The Third International Conference on Sensor Technologies and Applications

SENSORCOMM 2009

18-23 June 2009
Athens/Glyfada, Greece
SensorComm 1: PESMOSN I
A Link Quality Evaluation Model in Wireless Sensor Networks ......................................................1
Zhu Jian and Zhao Hai
Sensor Nodes Localization Algorithm in Noisy Environments .........................................................6
Antoine Amossé, Ioannis Lambadaris, and Jérôme Talim
CSMA-MAC Performance Evaluation for WSN Applications ..............................................................13
Christos Antonopoulos, Aggeliki Prayati, Fotis Kerasiotis, and George Papadopoulos
Distributed Source Coding for Sensor Data Model and Estimation of Cluster Head Errors Using Bayesian and K-Near Neighborhood Classifiers in Deployment of Dense Wireless Sensor Networks ..................................................19
Vasanth Iyer, S. S. Iyengar, N. Balakrishnan, Vir. Phoha, and G. Rama Murthy
SensorComm 2: PESMOSN II
On the Relationship between Network Congestion and Local Contention in IEEE 802.15.4 Based Networks .................................................................................................................25
Radosveta Sokullu
Zigbee Based Reconfigurable Clustered Home Area Network .............................................................32
Saad Ahmad Khan, Fahad Ahmad Khan, Arslan Shahid, and Zubair Ahmad Khan
Simulink Modeling of the 802.15.4 Physical Layer for Model-Based Design of Wireless Sensor Networks .................................................................38
  Al-Khateeb Anwar and Luciano Lavagno

Clustering with Discrete Power Control in Wireless Sensor Networks .................................................................43
  Nauman Aslam, William Robertson, and William Phillips

SENSORCOMM 3: PESMOSN III
An Evaluation of the Cost and Energy Consumption of Security Protocols in WSNs .................................................................49
  Kahina Kabri and Dominique Seret

Mobility Models for Delay-Tolerant Mobile Networks .................................................................55
  Ha Dang and Hongyi Wu

Performance Analysis of ZigBee-Based Wireless Sensor Networks with Path-Constrained Mobile Sink(s) .................................................................61
  N. Vlajic and D. Stevanovic

Estimation of Mobile Trajectory in a Wireless Network: A Basis for User's Mobility Profiling for Mobile Trajectory Based Services .................................................................69
  Sarfraz Khokhar and Arne A. Nilsson

SENSORCOMM 4: SECSED I
Cross Sensitivity Study for Ammonia Detection in Ultra Violet Region Using an Optical Fibre Sensor .................................................................75
  Hadi Manap, Gerald Dooly, Razali Muda, Sinead O'Keeffe, and Elfed Lewis

Fabrication of a Glucose Biosensor by Piezoelectric Inkjet Printing .................................................................82
  Tianming Wang, Chris Cook, and Brian Derby

CMOS Nanostructures with Improved Temperature Behavior Using Double Differential Structures .................................................................86
  Cosmin Radu Popa

Smart Sensing Polymeric Foil with Integrated Optic Fiber Sensors: Fabrication and Characterization of a Polymeric Foil Sensitive to Strain .................................................................90

SENSORCOMM 5: SECSED II
Multi-sensor Embedded System for Agro-Industrial Applications .................................................................94
  Chandani Anand, Shashikant Sadistap, Satish Bindal, and K. S. N. Rao

Inductive Displacement Sensor for Force Measuring in Humanoid Robotic Application: Testing the Invariance on Angular Displacement .................................................................100
  Snezana M. Djuric, Laszlo Nagy, and Mirjana Damnjanovic

ZigBee-Ready Wireless Water Leak Detector .................................................................105
  Anders Pettersson, Johan Nordlander, and Shaofang Gong
SENSORCOMM 6: SAPSN I

The RUNES Architecture for Reconfigurable Embedded and Sensor Networks .............................................. 109
  Frank Oldewurtel, Janne Riihijärvi, Krisakorn Rerkrai, and Petri Mähönen

Mote Runner: A Multi-language Virtual Machine for Small Embedded Devices .............................................. 117
  A. Caracaş, T. Kramp, M. Baentsch, M. Oestreicher, T. Eirich, and I. Romanov

Negotiated Rational Commitment and Decommitment in Sensor Webs ...................................................... 126
  Heather Amthauer, Edward Komp, and Costas Tsatsoulis

Energy Bucket: A Tool for Power Profiling and Debugging of Sensor Nodes .............................................. 132
  Jacob Andersen and Morten Tranberg Hansen

SENSORCOMM 7: SAPSN II

A Wireless Actuator-Sensor Neural Network for Evacuation Routing ................................................................. 139
  A. Jankowska, M. C. Schut, and N. Ferreira-Schut

Ontological Middleware for Dynamic Wireless Sensor Data Processing ..................................................... 145
  Laurent Gomez and Annett Laube

Indoor Location System Using ZigBee Technology ......................................................................................... 152
  Gomes Gonçalo and Sarmento Helena

An Elderly Health Care System Using Wireless Sensor Networks at Home .............................................. 158
  Hongwei Huo, Youzhi Xu, Hairong Yan, Saad Mubeen, and Hongke Zhang

SENSORCOMM 8: RIWISN I

Comparison between the Actual Microwave Terrestrial Links Performance and Different Models ................................................. 164
  Diaa Sayed, Hesham Badwy, and Hadya El Hennawy

An Ultra Low Power Wakeup Receiver for Wireless Sensor Nodes ................................................................. 167
  Marco Spinola Durante and Stefan Mahlknecht

Spatial Diversity for Short Range Communication in Home Care Systems Using One Antenna Element ................................................. 171
  Markku J. Rossi

Coupling and Correlation Reduction in Compact Arrays for WSN Nodes via Pre-fractal Defected Ground Plane ................................................. 175
  Constantine G. Kakoyiannis and Philip Constantinou

SENSORCOMM 9: RIWISN II

Frequency Scanning Using Software Defined Radio for Localised Range Estimation ................................................. 181
  K. Mohamad Yusof, John Woods, and Steve Fitz

Semidefinite Programming for Wireless Sensor Localization with Lognormal Shadowing ................................................. 187
  Abdullah H. Al-Dhalan and Ioannis Lambadaris

A Practical RF Propagation Model for Wireless Network Sensors ................................................................. 194
  Tsenka Stoyanova, Fotis Kerasiotis, Aggeliki Prayati, and George Papadopoulos
Coexistence Issues of 2.4GHz Sensor Networks with Other RF Devices at Home .................................................................200

Hongwei Huo, Youzhi Xu, Celal Can Bilen, and Hongke Zhang

SENSORCOMM 10: RIWISN III

A Study of the RF Characteristics for Wireless Sensor Deployment in Building Environment .................................................................206

Essa Jafer, Brendan O’Flynn, Cian O’Mathuna, and Rosta Spinar

Joint TOA Estimation and NLOS Identification for UWB Localization Systems .................................................................212

Abdelmadjid Maali, Abdelaziz Ouldali, Hassane Mimoun, and Geneviève Baudoin

A Retransmission Cut-Off Random Access Protocol with Multi-packet Reception Capability for Wireless Networks .................................................................217

Jahangir H. Sarker and Hussein T. Mouftah

Improving Location Identification in Wireless Ad Hoc/Sensor Networks Using GDOP Theory .................................................................223

Yifan Zhao, Chung-Horng Lung, Ioannis Lambadaris, and Nishith Goel

SENSORCOMM 11: ENOPT I

Energy-Efficient Circular Sector Sensing Coverage Model for Wireless Sensor Networks .................................................................229

Peter Soreanu and Zeev Volkovich

Coverage Efficient Clustering with a Minimum Number of Active Sensors for Wireless Sensor Networks .................................................................234

Ji Gong and Gihwan Cho

Scheduling Real-Time of the Synchronous Hybrid Tasks under Energy Constraint .................................................................240

Akli Abbas, Hamid Hentous, and Tayeb Kenaza

Energy Harvesting in Substations for Powering Autonomous Sensors .................................................................246

M. Zhu, M. D. Judd, and P. J. Moore

Particle Filtering Based on Sign of Innovation for Tracking a Jump Markovian Motion in a Binary WSN .................................................................252

Fatma Aounallah, Rim Amara, and Monia Turki-Hadj Alouane

SENSORCOMM 12: ENOPT II

Adaptive Cluster-Based Scheduling Management for Wireless Ad-Hoc Sensor Networks .................................................................256

Ying-Chih Chen and Chih-Yu Wen

Multiple Mobile Sinks Positioning in Wireless Sensor Networks for Buildings .................................................................264

Leila Ben Saad and Bernard Tourancheau

Implementation of Source and Channel Coding for Power Reduction in Medical Application Wireless Sensor Network .................................................................271

Richard Mc Sweeney, Christian Spagnol, Emanuel Popovici, and Luigi Giancardi
    Md Enamul Haque, Noriko Matsumoto, and Norihiko Yoshida

SENSORCOMM 13: UNWAT I

Experimental Study of Acoustic Forward Scattering on a Marine Shelf ..................................................284
    Alexander L. Matveev, Pavel I. Korotin, Victor I. Turchin, Daniel Rouseff, and Robert C. Spindel
A Simple Time Synchronization Method for Underwater Communication Receivers ................................................289
    Guosong Zhang, Jens M. Hovem, Hefeng Dong, and Tor A. Reinen
An RFID Based System for the Underwater Tracking of Pebbles on Artificial Coarse Beaches ..........................................................294
    Giuliano Benelli, Alessandro Pozzebon, Gianluca Raguseo, Duccio Bertoni, and Giovanni Sarti

SENSORCOMM 14: UNWAT II

Underwater Acoustic Networks - Survey on Communication Challenges with Transmission Simulations ........................................................................300
    Håkon Riksfjord, Ole Trygve Haug, and Jens M. Hovem
Software Architecture for Self-Adapting Sub-sea Sensor Networks: Work in Progress .........................................................306
    Svein Hallsteinsen and Richard Torbjørn Sanders
Performance Results of a Prototype Board Designed for Copper Data Transmission in KM3NeT ........................................................................310
    Fabrizio Ameli, Stefano Russo, Gabriele Giovanetti, and Fabrice Gensolen

SENSORCOMM 15: MECSN

Software Calibration of Wirelessly Networked Sensors ..............................................................................314
    Bernard Tourancheau, Yannis Mazzer, Valentin Gavan, Frédéric Kuznik, and Gérard Krauss
A Novel Quorum Based Location Management for Wireless Sensor Network with Mobile Sinks ........................................................................320
    Yi Li, Canfeng Chen, and Jian Ma
A Variable Threats Based Self-Organization Scheme for Wireless Sensor Networks .................................................................327
    Jian Zhong and Peter Bertok
    Valeria Losciri, Enrico Natalizio, Carmelo Costanzo, Francesca Guerriero, and Antonio Violi
Topology Control in Wireless Sensor Networks ..................................................................................339
    Nitin Choubey and Shrisha Rao
SENSORCOMM 16: RASQOFT
A Technique to Identify and Substitute Faulty Nodes in Wireless Sensor Networks ........................................................346
   Anas Abu Taleb, Dhiraj K. Pradhan, and Taskin Kocak
A Cellular Approach to Fault Detection and Recovery in Wireless Sensor Networks ......................................................352
   M. Asim, H. Mokhtar, and M. Merabti
Definition and Evaluation of Local Path Recovery Mechanisms in Wireless Sensor and Actuator Networks .................................358
   Pieter De Mil, Eli De Poorter, Benoît Latré, Ingrid Moerman, and Piet Demeester
A Survey on Fault Tolerant Routing Techniques in Wireless Sensor Networks ..........................................................366
   Hind Alwan and Anjali Agarwal

SENSORCOMM 17: DISN I
Agricultural Monitoring Based on Wireless Sensor Network Technology: Real Long Life Deployments for Physiology and Pathogens Control ........................................................372
   Luca Bencini, Francesco Chiti, Giovanni Collodi, Davide Di Palma, Romano Fantacci, Antonio Manes, and Gianfranco Manes
Experiences of Deploying an Indoor Building Sensor Network ..................................................................................378
   Malka N. Halgamuge, Toong-Khuan Chan, and Priyan Mendis
WILLEM: A Wireless InteLLigent Evacuation Method ..................................................................................382
   W. H. van Willigen, R. M. Neef, A. van Lieburg, and Martijn C. Schut
A Wireless Multimedia Sensor Network Based Intelligent Safety and Security System (IS³) ........................................388
   Nassar Ikram, Shakeel Durranii, Hasan Sajid, and Husnain Saeed

SENSORCOMM 18: DISN II
Design and Implementation of Sensor Tag Middleware for Monitoring Containers in Logistics Systems .................................................393
   Gihong Kim, Md. Kafil Uddin, and Bonghee Hong
Energy Efficient Sensor Network with Service Discovery for Smart Home Environments ..................................................399
   Harri Pensas, Henrik Raula, and Jukka Vanhala
Real-Time Wireless Sensor Network for Landslide Detection ............................................................................405
   Maneesha V. Ramesh
Sensor Network for Gas Meter Application ............................................................................................................410
   David C. Ni and Chou Hsin Chin
Real Deployments of Wireless Sensor Networks .......................................................................................................415
   Diana Bri, Miguel Garcia, Jaime Lloret, and Petre Dini
SENSORCOMM 19: SEMOSN I
Secure Broadcast in Wireless Sensor Networks .................................................................424
Qian Yu and Chang N. Zhang
The ANGEL WSN Security Architecture ..........................................................................430
Oscar García-Morchon and Heribert Baldus
Combined Malicious Node Discovery and Self-Destruction Technique
for Wireless Sensor Networks ............................................................................................436
Daniel-Ioan Curiac, Madalin Plastoi, Ovidiu Banias, Constantin Volosencu,
Roxana Tudoroiu, and Alexa Doboli
Establishing Pairwise Keys in Heterogeneous Two-Tiered Wireless Sensor
Networks ................................................................................................................................442
Manel Boujelben, Omar Cheikhrouhou, Mohamed Abid, and Habib Youssef

SENSORCOMM 20: SEMOSN II
SecSens - Security Architecture for Wireless Sensor Networks ..........................................449
Faruk Bagci, Theo Ungerer, and Nader Bagherzadeh
PDoS-Resilient Push Protocols for Sensor Networks ........................................................455
Matthias Enzmann, Christoph Krauß, and Claudia Eckert
A Game Theory Approach to Detect Malicious Nodes in Wireless Sensor
Networks ................................................................................................................................462
Yenumula B. Reddy

SENSORCOMM 21: Work in Progress
Transport Layer Multipath on Wireless Sensor Network Backhaul Links ..........................469
Nikolas Stephan, Socrates Varakliotis, and Peter Kirstein
BSCP: Buckup Scheduling Mecanism for Coverage Perserving in WSNs ........................473
Manel Chenait, Bahia Zebbane, Nadib Badache, and Houda Zeghilet
Building an Underwater Wireless Sensor Network Based on Optical:
Communication: Research Challenges and Current Results .............................................476
Davide Anguita, Davide Brizzolara, and Giancarlo Parodi

SENSORCOMM 22: DAIPSN
Inductive as a Support of Deductive Data Visualisation in Wireless Sensor
Networks .................................................................................................................................480
Mohammad Hammoudeh, Robert Newman, Christopher Dennett, and Sarah Mount
Sang Gi Hong, Young Bag Moon, Sang Joon Park, and Whan Woo Kim
Spatial Multiplexing Turbo Receiver with Reduced Complexity ....................................490
Andrei Nedelcu, Radu Lupoaie, Andrei A. Enescu, Cristian Anghel,
and Constantin Paleologu
Identification and Validation of Spatio-Temporal Associations in Wireless Sensor Networks ..........................................................496

Bakhtiar Qutub Ali, Niki Pissinou, and Kia Makki

K-RLE: A New Data Compression Algorithm for Wireless Sensor Network .................................................................502

Eugène Pamba Capo-Chichi, Hervé Guyennet, and Jean-Michel Friedt

SENSORCOMM 23: APASN I

An Efficient and Scalable Prioritized MAC Protocol (PMAC) for Backbone Communication in Wireless Sensor Networks ..........................................................508

Lei Pan, Hongyi Wu, and Nian-Feng Tzeng

A Proportional Load Balancing for Wireless Sensor Networks .......................................................................................514

İsmail Tellioglu and Haci A. Mantar

Nonparametric Boxed Belief Propagation for Localization in Wireless Sensor Networks ..........................................................520

Vladimir Savic and Santiago Zazo

Soft Threshold Based Cluster-Head Selection Algorithm for Wireless Sensor Networks ..........................................................526

Rong Ding, Bing Yang, Lei Yang, and Jiawei Wang

SENSORCOMM 24: APASN II

Energy-Efficient Multiple Query Optimization for Wireless Sensor Networks ..........................................................531

Yu Won Lee, Ki Yong Lee, and Myoung Ho Kim

A Location-Independent Node Scheduling for Heterogeneous Wireless Sensor Networks ..........................................................539

Huanzhao Wang, Fanzhi Meng, Hanmei Luo, and Ting Zhou

Processing Top-k Monitoring Queries in Wireless Sensor Networks .......................................................................................545

Mai Hai Thanh, Ki Yong Lee, Yu Won Lee, and Myoung Ho Kim

An Information Driven Sensornet Architecture ..................................................................................553

Eli De Poorter, Ingrid Moerman, and Piet Demeester

SENSORCOMM 25: APASN III

A Hotline-Based Reliable Topology for Wireless Sensor Networks ..........................................................562

Ali Tufail, Syed Ali Khayam, Son Dong Hwan, and Ki-Hyung Kim

Multi-objective Cross-Layer Algorithm for Routing over Wireless Sensor Networks ..........................................................568

Berta Carballido Villaverde, Susan Rea, and Dirk Pesch

Integrity-Checking Framework: An In-situ Testing and Validation Framework for Wireless Sensor and Actuator Networks ..........................................................575

S. Pennington, T. Baugé, and B. Murray
SENSORCOMM 26: APASN IV
Integrating Wireless Sensor Networks into Enterprise Information Systems
by Using Web Services .................................................................580
Ioakeim K. Samaras, John V. Gialelis, and George D. Hassapis
The CBK-Neigh Protocol for Symmetric Topology Control in Ad Hoc Networks ..................588
Farnoosh Jalalinia and Saeed Ghasemi
Graphical Models for Distributed Inference in Wireless Sensor Networks ..........................596
Neeta Trivedi and N. Balakrishnan
Energy-Efficient TDMA-Based MAC Protocol for Wireless Body Area Networks ................604
Stevan Marinkovic, Christian Spagnol, and Emanuel Popovici

SENSORCOMM 27: APASN V
Programming Wireless Sensor Networks in a Self-Stabilizing Style ..................................610
Christoph Weyer, Volker Turau, Andreas Lagemann, and Jörg Nolte
W-LBP: Wavelet-Based Loopy Belief Propagation for Wireless Sensor Networks .................617
Wei Zhao and Yao Liang
MLMAC-UL and ECTS-MAC - Two MAC Protocols for Wireless Sensor Networks with Unidirectional Links ..................................................623
Stephan Mank, Reinhardt Karnapke, and Jörg Nolte
Architecture Development for Efficient Sensor Tag Management .......................................630
Md. Kafil Uddin, Gihong Kim, and Bonghee Hong

SENSORCOMM 28: APASN VI
A Comparison of Bayesian Filter Based Approaches for Patient Localization during Emergency Response to Crisis .............................................636
Ashok-Kumar Chandra-Sekaran, Pascal Weiss, Klaus D. Müller-Glaser, and Christophe Kunze
Non-location-based Mobile Sensor Relocation in a Hybrid Static-Mobile Wireless Sensor Network .................................................................643
Fang-Jing Wu, Hsiu-Chi Hsu, Yu-Che Tseng, and Chi-Fu Huang
IPv6 Label Switching on IEEE 802.15.4 ..............................................................................650
Udo Payer, Stefan Kraxberger, and Peter Holzer
Jaehyun Kim, Jaiyong Lee, and Seoggyu Kim

SENSORCOMM 29: APASN VII
WSN Self-Address Collision Detection and Solving .........................................................665
Carlos Ribeiro, Ivo Anastácio, André Costa, and Márcia Baptista
Failure Tolerance Analysis of a Small Scale Underwater Sensor Network with RF Electromagnetic Communications .................................................................671
   Xianhui Che, Ian Wells, Gordon Dickers, Paul Kear, Xiaochun Gong, and Mark Rhodes
Adaptable Probabilistic Transmission Framework for Wireless Sensor Networks ..................................................................................................................676
   Chih-Kuang Lin, Vladimir Zadorozhny, and Prashant Krishnamurthy
Transaction Processing for Complete Reading of Semi-passive Sensor Tag .................................................683
   Soohan Kim, Wooseok Ryu, and Bonghee Hong

SENSORCOMM 30: APASN VII

Comparisons of 6LoWPAN Implementations on Wireless Sensor Networks .............................................689
   Yannis Mazzer and Bernard Tourancheau
A Fault-Tolerant Target Location Detection Algorithm in Sensor Networks .............................................693
   Chiu-Kuo Liang and Chih-Shiuan Li
On the Energy Consumption of Fast Convergecast in Wireless Networks ..............................................699
   Gruia Călinescu

Author Index ............................................................................................................................................705
An ultra low power Wakeup Receiver for Wireless Sensor Nodes

Marco Spinola Durante, Stefan Mahlknecht
Vienna University of Technology
Institute of Computer Technology, Gusshausstr. 27-29
1090 Vienna, Austria
{spinola,mahlknecht}@ict.tuwien.ac.at

Abstract

An ultra-low power 2.4 GHz RF Wakeup Receiver is designed for wireless sensor networks nodes. The receiver demodulates On-Off Keying at 100 kbps. A 120 nm CMOS chip includes the analog front-end and consumes only 7.5 μW from a single 1.5 V supply. The digital signal processing is implemented in an FPGA. The results of measures and simulations are evaluated for the use of this receiver in wireless sensor networks.

Keywords: Wakeup Receiver, OOK, ultra low power, Wireless Sensor Networks

1. Introduction

Nearly 75% [[1]] of the total power consumed from a typical WSN node is attributed to the radio transceiver. One main cause is the receiver which has to be turned on frequently in order to listen to possible incoming messages and to avoid high latency communication. The channel is sampled using intelligent strategies in the MAC layer such as described in [[1]] or [[3]] in order to synchronize communications and optimize power consumption. By using these strategies, very low power consumption is only achieved at cost of data throughput and latency, because communication occurs only during small time windows at low periods (e.g. once per second). In such situations packets have a worst case end-to-end delay equivalent ideally to the period of the cycle multiplied by number of hops.

The main task of this work was to realize a lower performance but very efficient receiver (called Wakeup Receiver or WUR) that consumes as little power as possible (the goal is 10 μW), so that it can be always active, detecting incoming wakeup messages (a few bytes) without compromising the lifetime of the node which can be of some years. The WUR acts as a remote control to activate the main transceiver for data communication. The biggest advantage of a WUR is that no synchronization between nodes is required for the communication, simplifying the MAC strategy and lowering the end-to-end delay of packets. Integrated Wakeup Receiver front-end designs have only been published by the Berkeley wireless research group [[4], [5]]. To a minor extent a concept can also be found in [[7]].

The work presented in [[4]] has a slightly different architecture: the RF signal is amplified by 10 dB (requiring 48 μW), the output is fed to the envelope detector that is sampled from a 6 bit ADC (requiring 13.8 μW). The additional energy needed from the digital baseband is not estimated at all.

The architecture of [[5]] differentiates from this work by mixing the RF signal to a lower frequency by the means of an imprecise local oscillator. The downmixed signal is then fed to the envelope detector that has looser requirements, because the operating frequency is much lower. This results in higher sensitivity (-72 dBm) because of mixing gain, although 28 μW are needed from the oscillator and mixer.

This work is divided in four sections. Section two explains the architecture of the wakeup receiver in its details. Section three presents the results of measures and simulations of this work. Section four gives an outlook on the work and presents its future developments.

2. Receiver architecture

In order to reach the goal of <10 μW in power consumption of the receiver, one has to simplify the design and to get rid of the power hungry components of typical radio receivers (like the superheterodyne receiver), such as the mixer or the low noise amplifiers that are found on the RF signal path. On-Off Keying (OOK) modulation is chosen because it allows
simplification of the RF demodulation and also because the short wakeup message with low bit count does not require highly precise synchronization. Together with a forward error correction (FEC) based correlation receiver, a better robustness of the wakeup link can be achieved with minimum power overhead.

The proposed block diagram of the WUR is shown in Fig. 1. The external matching builds a filter for the desired RF band as found in common receiver designs. The analog front-end (realized on-chip) converts the 2.4 GHz RF input signal into baseband signals, which are decoded by the correlation receiver realized on an FPGA.

### 2.1. Analog front-end

The front-end converts the OOK signal directly to baseband from the 50 Ω input eliminating the need of oscillators and PLLs using a simple envelope detector. This technique is also exploited in RFID tags and needs little other blocks to demodulate the incoming signal. Fig. 2 shows the schematic of the envelope detector as also described in [6] and [8].

The envelope detector is realized in two versions: on-chip with a MOS detector and off-chip with Schottky diodes and completely passive. Unfortunately, on-chip shottky diodes are not available in the given technology. Envelope detectors have the disadvantage that their exponential and quadratic nonlinearity means at least a factor two drop in efficiency that is a drop of 20 dB in the demodulated amplitude for each drop of 10 dB in the input RF amplitude.

![Fig. 2. MOS and Schottky envelope detectors](image)

This limits particularly the sensitivity of the detector and of the overall receiver. This behavior can be seen in Fig. 3, which shows measured values of the output amplitude versus input amplitude modulating the 100% AM RF carrier. The chart shows little difference between MOS and Schottky, because the external matching was trimmed to give equivalent results between the detectors. The 1:1 curve shows the ideal efficiency of the envelope detector. For a given matching, the MOS detector performs worse because the quadratic nonlinearity is lower than the exponential nonlinearity of the diode.

![Fig. 3. Detector efficiency](image)

In a second stage, the signal produced from the envelope detector is amplified with programmable gain (54 dB maximum gain) and variable bandwidth (0.1-10 KHz to 1 MHz). A programmable integrator is needed to reduce noise of the system adding only 1.5 µW in power consumption. The output of the integrator is then level shifted and processed from the correlation receiver.

### 2.2. Correlation receiver

For reasons of flexibility in implementation, the decoding of the signal in the digital domain is realized in an FPGA and will be realized on-chip in a future version. The first stage of the decoder is a state machine correlating the output of the integrator to one symbol and taking a decision on the value of the bit. The second stage decodes the bits if a synchronization sequence is detected. The decoded bit sequence is then used to extract data for the upper communication layers. Extensive use of Forward Error Correction (FEC) is done to lower the required Signal to Noise Ratio (SNR) at the input of the correlation receiver. The block diagram in Fig. 4 shows the architecture of the correlation receiver. The symbols must be zero-DC because the programmable amplifier is AC coupled. For the tests Manchester coding is chosen because of its self-synchronization feature although it is not as bandwidth efficient as other codes and halves the possible data rate to 100 kbps.

![Fig. 4. Correlation receiver block diagram](image)
The whole correlation receiver is implemented with low gate count (around 1000) and needs a clock frequency of around 400 KHz. This allows the signal processor to be implemented with state-of-the-art standard cell libraries adding a simulated maximum of 5 μW of power consumption for the given 120 nm CMOS technology. The required SNR at the input of the correlation receiver is 2.8 dB, under which a Bit Error Rate (BER) of 10⁻³ is achieved. BER measures are shown in Fig. 5.

### 3. Test setup and chip and performance

Before a test chip was implemented, a discrete setup with a Schottky diode detector, amplifier and integrator (without taking power consumption into consideration) has been built to verify the principle of the architecture. In a second stage a test chip has been designed incorporating two distinct setups one being the setup shown in Fig. 1. The second setup was realized without the envelope detector so that an external detector could be used and compared to the internal one and to characterize the programmable amplifier. A microscope photograph of the chip can be seen in Fig. 6. The reason for choosing the standard 120 nm low power CMOS process was its wide availability and low cost as well as the fact that leakage at this feature size is still limited compared to a 90 nm or smaller feature size process.

The WUR front-end draws only 7.5 μW from the single 1.5 V supply using the internal envelope detector. Using the external passive envelope detector reduces the power by 1.5 μW. The reason for this is the internal bias of the MOS detector transistor. The measured sensitivity does not relate to the data rate and is around -53 dBm using the internal envelope detector. The external envelope detector shows better sensitivity and reaches -57 dBm thanks to the higher nonlinearity and lower noise achieved. These sensitivity figures are measured at the reference BER of 10⁻³. Table 1 resumes the performance of the WUR.

#### Table 1. Key parameters of the WUR

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply Voltage</td>
<td>1.5 V</td>
</tr>
<tr>
<td>MOS Envelope detector power</td>
<td>1.5 μW</td>
</tr>
<tr>
<td>Amplifier Chain</td>
<td>Power: 4.5 μW</td>
</tr>
<tr>
<td>Max Gain: 54 dB</td>
<td></td>
</tr>
<tr>
<td>Bandwidth: 1 MHz</td>
<td></td>
</tr>
<tr>
<td>Integrator</td>
<td>1.5 μW</td>
</tr>
<tr>
<td>CMOS 120nm simulated power of the Correlation receiver</td>
<td>5 μW</td>
</tr>
<tr>
<td>Overall performance of the WUR based on the MOS detector</td>
<td></td>
</tr>
<tr>
<td>Power (estimation)</td>
<td>12.5 μW</td>
</tr>
<tr>
<td>Data Rate</td>
<td>100 kbps</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>-53 dBm</td>
</tr>
<tr>
<td>Overall performance of the WUR based on the Schottky detector</td>
<td></td>
</tr>
<tr>
<td>Power (estimation)</td>
<td>11 μW</td>
</tr>
<tr>
<td>Data Rate</td>
<td>100 kbps</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>-57 dBm</td>
</tr>
</tbody>
</table>

### 4. Conclusion and future work

This work presents the first complete implementation of a WUR with power consumption in the order of 10 μW. The architecture can be successfully adopted by wireless sensor node applications where short range wakeup capability is of advantage. In this way the overall power consumption of communication and communication latency can be reduced simultaneously.

#### Table 2. Performance comparison ( analog front-end)

<table>
<thead>
<tr>
<th>Reference</th>
<th>Sensitivity (dBm)</th>
<th>Power (μW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Berkeley 2007 [[4]]</td>
<td>-50</td>
<td>65</td>
</tr>
<tr>
<td>Berkeley 2008 [[5]]</td>
<td>-72</td>
<td>52</td>
</tr>
<tr>
<td>This work (int. detector)</td>
<td>-53</td>
<td>7.5</td>
</tr>
<tr>
<td>This work (ext. detector)</td>
<td>-57</td>
<td>6.5</td>
</tr>
</tbody>
</table>

The presented results power consumption and sensitivity are compared to other works in Table 2. The proposed work is comparable in sensitivity to [[4]] by requiring much less power. The work proposed in [[5]] shows promising figures in matter of sensitivity but has still higher power consumption. All the results shown represent the front-end only. The total power consumption of the proposed solution accounting also
for the fully integrated correlation receiver, would then consume about 12.5 µW in the worst case. The value is calculated synthesizing the digital part in the same technology as the front-end, with a low leakage standard cell library.

5. References


A good strategy to lower power consumption even further could be to duty cycle the Wakeup receiver in the order of milliseconds or even less thus not compromising delay and keeping the wakeup message short. This could be done very efficiently; since there is no significant turn-on time of the receiver other than in an oscillator based design where the turn-on times are of at least a few hundred µs.

In an already initiated follow-up project we intend to improve the envelope detector sensitivity and to integrate the complete receiver including clock generation in a single chip without increasing power consumption significantly.