Active current	550 μA
	Standby current	2 μA
CA3140	Supply voltage	4 V
	Supply current[1]	2 mA
PIC18LF23K22	Supply voltage	3 V
	System clock	16 MHz
	Instruction clock	4 MHz
	Active current	3 mA
	Standby current	10 nA

[1] Value obtained experimentally.

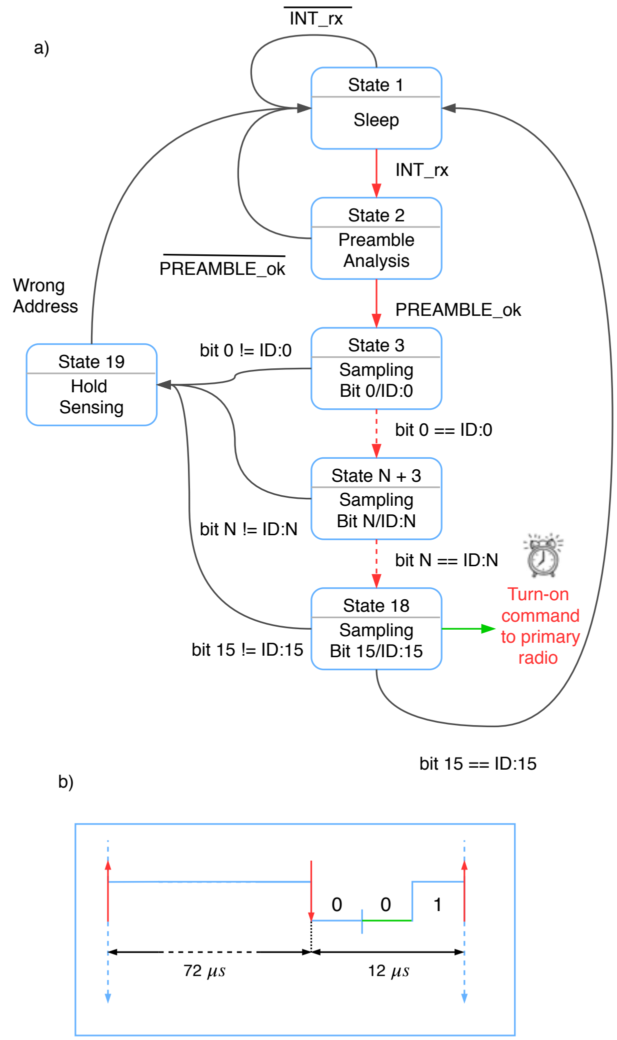

Fig. 4. a) State diagram for WuC processing, b) Preamble rising and falling symbol edges.

ID correlation instructions in order to check if the received WuC is addressed to the WuRx in hand. This has to be done without introducing synchronization fails. As a result of several tests, coding optimization techniques were required in order to sample correctly the input signal. The limited number of instruction cycles per received bit, made it impossible to implement both the sampling and Wake-up ID correlation logic by means of a loop covering the complete WuC bit sequence, and being synchronized with a hardware timer interruption at each bit period. In order to solve this issue, the bit sampling and Wake-up ID comparison routine were optimized using manual loop unrolling, which consists in converting the loop into a sequence of consecutive operations. Synchronization by means of the hardware timer interruption was substituted by a pre-calculated number of wait instructions (NOPs). The use of the 16 MHz clock is mandatory, being other clock frequencies unable to meet the requirements.

Fig. 4.a) shows the state diagram for WuC processing after a signal is detected by the interruption pin of the MCU. Initially, the MCU is in sleep state (State 1) and wakes up upon reception of a signal overpassing the reference threshold (2.4 V with V_{cc} of 3 V). When this happens, the interruption (INT_rx) is detected by the MCU, which starts processing the WuC signal, searching for a valid WuC preamble (State 2). The rising edge of the long pulse of 72 μs (Fig. 4.b)) makes the interruption that wakes the MCU up, being this pulse the shortest for the transition of the MCU from sleep to awake. Afterwards, the MCU has to sense the 12 μs sequence, which consists in the shortest sequence that serves for MCU synchronization using the falling and rising symbol edges highlighted in Fig. 4.b). Once the WuC preamble has been successfully received, the MCU goes into the Wake-up ID matching states (States 3 to 18), where one sample each 4 μs (OFDM symbol duration) is taken (using 16 MHz clock). If the reference threshold signal level is detected (over 2.4 V with V_{cc} of 3 V), it is decoded as a bit value of *one*. A low signal level (below 0.6 V with V_{cc} of 3 V) is decoded as a bit value of *zero*. This process is repeated 16 times, as the Wake-up ID for receiver identifier is composed of 16 bits. The Wake-up ID is not buffered, thus, if a non-matching bit is detected in one of the 16 Wake-up ID matching states, the WuRx assumes that the WuC is not addressed to it, and enters into the so-called Hold Sensing state (State 19). This state is characterized by a predefined waiting time before returning back to the sleep state (State 1), a procedure for avoiding consecutive erroneous Wake-up ID matchings within the same WuC reception. In case the complete Wake-up ID matches (State 18 is reached in Fig. 4.a)), the MCU sends a turn-on command in order to wake the host device (primary radio) up, and returns back to the sleep state (State 1) while waiting for the next WuC.

III. WuRx PERFORMANCE EVALUATION

To evaluate the performance of the WuRx that has been proposed, the WuTx has been built employing USRP B200 platform for WuC generation of Fig. 2. The WuC at USRP B200 output is shown in Fig. 5. Latency and power consumption for the procedure of waking the host device up

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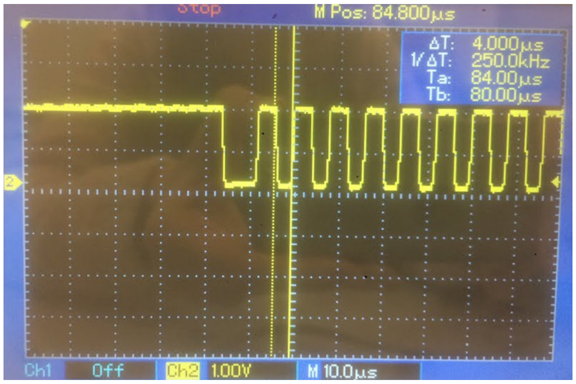

Fig. 5. WuC at USRP B200 output.

(primary radio) have been evaluated. This procedure includes the period between the WuC reception and the MCU sending a turn-on command for waking the host device up. Three cases have been considered for evaluation: 1) correct WuC reception, 2) incorrect preamble reception, 3) WuC addressed to a different node. If the preamble of the signal received is not the expected (case 2), it means that the signal does not correspond to a WuC. As a consequence, the MCU returns to the sleep state. For case 3, tests have been done forcing the first Wake-up ID bit to be incorrect. Table II shows the results for the three cases. As expected, less latency and power consumption are observed in case 2, as it only deals with the process of preamble processing, in which 163.8 μs and 793.90 μA are required, respectively, for the MCU to return to the sleep state. On the other hand, case 1 and case 3 show the same latency and similar power consumption values. Regards case 3, the MCU enters into the Hold Sensing state upon detection of a non-matching Wake-up ID bit, thus avoiding consecutive erroneous Wake-up ID matchings within the same WuC reception. The waiting time in the Hold Sensing state has been programmed with a series of NOP instructions, leading to slightly higher power consumption in comparison to case 1. Not implementing the aforementioned procedure will imply larger delays and consumption values when the WuC is addressed to a different node. Although the MCU used presents low-power characteristics, the LNA, RF-Power detector and operational amplifier devices require higher current consumption values (200 mA with 5 V, and 550 μA and 2 mA with 4 V, respectively). In this way, there is an increase in the WuRx power that is needed. This situation is acceptable, as the optimizing power consumption of the WuRx presented in this paper is not the objective of this research.

Considering the low-power IEEE 802.11 chipset in [10] with power consumption of 467 mW, 121 mW and 2.1 mW in transmission, listen and sleep states, respectively, and the transfer of two short messages of 100 bytes per hour on average [11], the attachment of the WuRx proposed allows significant power consumption decrease from 2.90 Wh/day (without WuRx) to 121.34 mWh/day (with WuRx).

TABLE II
LATENCY, CURRENT AND POWER CONSUMPTION RESULTS.

Case	Avg. Current	Avg. Active Time	Power*
1) Correct WuC	982.29 μA	230.4 μs	2.95 mW
2) Incorrect Preamble	793.90 μA	163.8 μs	2.38 mW
3) WuC addressed to other node	1090 μA	230.4 μs	3.27 mW

*For MCU voltage supply of 3 V

IV. CONCLUSION

We have presented a WuRx module for OOK based WuC decoding and using the fastest bit rate of 250 kbps allowed by TGba. The WuRx module has been implemented, and a proof-of-concept has been built, including a WuC transmitter for WuRx performance evaluation. Our receiver shows that it is feasible to build a WuRx module based on off-the-shelf components able to decode high rate OOK WuC of 250 kbps. Moreover, the evaluation of the performance of the several cases (correct WuC reception, incorrect preamble reception, WuC addressed to a different node), shows the WuRx robustness compared to frame receptions different from WuC, or addressed to other WuRx in the surrounding area, and the convenience of implementing the Hold Sensing state.

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