Microelectronics Journal 45 (2014) 1627–1633

Contents lists available at ScienceDirect

Microelectronics Journal

journal homepage: www.elsevier.com/locate/mejo

Wake-up radio receiver based power minimization techniques for wireless sensor networks: A review

M. Magno [a,*], S. Marinkovic [b], B. Srbinovski [c], E.M. Popovici [c]

[a] Department of Information Technology and Electrical Engineering, ETH Zurich, Switzerland
[b] ABB Corporate Research, Baden-Dättwil, Switzerland
[c] Department of Electrical and Electronic Engineering, University College Cork, Ireland

ARTICLE INFO

Article history:
Received 27 December 2013
Received in revised form
27 August 2014
Accepted 27 August 2014
Available online 16 October 2014

Keywords:
Power management
Power gating
Dynamic frequency voltage scaling
Wake-up radio receiver
Smart harvesting
Multi-radio wireless sensor networks

ABSTRACT

In a short period of time Wireless Sensor Networks (WSN) captured the imagination of many researchers with the number of applications growing rapidly. The applications span large domains including mobile digital health, structural and environmental monitoring, smart home, energy efficient buildings, agriculture, smart cities, etc. WSN are also an important contributor to the fast emerging Internet of Things infrastructure. Some of the design specifications for WSN include reliability, accuracy, cost, deployment versatility, power consumption, etc. Power consumption is (most often) the dominant constraint in designing such systems. This constraint has multi-dimensional implications such as battery type and size, energy harvester design, lifetime of the deployment, intelligent sensing capability, etc. Power optimization techniques have to explore a large design search space. Energy neutral system implementation is the ultimate goal in wireless sensor networks ensuring a perpetual/greener use and represents a hot topic of research. Several recent advances promise significant reduction of the overall sensor network power consumption. These advances include novel sensors and sensor interfaces, low energy wireless transceivers, low power processing, efficient energy harvesters, etc. This paper reviews a number of system level power management methodologies for Wireless Sensor Networks. Especially, the paper is focusing on the promising technology of nano-Watt wake-up radio receiver and its combination with mature power management techniques to achieve better performance. Some of the presented techniques are then applied in the context of low cost and battery powered toy robots.

1. Introduction

Wireless Sensor Networks (WSN) revolutionized many applications including environmental and structural monitoring, health and fitness, sports and entertainment, agriculture, smart grid, security, robotics, just to name a few [1]. The WSN technology is tipped to become a crucial component of the fast emerging Internet of Things infrastructure where sensors will be connected dynamically to the Internet. There are many WSN platforms which were proposed to support these applications [2], with the general trend being the focus on low power, small form factor, and very low cost [6]. Advances in sensor technologies, Radio Frequency(RF) communications, low power collaborative computing, power generation and power management have resulted in low cost, low power systems which operate battery-less, or on small batteries and/or using some smart multi-harvester systems [3]. Developments in low power computing architectures have resulted in a new trend in WSN, namely the migration from communication centric (sending sensed data which is often large in size) to information centric (sending processed data or information in much reduced size) WSN. Another trend is in the integration of the RF transceiver, the Micro Controller Unit (MCU) and Analog to Digital Converter (ADC) in a System on Chip (SoC) platform with the focus being shifted towards more computationally powerful MCU (from 8 bit to 32 bit architectures, from single core to multi core) with co-processors (ASIC or FPGAs) being frequently deployed in energy efficient systems [4].

The vast majority of the WSN nodes are battery-powered. Hence, the dominant constraint in designing WSN system is by far the power consumption. There are many models for power consumption in WSN and they are based on the main constituent blocks of a typical node (Fig. 1) namely: Radio (RF) communications, computing unit (MCU/FPGA and Memory), sensor/actuator unit, and power management unit.

The RF transceiver unit is often identified as one of the major power consumption component and significant research, development and standardization emphasis were on the design of ultra-low power wireless transceivers [26]. Given this characteristic for RF communications, a new type of energy neutral wireless sensor

* Corresponding author at: Department of Information Technology and Electrical Engineering, ETH, Zurich, Switzerland.

http://dx.doi.org/10.1016/j.mejo.2014.08.010
0026-2692/

networks is emerging rapidly [40,41]. For these systems, the availability of harvested energy is matched with the communication energy models to provide a perpetual, long life system [12]. The differentiation between these transceivers is in receiver sensitivity, data rate, selectivity, modulation schemes, standards, latency, etc. For a given frequency of operation, the power consumption is a function of such parameters. From a simplified perspective, the RF transceiver has to achieve reliable communication over a certain range in an application scenario. However, depending on the application, the sensor interface unit and the power management unit can also consume significant power, often exceeding that of a transceiver [5] and system level techniques are required to minimize the overall power consumption.

For the MCU, the general trend is represented by the migration from 8/16(Atmel/TI) bit towards 32 bit (ARM based) architectures. Signal (pre)processing is increasingly being performed close to the sensor and increase in computational power is often required. Low power accelerators based on FPGA can be also employed successfully along these MCU's [4,6] to accommodate these computational requirements and minimize energy. In order to reduce both cost and power consumption, many of the components presented in Fig. 1 are integrated into a single chip. This has also a direct repercussion on the size of the system.

While the focus of this paper is on power reduction techniques at physical/hardware level, efficient operating systems, signal processing and communication techniques can result in significant additional power savings [42].

Given the components of a wireless sensor node, many of the system level techniques can be used in the context of WSN. These include memory optimization, reduction of the number of clock cycles to perform a certain task, efficient clock and power gating, dynamic voltage and frequency scaling, frequency diversity, etc.

Application specific power minimization techniques can also be applied, including heterogeneous harvesters, antenna design and optimization, energy-availability aware acquisition and communication, etc. This brief review presents several architectures and techniques for power management and optimization used typically in system level design which can be applied to WSN. A connection with System Level Design can lead in future to an

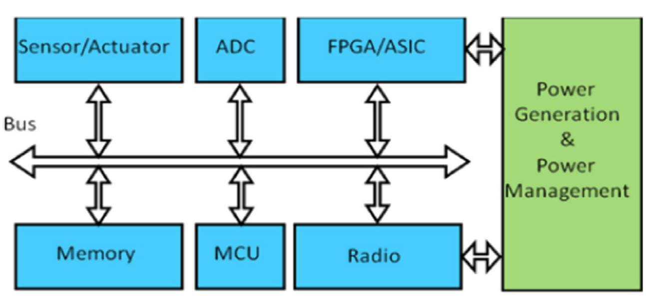

Fig. 1. Generic sensor node architecture.

electronic design automation flow for the next generation ultra-low power WSN platform design [27]. To create the premises for design automation in WSN, the paper reviews a number of techniques which can enable the implementation of these concepts in WSNs towards nano-Watt or energy neutral WSN systems. To reduce the design space, the paper presents several architectures and techniques for power optimization which are using the wake-up radio receiver technology. Some of these techniques are then applied to reduce the power consumption in the context of networked toy robot scenarios.

The paper is organized as follows. Section 2 presents a brief review of the wake-up radio architectures with an emphasis on low cost and low power consumption. Section 3 presents some aspects on smart power unit design using wake-up radio technology. Sections 4 and 5 present some low-power architectures for power gating and dynamic voltage-frequency scaling respectively. Section 6 presents some power reduction techniques based on multi-band radio communications. Finally, Section 7 presents some final remarks and conclusions.

2. Wake-up radio receivers

Similarly to the case of system level design, in WSN significant power consumption is spent during the data transport/communication (during both transmit and receive modes). In VLSI design it is widely accepted that asynchronous systems consume less power than the synchronous systems [7]. The asynchronous architectures are also more robust to variations and are optimized for the average case timing or power. In order to achieve the efficiency of asynchronous schemes in WSN, several wake-up radio receiver technologies were proposed in the recent literature. The main characteristic of such receiver is that the power consumption is orders of magnitudes lower than that of a typical transceiver. However, as a trade-off, the data rate is typically lower, sensitivity is also lower and the latency is usually higher. Some important features of a wake-up radio receiver are

a) Very low power consumption: the WUR power contribution to the overall power consumption should be negligible;
b) Very low number of false wake-ups: the WUR's ability to distinguish between the wake-up signal and unwanted signal as early as possible;
c) Flexibility and usability: in terms of re-use of existing transmitter and antenna.

A typical communication scenario involving a wake-up radio receiver is depicted in Fig. 2. A master node communicates with the slave node (which can also be a power hungry node or an IoT node) either through the wake-up radio receiver (WUR) or the main transceiver. GOOK modulation is typically used for wake-up

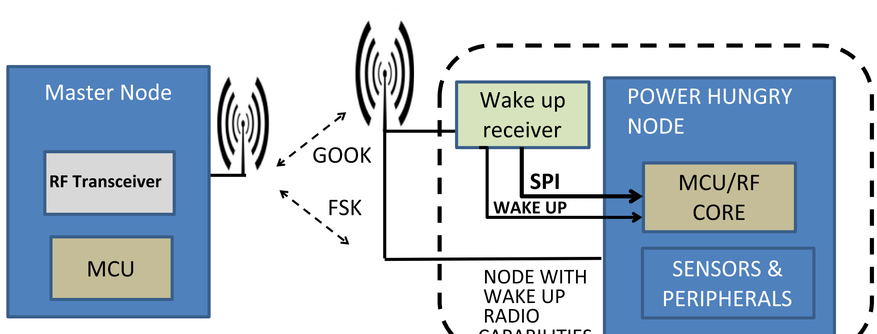

Fig. 2. Typical communication involving wake-up radio receiver, which uses a common antenna with the main transceiver.