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Enhancing Wake-Up Receivers Reliability Through Preamble Filtering and Minimum Energy Coding

Nour El Hoda Djidi
IRISA
Univ. Rennes
Lannion, France
nour-el-hoda.djidi@irisa.fr

Matthieu Gautier
IRISA
Univ. Rennes
Lannion, France
matthieu.gautier@irisa.fr

Antoine Courtay
IRISA
Univ. Rennes
Lannion, France
antoine.courtay@irisa.fr

Olivier Berder
IRISA
Univ. Rennes
Lannion, France
olivier.berder@irisa.fr

***Abstract*—Wake-up Receivers (WuRs) represent one of the most promising solutions for allowing an ultra low power consumption in wireless sensor networks. However, WuRs have several limitations such as low sensitivity, inducing a miss-interpret of the wake-up signal, and thus a performance degradation of the whole system. This work introduces two complementary schemes, namely minimum energy coding and preamble filtering, in order to enhance the WuR reliability while being energy efficient. It is shown through experimental measurements an enhancement on the reliability up to 22% and a total energy saving of 42% while applying minimum energy coding. Moreover, a significant reduction of the false wake-up is realized through preamble filtering.**

***Index Terms*—Minimum energy coding, Reliability, Wake-up receivers, Wireless sensor networks, Energy efficiency, IoT**

I. INTRODUCTION

Internet of Things (IoTs) is rapidly gaining ground in several fields such as smart cities, e-health and smart farms. The things forming wireless sensor networks are low power and resource-constrained devices. Traditionally, the energy consumption of the wireless communications is reduced by using duty-cycled protocols. However, this technique still wastes energy due to idle listening and overhearing [1].

In recent years a new promising wireless technology has emerged, called Wake-up Receiver (WuR), allowing an asynchronous communication with an ultra low power consumption and a low latency [2], [3]. WuR consists in a secondary ultra low power receiver that is always listening to the channel, consuming orders of magnitude less power than traditional receivers. The WuR wakes up the main receiver from sleep state when a specific signal, called Wake-Up Beacon (WUB) is received. The WUB consists in a preamble and a destination address. The preamble wakes up the Ultra Low Power (ULP) Microcontroller (MCU) of the WuR that decodes the received address. However, the WUB is prone to channel errors which induces either *missed wake-up* (when the WuR receives an incorrect address and will not wake up the main node while it should) or *false wake-up* (when the WuR will wake up the main node while it should not).

Errors can be reduced through channel coding by adding some extra bits. Rakovic et al. presented in [4] a channel coding to improve the reliability and the energy consumption of WuR. The study compares the performance of Hamming code, repetition code and Walsh code. Walsh code outperforms all these codes, but it requires a large addressing size (32B) and thus a high memory cost that is practically impossible.

We propose in this work two complementary schemes to improve the WuR reliability and reduce the false wake-up and the missed wake-up while being energy efficient. *The first one* concerns the preamble and consists in filtering a valid preamble duration by the ULP-MCU before checking the correctness of the address in the WUB. To the best of our knowledge, no previous work proposed to check the validity of the preamble, which is just used to wake up the ULP-MCU of the WuR. *The second scheme* deals with the received address and resides in applying Minimum Energy (ME) coding. This scheme works for WuRs based on On-Off Keying (OOK) as are most of WuR circuits [2], and its performance efficiency was proven by Tanget et al. in [5] for this type of circuits.

This paper is organized as follows. In Section II, both WuR circuit design and the preamble filtering technique are given. ME coding principle and energy consumption model are addressed in Section III. Section IV presents experimental measurements and analytical evaluation of different performance metrics of the WuR. Finally a conclusion is given in Section V.

II. WAKE-UP RECEIVER AND PREAMBLE FILTERING

A. Wake-up receiver circuit design

WuR is an ultra low power receiver that is continuously listening to the channel, while the main node is in sleep mode. Most circuits design in the literature are based on OOK demodulator [2]. Fig. 1(a) shows the block diagram of the WuR based on non-coherent OOK receiver that was considered in this work [6]. The first stage contains a matching filter that guarantee the maximum transfer of power from the antenna to the receiver circuit at 868 MHz. Then, an envelope detector rectifies the bandpass signal to a baseband signal. This signal passes through a comparator to reconstruct the bits of the WUB. After the comparator, a low pass filter acts as a preamble detector that induces a delay of t_d as shown in Fig. 1(b). If the preamble duration is longer than t_d, then the

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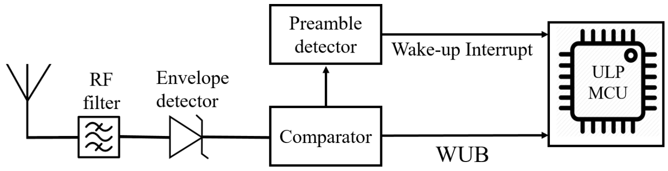
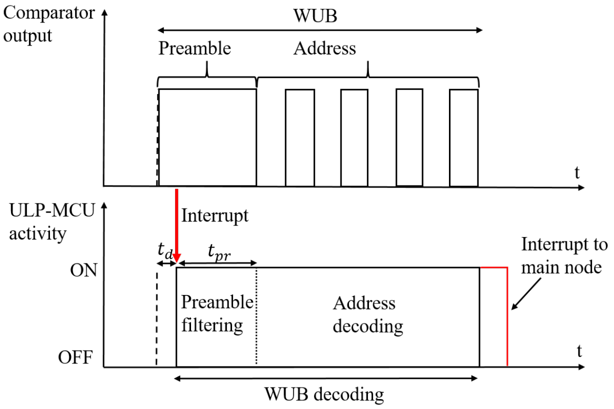
preamble detector generates an interrupt to wake up the ULP-MCU. Finally, the ULP-MCU decodes the received WUB.

B. Preamble filtering

The WUB comprises two fields, the first one is a preamble of l_{pr} bits that traditionally serves to wake up the ULP-MCU, and the second field contains the destination address as illustrated in Fig. 1(b). When the received address corresponds to the destination node, the ULP-MCU generates an interrupt to wake up the main node. The novel technique that we propose is that the ULP-MCU filters the preamble once it is woken up after a delay t_d. If the preamble duration denoted t_{pr} (Fig. 1(b)) is in a predefined interval, that corresponds to the duration of a valid preamble, then the ULP-MCU continues decoding the address, otherwise it is turned off. This technique will reduce the false wake-up that occur due to other signal in the 868 MHz band. Indeed, it could exist external signals that have different preamble duration and will be interpreted as valid WUB if the preamble is not checked and the address corresponds to the destination node. Thus, the ULP-MCU will wake up the main node via an interrupt, while it should not, which will induce a waste of energy.



(a) WuR block diagram.



(b) ULP-MCU activity as a function of the comparator output.

Fig. 1: WuR system design.

III. MINIMUM ENERGY CODING

A. Principle

ME (n, k) coding consists in mapping every k bits of information into n bits codeword, with n equals to $2^k - 1$ as illustrated in TABLE I. The all-zeros source symbol is mapped into n-bit all-zeros codeword. All other source symbols are mapped into n-bit codewords with only one bit at '1' in the position of the source symbol.

TABLE I: Minimum energy coding mapping table.

Source symbol (k)	Mapped symbol ($n = 2^k - 1$)
00..00	0000..000
00..01	0000..001
...	...
...	...
...	...
11..10	0100..000
11..11	1000..000

B. Energy consumption model

A point-to-point communication between a transmitter and a WuR is considered. The transmitter keeps transmitting the same packet N_{tx} times until it is successfully received. N_{tx} is expressed as:

$$N_{tx} = \frac{1}{1 - MWR}, \tag{1}$$

with MWR the Missed Wake-up Rate.

The average power consumption of both transmitter and WuR will be presented with the two different scheme, i.e. uncoded scheme and when applying ME (n, k).

1) Average power consumption with uncoded scheme:

- Transmitter power consumption: The average power consumption of the WUB transmission until it is successfully received denoted $P_{tx}^{uncoded}$ is:

$$P_{tx}^{uncoded} = N_{tx}\lambda t_b \cdot \left(P_{tx_1} \cdot (l_{pr} + \frac{k}{2}) + P_{tx_0} \cdot (\frac{k}{2})\right), \tag{2}$$

  with P_{tx_1} and P_{tx_0} the power consumed to send '1' and '0', respectively, t_b the bit duration, k the number of bits used in the address and λ the packet transmission rate.
- WuR power consumption: The average power consumed by the WuR denoted $P_{WuR}^{uncoded}$ is:

$$\begin{aligned} P_{WuR}^{uncoded} &= N_{tx}\lambda(t_{pr} + kt_b) \cdot P_{rx}^{wur} \\ &+ (1 - N_{tx}\lambda(t_{pr} + kt_b)) \cdot P_{idle}^{wur}, \end{aligned} \tag{3}$$

  with P_{rx}^{wur} the power consumed by the WuR when receiving and processing the WUB, and P_{idle}^{wur} the power consumed by the WuR when it is listening to the channel while the ULP-MCU is sleeping.

2) Average power consumption with ME (n,k) scheme:

- Transmitter power consumption: The average power consumption of transmitting the WUB until it is successfully received when using ME (n, k) denoted P_{tx}^{ME} is:

$$P_{tx}^{ME} = N_{tx}\lambda t_b \cdot \left(P_{tx_1} \cdot (l_{pr} + \frac{n}{n+1}) + P_{tx_0} \cdot (\frac{n^2}{n+1})\right). \tag{4}$$

- WuR power consumption: The average power consumption of the WuR based on ME denoted P_{WuR}^{ME} is given by:

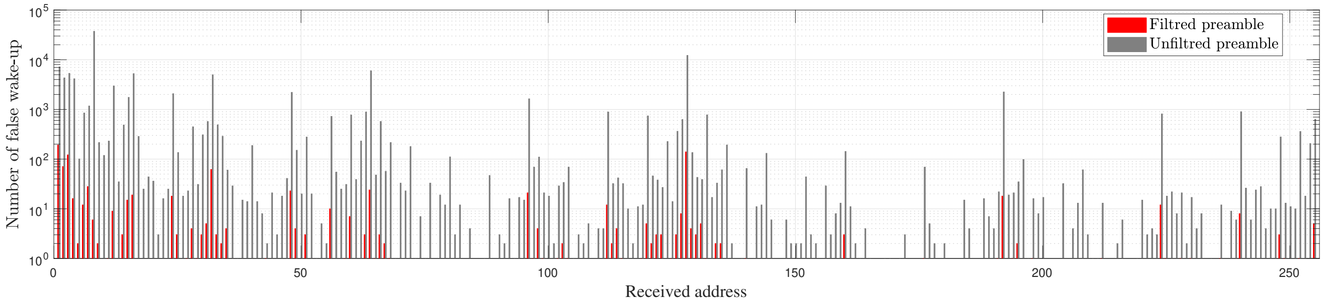


Fig. 2: Number of false wake-up.

$$\begin{aligned} P_{WuR}^{ME} &= \lambda N_{tx}(t_{pr}+nt_b)\cdot P_{rx}^{wur} \\ &+ (1-(t_{pr}+nt_b)\lambda N_{tx})\cdot P_{idle}^{wur}. \end{aligned} \tag{5}$$

IV. PERFORMANCE EVALUATION

A. Preamble filtering

Two different schemes of decoding the received WUB were implemented in the WuR designed in [6] that has a measured sensitivity of -45 dBm and is working at 1 kbps. The traditional does not check the duration of the preamble and then starts decoding the received address right after the end of the preamble, and the novel scheme is by filtering the received preamble duration. A valid preamble contains l_{pr} of 3 bits and t_d is around 400 μs, therefore if the preamble duration t_{pr} is between 2.4 ms and 2.7 ms, then it is considered as a valid one and thus the ULP-MCU decodes the received address, otherwise it is turned off.

1) False wake-up measurements: The WuR was placed 24h in a laboratory office listening to the channel, no WUB was sent and the number of false wake-up was measured.

Fig. 2 shows the false wake-up amount as a function of the received addresses of 8 bits. It can be seen that there are several false wake-up, as the WuR is based on OOK detector so any presence of an external signal of another wireless technology with different modulation is translated to a bit '1' and an off signal is translated to a bit '0'. Fig. 2 also shows that filtering the preamble considerably reduces the number of false wake-up and thus avoiding the wake-up of an undesirable node. If the node address is for example 4, it can be seen that 4154 false wake-up occur with unfiltered preamble against 16 with filtering. 99.6% of false wake-up are thus reduced with preamble filtering, which will reduce the energy consumption of 259.6 times. For some addresses, such as the address 170, there are no false wake-up with both schemes. The total false wake-up is 120139 with unfiltered scheme against 982 with preamble filtering, thus 99% of all false wake-up are reduced with preamble filtering, with a total energy saving up to 122.34 times. The same experiment was done in a house, the total false wake-up in 24 h was equal to 27457 when not filtering, against zero false wake-up when filtering. This reduction amount clearly depends on the environment in which the WuR is located. Regardless of the environment, the preamble filtering will reduce the false wake-up and the energy consumption.

B. ME coding

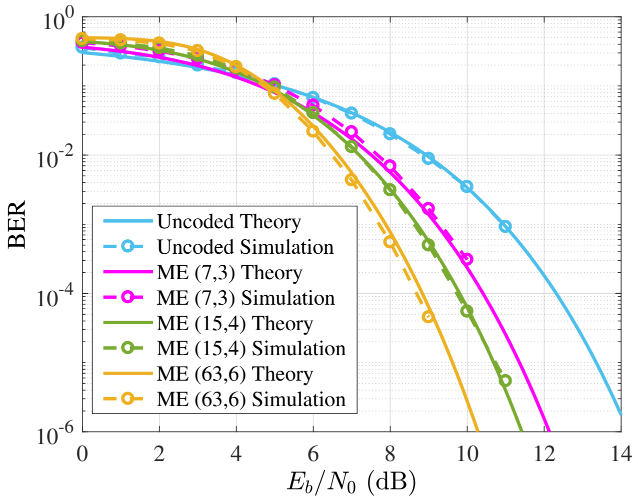


Fig. 3: BER as a function of E_b/N_0.

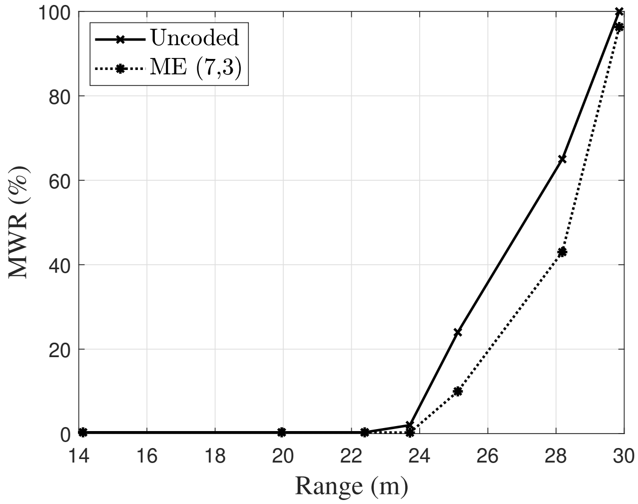
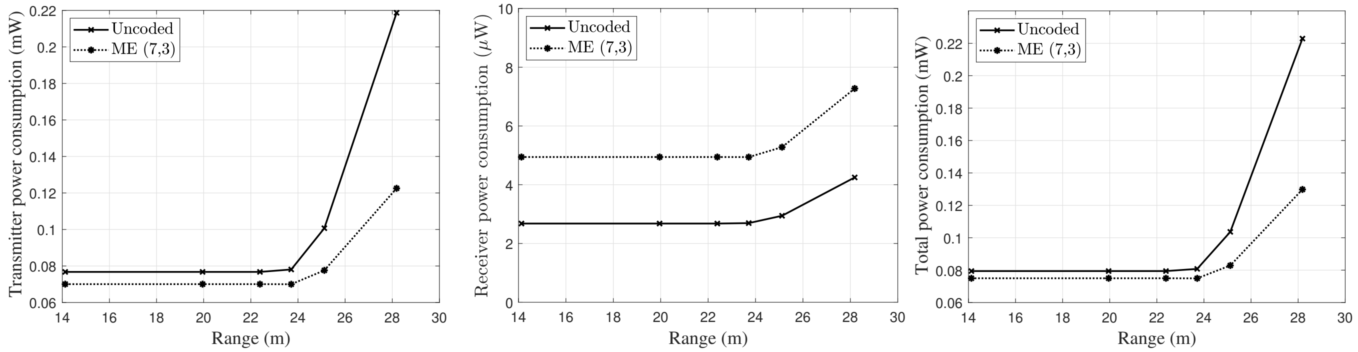


Fig. 4: MWR measurements as a function of the range.

1) Bit error rate evaluation: To demonstrate the efficiency of ME coding, the theoretical bit error probability from [5]



(a) Transmitter (b) WuR (c) Total

Fig. 5: Average power consumption per successful packet.

and a monte carlo simulation of Bit Error Rate (BER) as a function of $\frac{E_b}{N_0}$, with uncoded scheme and when applying ME coding, are shown in Fig. 3. It can be seen that the theoretical derivation fits the simulation results (circle symbols). A coding gain is defined as the reduction of the $\frac{E_b}{N_0}$ that is needed at some specific level of BER when coding is used compared to the uncoded scheme. It is apparent from Fig. 3 that with a BER of 10^{-4}, a coding gain of 1.9dB, 2.5dB and 3.4dB, respectively is achieved with ME (7,3), ME (15,4) and ME (63,6). It can also be seen that at the same level of $\frac{E_b}{N_0}$, the BER is reduced when applying ME coding, thus ME coding can either improve $\frac{E_b}{N_0}$ at a fixed level of BER or reduce the BER at a fixed $\frac{E_b}{N_0}$. It can also be seen that the higher the size k is, the more the performance of ME coding is improved. However, using a large value of k will induce more latency and more power consumption. Therefore ME (7,3) is implemented in real field and the experimental results are given in the next Section.

2) Missed wake-up measurements: The MWR are measured for 7215 WUB packets sent at a rate of 4 packets/s. The WuR and the transmitter are placed at a distance of 1 m from each other in an anechoic chamber. The MWR are measured for different transmission power levels ranging from -13 dBm to -19.5 dBm and these results are expressed in theoretical range by considering the Friis formula [7] and a transmission power of 10 dBm. Fig. 4 illustrates the MWR as a function of the range. It can be seen that below a range of 22 m, the MWR is the same when applying ME (7,3) and with uncoded scheme. When the range exceeds 22 m, ME (7,3) improves the MWR. At a range of 28 m the MWR is reduced by 22%.

3) Energy consumption evaluation: The transmitter from ST which is considered [8] has P_{tx_1} and P_{tx_0} equal to 3.8 mW and 420 μW, respectively. For the WuR designed in [6], P_{rx}^{wur} and P_{idle}^{wur} are equal to 284 μW and 1.83 μW, respectively. t_b is equal to 1 ms and λ is fixed at 1 packet/s. These values are used to feed the models given in Section III-B. Fig. 5(a) shows the average power consumption of the transmitter per successful packet when using both uncoded and ME (7,3) schemes. It can be seen that ME consumes less than uncoded scheme, as with ME coding more '0' are transmitted consuming less power than '1'. When the range is under 22 m, ME (7,3) consumes 8.7% less than uncoded scheme, and beyond 22 m the gain becomes more important achieving 43.9% at a distance of 28 m, as at a longer range the transmitter with uncoded scheme has a higher MWR and thus needs to re-transmit more packets than ME (7,3). Fig. 5(b) illustrate the average power consumption of the WuR per successful packet. It can be seen that ME consumes more than uncoded scheme as the WuR should decode a longer packet with ME coding. It consumes 43% more than uncoded scheme, but it is in the order of few micro-watts. Fig. 5(c) details the total average power consumption of both transmitter and WuR per successful packet. It is apparent that uncoded scheme consumes more than ME coding. The higher the range is, the more the energy is saved with ME. At a range under 22 m, ME coding saves 5.58% of energy, and at a range of 28 m 41.76% of energy is saved.

V. CONCLUSION

This paper presented two schemes that can be applied to WuR to enhance its reliability and save energy. The first one is to filter the received preamble and accept only a valid one to decode the received address. The other scheme is to apply Minimum Energy coding (ME). A detailed study of the energy consumption was presented. Both preamble filtering and ME coding were implemented in a real platform and the false wake-up and missed wake-up were measured. Results show that ME reduces the missed wake-up up to 22% and saves 42% of the total energy. It also appears the efficiency of filtering a valid preamble in reducing 99% of false wake-up.

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