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

$a_{f,n}$  $n$th order Fourier cosine coefficient of function $f(t)$
$a_n$  Bit $n$ from the bipolar bit sequence
$\varphi_n$  Phase of the receiver generated noise vector
$\varphi_r$  Phase of the received FSK signal corrupted by the LO phase noise
$b_{f,n}$  $n$th order Fourier sine coefficient of function $f(t)$
$c_{f,n}$  $n$th order complex Fourier series coefficient
$C_{LO}$  Phase noise thermal noise parameter
$\Delta\omega$  FSK frequency deviation
$\Delta P_x$  Power consumption increase in mode $x$ compared to sleep mode $P_x - P_{sleep}$
$\Delta T[n]$  Cycle-to-cycle jitter of the $n$th period
$\varepsilon$  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 $h = \frac{\Delta\omega}{\pi R_b}$
$H_{I&D}(\omega)$  Integrate-and-Dump filter
$H_{IF}(\omega)$  Intermediate frequency filter
$k$  Packet length
$k_B$  Boltzmann’s constant $1.38065 \times 10^{-23}$ m$^2$ kgs$^{-2}$K$^{-1}$
$K_{LO}$  Phase noise 1/f noise parameter
$L(f)$  Phase noise at $f$ Hz offset given in dBc/Hz
$l$  Address length
$\lambda$  Average packet rate
$M_{rx}(t)$  Receiver matrix
$\mu$  Electron mobility
$\mu_{ACKx}$  Expected number of acknowledgment retransmissions
$\mu_{bcn/pkt}$  Expected number of synchronization beacons per received packet
$\mu_{FACKx}$  Expected number of retransmitted false acknowledgments
\( \mu_{\text{slot}} \) Expected number of TDMA slots per received packet

\( \mu_{\text{WUC}} \) Expected number of wake-up calls

\( n_{\text{bb}} \) Baseband input related noise

\( n_i(t) \) Receiver input noise

\( N_{\text{node}} \) Number of nodes in the network

\( n_f \) RF input-related noise

\( N_{\text{WUC}}^+ \) Maximal number of wake-up call transmissions

\( \omega_o \) Carrier frequency

\( \omega_{\text{off}} \) FSK frequency offset

\( P_{1\text{dBc}} \) Input referred 1dB compression point

\( P_{\text{ACK}} \geq 1 \) Probability of initial acknowledgment transmission

\( P_{\text{BB}}(\tau) \) Baseband-generated noise power at the output of the FSK demodulator

\( P_{\text{click}}(\tau) \) Click noise power at the output of the FSK demodulator

\( P_{\text{FACK}} \geq 1 \) Probability of at least one false acknowledgment transmission

\( P_{\text{FACK},n} \) Probability that \( n \) false acknowledgment packets are send

\( p_{\text{false}} \) False wake-up probability

\( \phi(t) \) Instantaneous phase of FSK modulated signal

\( \phi(t) \) FSK signal phase

\( P_{\text{HP3}} \) Input referred third order interception point

\( P_{\text{LO}} \) Local oscillator power used to drive the mixer

\( p_{\text{miss}} \) Packet miss probability

\( P_R \) Power consumption in receive mode

\( P_{\text{RF}}(\tau) \) RF-generated noise power at the output of the FSK demodulator

\( P_{\text{Reset}} \) Power consumption when settling to receive mode

\( P_s(\tau) \) Signal power at the output of the FSK demodulator

\( P_{\text{Sleep}} \) Power consumption in sleep mode

\( P_{\text{Standby}} \) Power consumption in standby mode

\( P_T \) Power consumption in transmit mode

\( P_{\theta}(\tau) \) Phase noise power at the output of the FSK demodulator

\( P_{\text{Reset}} \) Power consumption when settling to standby mode

\( P_{\text{Wake}} \) Power consumption when switching between sleep and standby mode

\( r \) Radius of gyration

\( R_s(\tau) \) Autocorrelation of the total demodulator output noise

\( R_{\text{bb}}(\tau) \) Autocorrelation of the baseband noise phase component at the output of the receiver front-end

\( R_{\text{rf}}(\tau) \) Autocorrelation of the RF noise phase component at the output of the receiver

\( R_{\text{bw}} \) Wake-up receiver bit rate

\( R_{\text{bw}} \) Wake-up receiver bit rate

\( R_{\text{f}}(\tau) \) Autocorrelation of the transfer function from the baseband noise source to the signal phase at the receiver output

\( R_{\text{g}}(\tau) \) Autocorrelation of the transfer function from the RF noise source to the signal phase at the receiver output

\( \rho \) Carrier to noise ratio
Symbols

\( R_L \)  Normalized load impedance
\( R_{\text{nnb}}(\tau) \) Autocorrelation of the baseband noise source
\( R_{\text{nref}}(\tau) \) Autocorrelation of the RF noise source
\( r_{\text{sw}} \) Switch on-resistance
\( r(t) \) Received signal
\( s \) Signal vector at the output of the receiver front-end
SAW Surface Acoustic Wave
\( \sigma_{\text{abs}} \) Absolute time jitter standard deviation
\( \sigma_{\text{bb}} \) Standard deviation of the baseband-generated noise
\( \sigma_{\text{i}} \) Standard variation of the receiver input noise
\( \sigma_{\text{pn}} \) Standard deviation of the receiver-generated phase noise
\( \sigma_{\text{rf}} \) Standard deviation of the RF-generated noise
\( s_n \) Receiver-generated noise vector
\( S_{\text{nnb}}(\omega) \) Power spectral density of the baseband noise at the FSK demodulator output
\( S_{\text{nrf}}(\omega) \) Power spectral density of the RF noise at the FSK demodulator output
\( s_r \) FSK signal vector corrupted by LO phase noise
\( S_{\text{y}}(\omega) \) Power spectral density of the FSK demodulator output
\( T \) Address decoding threshold
\( T_{\text{abs}}[n] \) Absolute jitter measure over n periods
\( T_b \) Bit period \( \left( \frac{1}{R_L} \right) \)
\( T_{\text{beacon}} \) Maximal time between two TDMA synchronization beacons
\( \theta(t) \) Local oscillator phase noise
\( T_{\text{lat}} \) Maximally allowed link-setup latency
\( T_{\text{mavg}} \) Integration time constant of the moving-average filter
\( T_{\text{off}} \) Mixer time constant when the switch is turned off
\( T_{\text{off},n} \) Mixer switch turn-off time of phase n
\( T_{\text{off}} \) Mixer normalized off-state RC time constant
\( T_{\text{on}} \) Mixer time constant when the switch is turned on
\( T_{\text{on},n} \) Mixer switch turn-on time of phase n
\( T_{\text{on}} \) Mixer normalized on-state RC time constant
\( T_s \) Sample time
\( T_{\text{set}} \) Receiver or transmitter settling period
\( T_{\text{skew}} \) Maximal allowed clock skew between a TDMA master and sensor node
\( T_{\text{wake}} \) Transition time between sleep and standby mode
\( V_T \) Thermal voltage \( \left( \frac{kT}{q} \right) \)
\( y(t) \) FSK demodulator output signal
\( Z_{\text{in}} \) Mixer input impedance at the carrier frequency