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Wake-up Receiver Based Ultra-Low-Power WBAN

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Preface

Wireless body area networks (WBAN) need to operate on small batteries or energy harvesters for a long time. At the same time it is impossible to replace the batteries on a regular basis. Therefore, the sensors need to have very low power consumption. The overall power consumption is reduced by placing the sensor node in sleep mode as often and long as possible. It listens for a wake-up call transmitted by the network coordinator, and wakes up the rest of the node when needed. The book targets the design of the wake-up receiver. To minimize the power consumption it needs to be optimized for the WBAN applications.

A lot of research is done in the areas of network and system design of wireless body area networks on one hand and low-power receiver circuit design on the other hand. This book presents the cross-layer design and optimization of wake-up receivers for wireless body area networks (WBAN), with an emphasis on low-power circuit design. This includes the analysis of medium access control (MAC) protocols, mixer-first receiver design, and implications of receiver impairments on wideband frequency-shift-keying (FSK) receivers. The overall power consumption is reduced by exploiting the characteristics of body area networks. Specifically, the power consumption of FSK wake-up receivers is reduced by exploiting wideband FSK modulation, removing the LNA from the receiver chain and exchanging the ubiquitous PLL for the low-power automatic frequency control (AFC) loop. Within this book these effects are analyzed in-depth and validated by CMOS implementations.

The reader will get an overview of wireless body area network design from the network layer to the circuit implementation, and an overview of the cross-layer design trade-offs. Furthermore, the mixer-first receiver topology is analyzed and the implications of receiver impairments are analyzed. The theory is validated by two different receiver implementations, one in 90 nm and one in 40 nm CMOS technology. Moreover, the book gives a good overview of state-of-the-art wake-up-receiver research.

Contents

Abbreviations

ACK	Acknowledgment
AFC	Automatic Frequency Control
ARE	Average Relative Error
BAN	Body Area Network
BAW	Bulk Acoustic Wave
BER	Bit Error Rate
CNR	Carrier-to-Noise-Ratio
CW	Continuous-Wave
DCDM	Digital Cross-Differentiate Multiply
DCO	Digitally Controlled Oscillator
DNL	Differential Nonlinearity
EVM	Error Vector Magnitude
FACK	False Acknowledgment
FOM	Figure of Merit
FSK	Frequency Shift Keying
FSPL	Free Space Path Loss
IC	Inversion Coefficient
IIP3	Input referred third order interception point
LNA	Low Noise Amplifier
LO	Local Oscillator
MAC	Media Access Control
OOK	On-Off Keying
Pdf	Probability Density Function
PLL	Phase-Locked Loop
PSD	Power Spectral Density
PVT	Process, Voltage, and Temperature
RSSI	Received Signal Strength Indicator
SIR	Signal-to-Interferer-Ratio
SNR	Signal-to-Noise-Ratio
TDMA	Time Division Multiple Access
VGA	Variable Gain Amplifier
WBAN	Wireless Body Area Network
WUC	Wake-up call
WURx	Wake-up Receiver

Symbols

$a_{f,n}$	nth order Fourier cosine coefficient of function $f(t)$
a_n	Bit n from the bipolar bit sequence
α_n	Phase of the receiver generated noise vector
α_r	Phase of the received FSK signal corrupted by the LO phase noise
$b_{f,n}$	nth order Fourier sine coefficient of function $f(t)$
$c_{f,n}$	nth order complex Fourier series coefficient
C_{LO}	Phase noise thermal noise parameter
$\Delta\omega$	FSK frequency deviation
ΔP_x	Power consumption increase in mode x compared to sleep mode $P_x - P_{sleep}$
$\Delta T[n]$	Cycle-to-cycle jitter of the nth period
ε	I/Q phase error
F	Noise factor
f_{osc}	Oscillator oscillation frequency
g	I/Q gain error
G_{BB}	Gain in the baseband stage
G_{RF}	RF gain
G_t	Mixer transducer power gain
G_v	Mixer voltage conversion gain
h	FSK modulation index $h = \frac{\Delta\omega}{\pi Rb}$
$H_{I\&D}(\omega)$	Integrate-and-Dump filter
$H_{IF}(\omega)$	Intermediate frequency filter
k	Packet length
k_B	Boltzmann's constant $1.38065 \times 10^{-23} \mathrm{m^2\ kgs^{-2}K^{-1}}$
K_{LO}	Phase noise 1/f noise parameter
$\mathscr{L}(f)$	Phase noise at f Hz offset given in dBc/Hz
l	Address length
λ	Average packet rate
$\boldsymbol{M}_{rx}(t)$	Receiver matrix
μ	Electron mobility
μ_{ACKx}	Expected number of acknowledgment retransmissions
$\mu_{bcn/pkt}$	Expected number of synchronization beacons per received packet
μ_{FACKx}	Expected number of retransmitted false acknowledgments

μ_{slot}	Expected number of TDMA slots per received packet
μ_{WUC}	Expected number of wake-up calls
n_{bb}	Baseband input related noise
$n_i(t)$	Receiver input noise
N_{node}	Number of nodes in the network
n_{rf}	RF input-related noise
N_{WUC}^{+}	Maximal number of wake-up call transmissions
ω_o	Carrier frequency
ω_{off}	FSK frequency offset
P_{1dBc}	Input referred 1dB compression point
$p_{ACK\geq 1}$	Probability of initial acknowledgment transmission
$P_{BB}(\tau)$	Baseband-generated noise power at the output of the FSK demodulator
$P_{click}(\tau)$	Click noise power at the output of the FSK demodulator
$p_{FACK\geq 1}$	Probability of at least one false acknowledgment transmission
$p_{FACK,n}$	Probability that *n* false acknowledgment packets are send
p_{false}	False wake-up probability
$\varphi(t)$	Instantaneous phase of FSK modulated signal
$\varphi(t)$	FSK signal phase
P_{IIP3}	Input referred third order interception point
P_{LO}	Local oscillator power used to drive the mixer
p_{miss}	Packet miss probability
P_R	Power consumption in receive mode
$P_{RF}(\tau)$	RF-generated noise power at the output of the FSK demodulator
P_{Rset}	Power consumption when settling to receive mode
$P_s(\tau)$	Signal power at the output of the FSK demodulator
P_{sleep}	Power consumption in sleep mode
$P_{standby}$	Power consumption in standby mode
P_T	Power consumption in transmit mode
$P_{\dot{\theta}}(\tau)$	Phase noise power at the output of the FSK demodulator
P_{Tset}	Power consumption when settling to standby mode
P_{wake}	Power consumption when switching between sleep and standby mode
r	Radius of gyration
$R_{\dot{\alpha}_n}(\tau)$	Autocorrelation of the total demodulator output noise
$R_{\alpha_{nbb}}(\tau)$	Autocorrelation of the baseband noise phase component at the output of the receiver front-end
$R_{\alpha_{nrf}}(\tau)$	Autocorrelation of the RF noise phase component at the output of the receiver
R_b	Bit rate
R_{bw}	Wake-up receiver bit rate
$R_f(\tau)$	Autocorrelation of the transfer function from the baseband noise source to the signal phase at the receiver output
$R_g(\tau)$	Autocorrelation of the transfer function from the RF noise source to the signal phase at the receiver output
ρ	Carrier to noise ratio

$R_L^{'}$	Normalized load impedance
$R_{nbb}(\tau)$	Autocorrelation of the baseband noise source
$R_{nrf}\,(\tau)$	Autocorrelation of the RF noise source
r_{sw}	Switch on-resistance
$r(t)$	Received signal
$\boldsymbol{s}$	Signal vector at the output of the receiver front-end
SAW	Surface Acoustic Wave
σ_{abs}	Absolute time jitter standard deviation
σ_{bb}	Standard deviation of the baseband-generated noise
σ_i	Standard variation of the receiver input noise
σ_{pn}	Standard deviation of the receiver-generated phase noise
σ_{rf}	Standard deviation of the RF-generated noise
$\boldsymbol{s_n}$	Receiver-generated noise vector
$S_{nbb}(\omega)$	Power spectral density of the baseband noise at the FSK demodulator output
$S_{nrf}(\omega)$	Power spectral density of the RF noise at the FSK demodulator output
$\boldsymbol{s_r}$	FSK signal vector corrupted by LO phase noise
$\mathrm{S_y}(\omega)$	Power spectral density of the FSK demodulator output
T	Address decoding threshold
$\mathrm{T_{abs}}[n]$	Absolute jitter measure over n periods
$\mathrm{T_b}$	Bit period $\left(\frac{1}{R_b}\right)$
T_{beacon}	Maximal time between two TDMA synchronization beacons
$\theta(t)$	Local oscillator phase noise
T_{lat}	Maximally allowed link-setup latency
T_{mavg}	Integration time constant of the moving-average filter
τ_{off}	Mixer time constant when the switch is turned off
$T_{off,n}$	Mixer switch turn-off time of phase n
$\tau_{off}^{'}$	Mixer normalized off-state RC time constant
τ_{on}	Mixer time constant when the switch is turned on
$T_{on,n}$	Mixer switch turn-on time of phase n
$\tau_{on}^{'}$	Mixer normalized on-state RC time constant
T_s	Sample time
T_{set}	Receiver or transmitter settling period
T_{skew}	Maximal allowed clock skew between a TDMA master and sensor node
T_{wake}	Transition time between sleep and standby mode
V_T	Thermal voltage $\left(\frac{kT}{q}\right)$
$y(t)$	FSK demodulator output signal
Z_{in}	Mixer input impedance at the carrier frequency

Chapter 1
Introduction

Wireless Body Area Networks (WBANs) are small-scale, in both area and node count, networks centered on a human body. The low-power wireless nodes can contain many different sensors, for example: ECG, EEG, blood-pressure and temperature sensors.

While the required bit rate of the different sensors varies from a few kilobits per second up to a few hundred kilobits per second, most applications require a bit rate around 100 kbps, see [1, 2]. Additionally, the average packet rate of a sensor node is very low. Some nodes like temperature sensors may only transmit the measured data a couple of times a day, hence they are in sleep mode for more than 90 % of the time. Other sensor types like EEG and ECG might have high peak bit rates when they are active. However they are not activated most of the time. Additionally the required link to link setup latency requirement is relaxed, which favors asynchronous networks.

The sensor nodes are battery powered and have to operate for a long period of time, while it is often impossible or impractical to recharge or replace the batteries on a regular basis. Therefore, the sensor nodes need to have very low power consumption. Furthermore, since the network is centered around the human body, it is a small scale network by definition. The maximal distance between two nodes is approximately 10 m. Combining the small network scale with the low power requirement, a single-hop star network topology is a good fit. In such a network there is one master node, for example a smart phone, with a bigger power supply and higher processing capabilities. Thus the body area sensor network is highly asymmetric. The asymmetric nature of the network can be used to reduce the power consumption of the sensor nodes by mapping power intensive tasks on the high power master node or by choosing a synchronization scheme to make maximal use of the asymmetric power supply. Additionally, the sensitivity of the sensor node can be decreased by increasing the transmit power of the master node.

M. Lont et al., *Wake-up Receiver Based Ultra-Low-Power WBAN*,
Analog Circuits and Signal Processing, DOI: 10.1007/978-3-319-06450-5_1,

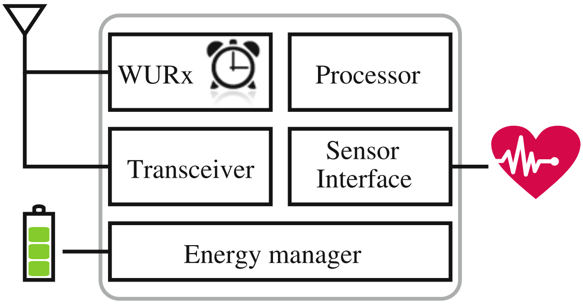

Fig. 1.1 A general wireless sensor node overview

1.1 Wake-Up Receiver

To reduce the sensor node power consumption to a level where the node can operate for months on a small battery the node needs to sleep as long and often as possible. A low-power Wake-up Receiver (WURx) is added to the sensor node which wakes up the node when it receives a Wake-up call (WUC) transmitted by the master node. Figure 1.1 gives the overview of a general wireless sensor node. Depending on the application the main transceiver might be omitted. A remote control application might only need a WURx for example.

The WURx should be capable of receiving and decoding a Wake-up call containing an address and possibly a few bits of settings and information. An address should be sent since we do not want to wake-up all the nodes in the network, as this would lead to a waste of power. In fact, the WURx is used to synchronize the master and sensor nodes only during the transmission of a packet. In between packet transmissions the network is not synchronized in order to save power.

This book focuses on the design and implementation of the wake-up receiver, both on the system level and circuit level.

1.2 Wake-Up Receiver Challenges

Figure 1.2 shows a schematic overview of the required bit rates and corresponding power consumption of current wireless standards. The depicted bit rate is the bit rate over the air. From the application point of view the actual bit rate may be lower because of channel coding, and synchronization overhead such as packet headers. It has to be noted that besides the bit rate and power consumption also sensitivity and linearity are important parameters. There is a clear trade-off between bit rate and power consumption. Within this book we target the low-power WURx application scenarios and low-bit-rate applications. As can be seen the targeted power consumption is much lower than state-of-the-art low-power standards like Zigbee, while still

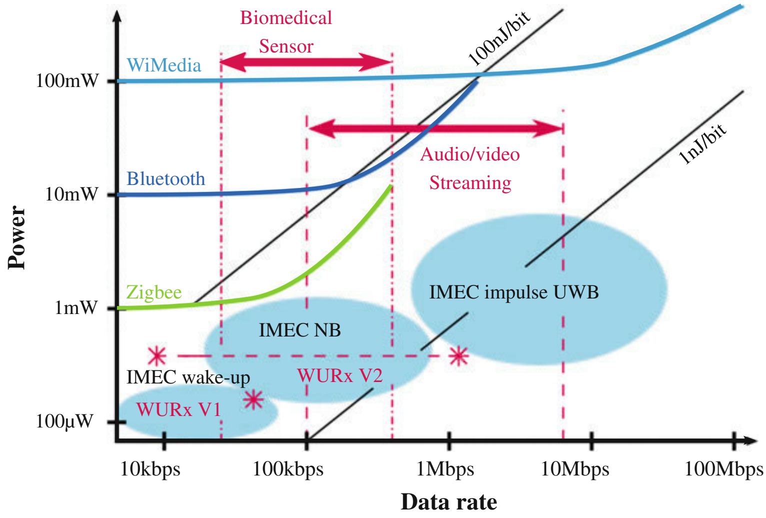

Fig. 1.2 Schematic overview of wireless standards and the presented wake-up receiver application areas

fulfilling the WBAN specific receiver requirements. The stars show the measurement results of the first (WURxV1) and second (WURxV2.1) wake-up receiver presented in Chaps. 5 and 6 in this book. The first version of the wake-up receiver front-end has a fixed bit rate of 50 kbps with a power consumption of 126 µW. While the second version has a constant power consumption of 329.6 µW with a variable bit rate between 6.25 and 1,250 kbps. Therefore, the second WURx is denoted by a region confined by two stars. For more information on the first and second version of the wake-up receiver front-end see Chaps. 5 and 6, respectively.

A small scale WBAN is targeted. Since the WBAN is inherently small-scale, the maximal transmission distance is 10 m. To reduce the power in the sensor nodes an asymmetric star-topology network is chosen. Moreover, there is a clear trade-off between power consumption and linearity. To reduce the power consumption the linearity is sacrificed. To avoid in-band interferer collision the master node manages the network, making sure that only one node is active. Additionally, the master node can avoid collisions with other networks by means of carrier sensing. The WURx itself should be able to cope with out-of-band interference. For a more in-depth discussion on the WURx specifications and requirements see Sect. 3.6.

1.3 Scope of the Book

Within this book the implications of Media Access Control (MAC)-layer synchronization on the power consumption will be studied, but the implementation of MAC protocols is beyond the scope of this book. Furthermore, there exists a large variety

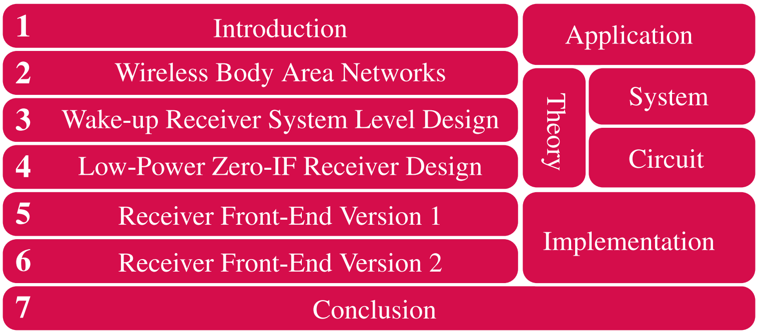

Fig. 1.3 Book outline

of wireless sensor networks with widely different requirements and characteristics. Each different network type demands different design trade-offs in order to come to an optimal low-power receiver front-end. Therefore, the book will only focus on small scale wireless networks, like wireless body area networks, and the design of low-power receiver front-ends used in the low-power sensor nodes in these networks. Moreover, this book focuses on the optimal circuit design of low-power Frequency Shift Keying (FSK) modulation based wake-up receivers. On-Off Keying (OOK) modulation will be mentioned but not analyzed in further detail since it is less robust against interferers. Circuits will only be implemented in silicon with the aim of validating proposed power reduction strategies. This book does not have as a goal to demonstrate a fully-integrated transceiver system. The circuits will only be implemented in CMOS technology since it is the most widely used technology and the technology of choice for highly integrated mixed-signal systems.

1.4 Book Outline

The outline of this book is depicted in Fig. 1.3.

Chapter 1 introduces Wireless Body Area Networks and the Wake-up Receiver concept. Furthermore, the trends in both industrial and academic research are summarized and remaining research challenges are identified.

In Chap. 2 several network and applications aspects of body area networks are studied. Since low energy consumption is essential, the impact of network synchronization on the energy consumption is studied at the MAC level. Additionally, common application related requirements are extracted from literature. By combining the application related WURx requirements and the MAC layer study the WURx solution space is derived.

Chapter 3 delves into the system-level aspects of the WURx design, starting with a literature study of state-of-the-art low-power receivers with special attention on the chosen modulation schemes. A Zero-IF receiver architecture is chosen, because of the