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Wireless Powered Wake-up Receiver for Ultra-Low-Power Devices

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Abstract—Energy-constrained wireless networks and devices are mainly powered by batteries, which have severely limited capacities, demanding to be regularly recharged or replaced. Thus energy conservation plays a pivotal role in the operational lifetime of such networks. In this paper, the concept of a wireless powered wake-up receiver is studied, aiming to reduce energy consumption of the wireless node. The proposed wireless powered wake-up receiver scheme can be utilized for a range of energy-constrained wireless applications such as wireless sensor actuator networks, machine-to-machine communications, and the Internet-of-Things. Preliminary numerical results show that such a scheme can reduce energy consumption of wireless nodes considerably, at the cost of an extra low-power low-cost wake-up receiver.

Index Terms—energy efficiency, energy harvesting, wireless sensor actuator networks, wake-up receiver, Internet-of-Things.

I. INTRODUCTION

Traditional automation and control networks often are too inflexible to absorb the dynamics of environments swiftly; the main reason for the rigidity of such networks is the dependence on the wired communications [1]. The need for innovative and simple approaches for automation, monitoring and control systems has triggered much attention on wireless sensor actuator networks (WSANs) [2].

WSANs are heterogeneous networks that comprise wireless actuator/sensor nodes to perform distributed sensing and actuation tasks. It is expected that by 2020, there will be more than 50 billion of wireless nodes, which require to operate and integrate with the Internet [3]. As a result of such technological developments in WSANs, a new networking paradigm, Internet-of-Things (IoT) has emerged. IoT faces enormous challenges and requirements on operational lifetime, which is a perennial problem for the network [4]. This problem can be alleviated by the following approaches:

1) Extending energy density of batteries: while the computing power of microchips and wireless data rates have been growing exponentially, there is no Moore's law for batteries, and energy density of batteries has increased just a few percent during the last decade [5]. In other words, the battery evolution lags far behind the advances in semiconductor industry. Recently, improving energy density of batteries has attracted

vast research attention from both academia and industry, and has become part of new emerging research topics. However, advances from research and development require years to be translated to commercial deployments.

2) Harvesting ambient energy: recently, integrating energy harvesting technologies into WSANs has attracted much attention. However, most of IoT devices require a stable power supply to operate reliably [4]. The intermittent and unpredictable nature of the ambient energy sources may make this approach undesirable and unreliable, e.g., for mission-critical IoT communication [6].

3) Reducing the power consumption: the wireless node consists of transceiver (transmitter and receiver), battery, and actuator/sensor. Despite the fact that the transmitter has considerably higher power consumption, it is important to reduce energy consumption of the node in receive mode too; the main reason is that, in typical applications of WSANs, most of time the node operates in receive mode, and its energy consumption can accumulate during a day, and eventually surpasses transmit energy consumption.

In this work, in order to prolong the lifetime of the wireless node, the second and third approaches are combined together; as a result, an extra low-cost low-power receiver, referred to as a wireless-powered wake-up receiver (WPWRx) is introduced to the wireless node.

This paper is organized as follows. Section II describes the problem that needs to be addressed. Further, the proposed solution to improve energy efficiency of a wireless node is explained in Section III. Signaling structure and system model are discussed in Sections IV and V, respectively. These are followed by numerical results and conclusion in Sections VI and VII.

II. PROBLEM DESCRIPTION

In this work we assume that actuators/sensors are attached to the environment, and their measurements are sent to a base station (BS). Furthermore, we consider the on-demand also known as query-driven mode, where the BS decides when to gather data or send a command [7]. The BS sends instructions to the nodes indicating that it wishes to receive data, and then wait for the required type of data to be sent in the requested format.

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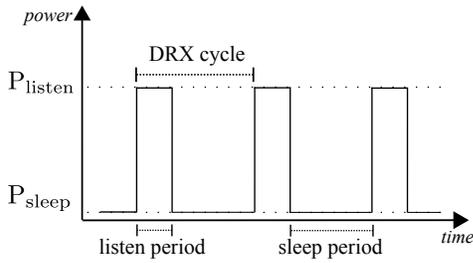


Fig. 1. Power consumption behavior of the wireless node during DRX

WSANs have sporadic traffic, in which wireless nodes frequently have bursty transmission characteristics, with occasional periods of transmission activity followed by longer periods of silence. Thus, in order to reduce power consumption, each node goes into discontinuous reception (DRX), meaning that it switches the radio off, and sets a timer to awake and listen [8]. The node can receive and transmit data during the listen period. The power consumption behavior of the wireless node during DRX is illustrated in Fig 1.

A wireless node consumes considerably more power during listen period (P_{listen}), compared with sleep period (P_{sleep}). According to experimental findings on actual wireless nodes, the time period that wireless devices monitors channel without any data allocation has a major impact on battery consumption [9]. In other words, the main issue with DRX, is high wasted energy consumption of the node during listen period, while it does not contain any actual data traffic [9]; this issue can become severe, e.g., in ultra-reliable low-latency applications, due to need for highly-frequent channel monitoring.

III. WIRELESS POWERED WAKE-UP RECEIVER

The limited battery capacity implies that in order to ensure longevity of the wireless node, the energy consumption of individual node needs to be optimized. As mentioned in Section II, a considerable amount of energy is consumed to monitor the channel. In this work, energy consumption of the wireless node during listening period is reduced by introducing and adopting a low-cost low-power WPWRx.

Harvesting ambient energy such as light or solar or wind on individual node level may be unreliable and expensive [6]; to this end, Radio frequency (RF) energy harvesting technology can potentially overcome the aforementioned limitations. However, wireless power transfer can be very inefficient over long distance. Thus, the RF-harvested energy is not alone sufficient for the reliable wireless communication of the main data communication transceiver, and is more suitable for ultra-low power applications.

Interestingly, transfer of wake-up data and power for WPWRx by utilizing time switching, can reduce or even eliminate the need for consuming battery of the node for listen period, leading to significant energy consumption reduction of the battery. In the proposed scheme, each WPWRx operates as either wake-up signaling receiver or an energy receiver at any given time in time switching manner. We refer to the single-bit

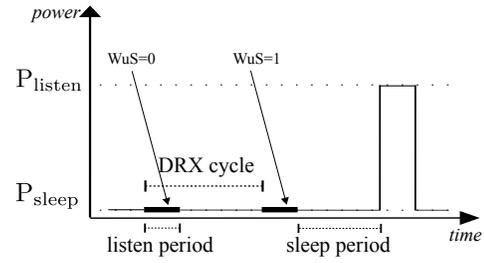


Fig. 2. Power consumption behavior of wireless node with WPWRx during DRX

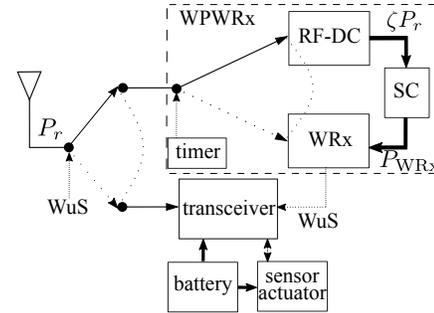


Fig. 3. Block diagram of the wireless node with WPWRx, the bold lines represent power transfer between submodules

of wake-up control information as wake-up signaling (WuS). Intuitively, power consumption characteristics of the wireless node with WPWRx is shown in Fig. 2.

WPWRx consists of a RF to direct current (RF-DC) converter to provide harvested RF energy, a wake-up receiver (WRx), a programmable timer, and a switch. Additionally, a supercapacitor (SC) as energy storage is employed to store the harvested energy during sleep period. The energy harvesting operation performed in the RF domain may degrade the information content [6]. Therefore in order to achieve interference-free channel, the receiving antenna periodically switches between the WRx and RF-DC converter. During listen period received signal is guided to WRx in order to detect WuS, and during sleep period, received signal converts to DC by means of RF-DC converter, and stores energy in SC for use by WRx in listen period.

The proposed WRx has small power consumption (P_{WRx}), and is powered up by wireless power transfer. The battery provides energy to actuator/sensor, timer, switches and the main transceiver. Schematic block diagram of the overall wireless node is presented in Fig. 3, where RF-DC harvests and provides energy, and WRx decodes WuS separately from the received signal by the antenna. In the general case, the main transceiver and the WPWRx may also operate at different frequency bands.

WuS informs of potential upcoming data on next listen slot or rather if it can skip it. Because of signal structure described in detail in the next section, the required energy to decode it, is much less than listen period of the main transceiver.

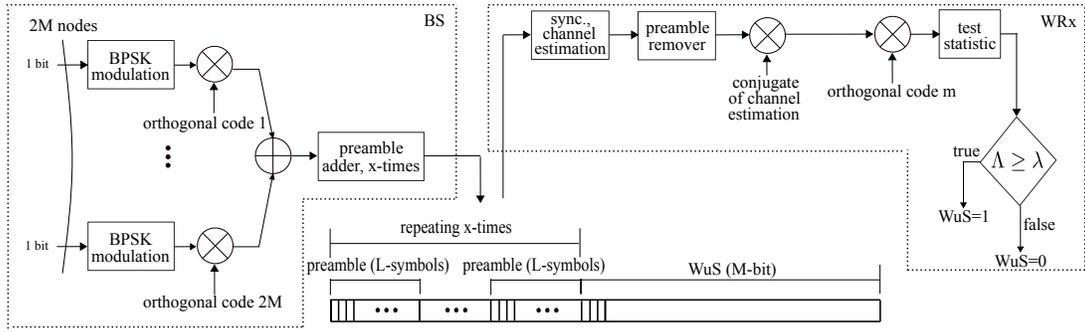


Fig. 4. Wake-up signaling generation at BS, WRx in the wireless node, and frame structure of the signal

Moreover RF energy harvested from the signal during sleep period provides sufficient power to decode such a signal during listen period.

Assume that the BS has upcoming data for the node on the second listen slot. As shown in Fig. 1, in case of conventional node, its main transceiver checks channel during every listen period, and in second listen slot it realizes that there is upcoming data. However, in the proposed mechanism, WPWRx checks the WuS every listen period. As shown in Fig. 2, the WPWRx knows from decoding WuS in the first listen slot that there is no grant for the second listen slot; therefore during the second listen slot, the WPWRx only needs to decode WuS. In the second listen period, decoded WuS indicates that there is upcoming data for the third sleep period, thus the main transceiver starts processing instructions in the third listen slot.

IV. WAKE-UP SIGNAL STRUCTURE

The proposed structure of wake-up signal consists of preamble and WuS as shown in Fig. 4. The preamble sequence is indication of wake-up signal arrival time, and is used for time synchronization by all WRxs. WuS is followed by data load for the transceivers.

Due to the uncertainty of WRx about the exact arrival time of WuS, the preamble needs to be selected from sequences with good auto- and cross-correlation properties. For this purpose, the Zadoff-Chu sequence with length of L is applied to allow precise appreciation of WuS position in time. In order to increase the observation time, it is repeated for x -times; therefore if a node could not obtain its synchronization using the first sequence, it can acquire it from the rest of $x - 1$ sequences. Moreover, preamble sequences provide channel estimation capabilities for the WRx.

After obtaining synchronization by means of the repeated preamble, each WRx decodes WuS, in order to decide whether it needs to switch on transceiver in next listen period ($WuS = 1$) or not ($WuS = 0$). For this purpose, a structure, where multiple wireless nodes' WuSs are code multiplexed on to a common WuS is applied. Then, in case that $WuS = 0$, during sleep period, the RF-DC converter harvests energy of received RF signal corresponds to shared data channel. The harvested energy stores in SC for WRx.

Therefore, each single-bit of WuS can be spread over time to reduce the power differences while at the same time providing the sufficient time diversity for accurate reception. The WuS is BPSK modulated, followed by spreading with a length- M orthogonal sequence, referred to as \mathbf{q}_m with dimension of M ; because of orthogonality among the codes, $\sum_{m=1}^M q_r^{(m)} q_f^{(m)}$ equals 0, if $f \neq r$, and equals M , if $f = r$.

For the code length of M , there are $2M$ orthogonal codes available, in other words $2M$ WuSs can be transmitted on the same time without causing interference. Therefore, it is essential to satisfy the following condition, $N \leq 2M$, where N is the number of nodes in the network. The first set of M orthogonal codes are formed by $M \times M$ Hadamard matrix, and the second set of M codes are in quadrature ($\times j$) to the first set.

According to the law of energy conservation, it can be assumed that the total harvested RF-band power at the converter is proportional to that of the received signal power, expressed as ζP_r , where ζ is a constant that accounts for the loss in the RF-DC circuit for converting the harvested energy to DC.

The total harvested energy (E_h) during a sleep cycle can be written as follows

$$E_h = t_{\text{sleep}} \zeta P_r. \quad (1)$$

Similarly, the required energy for a successful reception of WuS equals

$$E_{\text{WRx}} = t_{\text{listen}} P_{\text{WRx}}. \quad (2)$$

The essential condition for the accurate operation of the proposed method is that $E_{\text{WRx}} \leq E_h$. By combining Eq. (1) and Eq. (2), and assuming that discharging current of SC is negligible, this condition can be written as follows

$$\frac{P_{\text{WRx}}}{\zeta P_r} \leq \beta. \quad (3)$$

where $\beta = \frac{t_{\text{sleep}}}{t_{\text{listen}}}$ is the sleep-to-listen ratio. Therefore, β is required to be configured in such a way to satisfy Eq. (3). In other words, for low-coverage scenarios, β can be reduced, while for high-coverage scenarios, β needs to increase in order to provide sufficient power for cell-edge WPWRxs, and as a result communication delay increases.

The introduction of WuS imposes two different errors, mis-detection and false alarm. In latter case, WPWRx erroneously

identifies 0 as 1 for its decoded WuS, leading to unnecessary power consumption of transceiver, thus the false alarm rate is required to be minimized. The former is corresponding to the case, where the node decodes WuS as 0 incorrectly, while 1 sent. The misdetection can add an extra delay, and waste capacity in the main shared data channel. Therefore, the misdetection rate requirement of WuS is eventually stricter than false alarm rate.

V. SYSTEM MODEL

The samples of the received baseband signal of WuS, with assumption of a slow fading channel, and also that transmit power per code (P) is identical for all $2M$ codes, can be represented as a vector \mathbf{y} with dimension of M as

$$\mathbf{y} = \sqrt{\frac{P}{2}}h\left(\sum_{m=1}^M i_m \mathbf{q}_m + j \sum_{m=1}^M i'_m \mathbf{q}_m\right) + \mathbf{w}, \quad (4)$$

where $i_m \in \{-1, +1\}$ for $m \in \{1, \dots, M\}$ is a BPSK modulated symbol of WuS belonging to m^{th} wireless node; similarly, i'_m is a BPSK symbol, for $(m+M)^{\text{th}}$ node. Also, h is slow fading channel gain. Finally, we assume that noise is circularly symmetric zero-mean complex Gaussian, represented through an M -dimensional complex vector \mathbf{w} with covariance matrix of $\sigma_w^2 I$. The likelihood function for decoding WuS of the first wireless node, corresponds to the following test statistic

$$\Lambda = \Re\left(\hat{h}^* \mathbf{q}_1 \circ \mathbf{y}\right), \quad (5)$$

where \hat{h} is a channel estimate for coherent detection, and is acquired based on the set of repeated preambles. The WRx compares calculated value of Λ from Eq. (5) with a fixed detection threshold λ , and then makes a decision whether WuS is zero (null hypothesis \mathcal{H}_0) or one (alternate hypothesis \mathcal{H}_1), as shown in Fig. 4.

By denoting with A the inter distance between means of \mathcal{H}_0 and \mathcal{H}_1 , where $A = \sqrt{2|h|^2 P}$, the false alarm (fa) and missed detection (md) probabilities can be written under AWGN channel assumption which yields [10]

$$P_{fa,AWGN} = \Pr(\Lambda \geq \lambda | \mathcal{H}_0) = Q\left(\frac{\frac{1}{\sqrt{2}}\sqrt{|h|^2 P} + \lambda}{\sigma_w}\right), \quad (6)$$

and

$$P_{md,AWGN} = \Pr(\Lambda < \lambda | \mathcal{H}_1) = Q\left(\frac{\frac{1}{\sqrt{2}}\sqrt{|h|^2 P} - \lambda}{\sigma_w}\right), \quad (7)$$

where Q is the Q-function representing the tail probability of the standard Gaussian distribution.

In general, the wake-up scheme requires to have asymmetric error rates with considerably smaller misdetection rate compared to false alarm rate. Hence, λ should be adjusted to satisfy the corresponding error rates. The probability of false alarm and misdetection in a slow Rayleigh fading channel, denoted

by P_{fa} and P_{md} respectively, can be evaluated by averaging over channel realizations as follows [10]

$$P_{fa} = \frac{1}{2} \left(1 - \sqrt{\frac{\bar{\beta}}{\frac{2P}{(\sqrt{2P}+\lambda)^2} + \bar{\beta}}}\right), \quad (8)$$

and

$$P_{md} = \frac{1}{2} \left(1 - \sqrt{\frac{\bar{\beta}}{\frac{2P}{(\sqrt{2P}-\lambda)^2} + \bar{\beta}}}\right), \quad (9)$$

where $\bar{\beta}$ is average of SNR over different channel realizations.

For specific network settings and noise level, λ and β need to be configured in such a way to satisfy (3), (8), (9), $P_{fa} < 0.1$, and $P_{md} \leq 0.01$. β can be set statically based on cell size. Furthermore, we assume that the WSAW under our study operates at high SNR regime for wireless nodes, for which the main reason is the need for the high-power operating requirement of harvester.

VI. EXAMPLE NUMERICAL RESULTS

For comparison purposes, a relative power saving parameter, referred to as $\eta = \frac{P_{wo} - P_w}{P_{wo}}$ is defined, where P_{wo} and P_w are power consumption of wireless node without WPWRx and with WPWRx. The value of η ranges from 0 to 1, and greater η indicates that the wireless node using the proposed mechanism conserves energy much better than a node without WPWRx.

In our example numerical evaluations, we assume that the distance between the BS and the wireless node is in the order of 10-100 meters for practical purposes, and that the BS antenna height is in the order of 10 m. For pathloss modeling, we adopt the ITU-R Urban Micro (UMi) non-line-of-sight (NLoS) model described in [11], and that the system center-frequency is 900 MHz. We consider two cases of BS transmit power and antenna gain, namely +33 dBm and 3 dB, and +37 dBm and 13 dB.

The bandwidth of the transmitted signal for WRx and the main transceiver are assumed to be 100 kHz and 10 MHz, respectively, while the channel noise is assumed to be white Gaussian with power spectral density of -174 dBm/Hz. This correspond to total noise powers of -104 dBm over the shared data bandwidth of 10 MHz and -124 dBm over the WuS bandwidth. Furthermore, the noise figure of WRx is assumed to be 10 dB. Additionally, it is assumed that WRx and wireless node consume power of about 50 μ W and 20 mW, respectively. Additionally, we assume that $\zeta = 90\%$, $L = 63$, $x = 1$, and $M = 8$.

The dependency of minimum required value of β over distance is depicted in Fig. 5. For lower distances such as 50 m, minimum required values of β are 3396 and 135 for +33 dBm and 3 dB, and +37 dBm and 13 dB scenarios, respectively. With an additional assumption that t_{listen} is fixed for example at 10 ms, the value of t_{sleep} varies according to β . Moreover, we assume that the main communication transceiver requires 10 ms for data reception and processing, once a packet arrives.

For the aforementioned distance range of 10-100 meter, the received wake-up signal SNR is at least 55 dB and 69 dB,

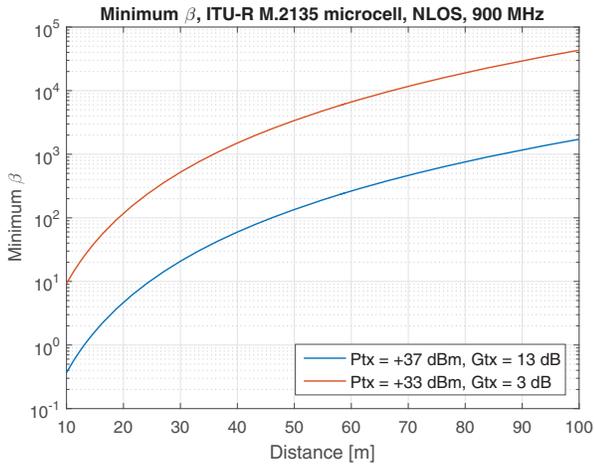


Fig. 5. Minimum required of β as a function of distance.

for +33 dBm and 3 dB, and +37 dBm and 13 dB scenarios, respectively. Because of such very large values of SNR, both P_{fa} and P_{md} are essentially zero throughout the considered distance range of 10-100 m.

In general, the amount of η is largely dependent on $\Pr(\mathcal{H}_0)$ and P_{fa} . We next evaluate the power saving parameter behavior, for the cases of $P_{fa} = 0$ and $P_{fa} = 1$, and the results are shown in Fig. 6. As can be observed, especially for higher values of $\Pr(\mathcal{H}_0)$, WuS reduces power consumption efficiently. The main reason for such a trend is high frequent occurrence of empty sleep periods for higher value of $\Pr(\mathcal{H}_0)$. Non-zero value of P_{fa} , in turn, imposes some excess power consumption, due to switching on the main transceiver falsely. In general, however, the results in Fig. 6 show that for any realistic value of P_{fa} between 0 and 0.1, the WRx approach yields substantial savings in the wireless node power consumption.

VII. CONCLUSION

In this paper, the concept of WPWRx is introduced in order to reduce energy consumption of the wireless node during receive mode. For this purpose, wake-up signaling approach is introduced, together with an efficient signal structure, such that reliable wake-up detection, and thus large energy savings can be obtained in wireless nodes. WPWRx detection performance was quantified analytically, while it was also shown through numeric results that the proposed approach is able to reduce the power consumption of the wireless node considerably. In our future work, we will continue to further investigate the design and optimization aspects of WPWRx.

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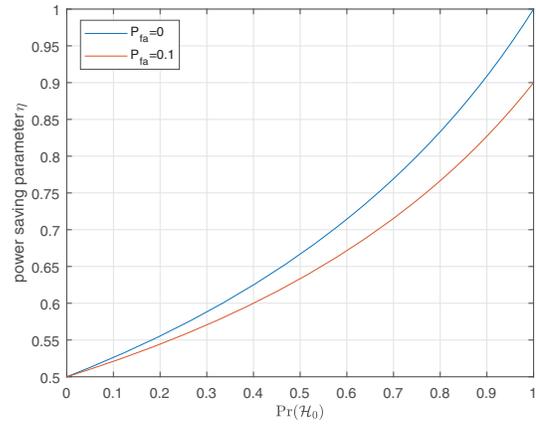


Fig. 6. Power saving parameter η as a function of the probability of null hypothesis.

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