# Ultra-Low Power FM-UWB Transceivers for IoT

## RIVER PUBLISHERS SERIES IN CIRCUITS AND SYSTEMS



Indexing: All books published in this series are submitted to the Web of Science Book Citation Index (BkCI), to SCOPUS, to CrossRef and to Google Scholar for evaluation and indexing.

The "River Publishers Series in Circuits and Systems" is a series of comprehensive academic and professional books which focus on theory and applications of Circuit and Systems. This includes analog and digital integrated circuits, memory technologies, system-on-chip and processor design. The series also includes books on electronic design automation and design methodology, as well as computer aided design tools.

Books published in the series include research monographs, edited volumes, handbooks and textbooks. The books provide professionals, researchers, educators, and advanced students in the field with an invaluable insight into the latest research and developments.

Topics covered in the series include, but are by no means restricted to the following:

- Analog Integrated Circuits
- Digital Integrated Circuits
- Data Converters
- Processor Architecures
- System-on-Chip
- Memory Design
- Electronic Design Automation

For a list of other books in this series, visit www.riverpublishers.com

# Ultra-Low Power FM-UWB Transceivers for IoT

**Vladimir Kopta**

CSEM SA
Switzerland

**Christian Enz**

EPFL
Switzerland

River Publishers

*Published, sold and distributed by:*
River Publishers
Alsbjergvej 10
9260 Gistrup
Denmark

River Publishers
Lange Geer 44
2611 PW Delft
The Netherlands

Tel.: +45369953197
www.riverpublishers.com

ISBN: 978-87-7022-144-3 (Hardback)
978-87-7022-143-6 (Ebook)

# Contents

# Foreword

Low-power and ultra-low-power communication technology is enabling the internet of things (IoT). The technology described by Kopta and Enz in this book is energy-efficient, robust and offers the capability of license-free communication – all desirable attributes for future IoT devices. Wideband- and ultrawideband-FM (FM-UWB) radio transceivers have been pioneered by researchers affiliated with the Swiss Center for Electronics and Microtechnology (CSEM), and elsewhere in Europe, since 2002. The technology offers an elegant and simple solution to the energy and performance constraints for many IoT applications. Kopta and Enz continue the research tradition established by John Gerrits at CSEM in 2002–2003, and have brought UWB-FM even closer to its goal of commercial exploitation.

After a brief introduction outlining the constraints and motivation for transceivers integrated in silicon CMOS for wireless sensor networking applications, a survey of narrowband and wideband transceivers is presented in Chapter 2. Chapter 3 is devoted to a tutorial on FM-UWB, which gives the reader a concise overview of the principles behind the double-FM method of modulation/demodulation, and a review of the transceiver implementations reported in the recent literature based on FM-UWB schemes. A key advantage intrinsic to FM-UWB is network scalability. Multiple data sources can share the same RF band easily using separate FSK-modulated subcarriers. This multi-user concept was proposed by Gerrits early in his development of the FM-UWB concept, and the authors devote much of this book to their development of an experimental, low-power FM-UWB transceiver that supports multi-user scenarios.

Many of the radio technologies described in the book will be familiar to experienced CMOS practitioners. However, the authors have also provided sufficient details for the novice to easily follow their hardware demonstrator descriptions. The first designs outlined in Chapter 4 use direct conversion to baseband (i.e., zero-IF architecture) in the receiver. Rather than relying on a fixed intermediate frequency (IF), the concept of a sliding or *uncertain* IF is explained. The authors then propose an *approximate* IF receiver that leverages the uncertain-IF concept to conserve power. Both single-ended and quadrature downconversion schemes are described, and system-level simulations are presented which estimate the expected performance of the two receivers. Chapter 5 describes implementation of the quadrature approximate-zero-IF receiver concept. Circuit blocks comprising the receiver are detailed and key simulation results are presented and compared with measurements. Performance is characterized with narrowband and wideband interferers present, allowing the unique features of the FM-UWB approach to be highlighted.

While simple in concept, implementation of a practical FM-UWB transceiver requires attention to many details, and Kopta does not disappoint the reader when describing prototype implementations in 65-nm bulk CMOS in Chapter 6. Sub-carrier synthesis, the digitally-controlled carrier oscillator, and antenna amplifiers are detailed for the transmitter, including calibration schemes used to ensure robustness of the final prototypes. On the receive side, each of the circuits blocks in the receive chain are presented in depth, including an N-path channel selection filter. The emphasis in Kopta's design is on robustness to narrowband interferers, in particular interference from the 2.4-GHz ISM band. Tolerance to frequency offsets is also considered. The final prototype is able to tolerate clock offsets large enough to obviate the need for a reference oscillator, making it the first FM-UWB transceiver that can be implemented without an external quartz crystal.

In summary, readers of this book will find a complete description of the current state-of-the-art in FM-UWB technology, including detailed circuit descriptions and convincing proof-of-concept verifications of CMOS prototypes within its covers.

John R. Long
Waterloo, Ontario
November 11, 2019

# Preface

This book is a result of more than four years of research work on a Ph.D. thesis at Swiss Federal Institute of Technology (EPFL) and Swiss Center for Electronics and Microtechnology (CSEM). The main motivation comes from the *WiseSkin* project, that had as a goal the integration of a sensory "skin", intended for use in prosthetic devices. Such skin would allow persons that have lost a limb to regain a natural sense of touch and perceive the artificial limb as part of their body. Tactile capability of the skin was provided by the means of a network of connected, highly miniaturized, sensor nodes, able to detect pressure and communicate data. FM-UWB imposed itself as an approach that suited all of the system needs and was quickly adopted for our solution. Beyond the scope of the *WiseSkin* project, the FM-UWB is considered here in a broader context of wireless sensor networks and IoT, topics still gaining on popularity today.

The aim of the book is to provide in depth coverage of FM-UWB as an efficient modulation scheme in the context of low-power, short range communications. It showcases FM-UWB as an alternative to commonly used narrowband radios, such as Bluetooth or ZigBee, and attempts to emphasize its potential in the IoT application space. The book also covers a design of a fully integrated FM-UWB transceiver, from high-level considerations and system specifications to transistor level design. Some of the basic concepts in circuit design are omitted in this book in order to focus on the topic of interest. The assumption is that the reader has a good foundation in analog and RF IC design, and that he is already familiar with fundamentals of communication theory. The book is intended for graduate students and academic staff engaged in electrical and electronic engineering, as well as more experienced engineers looking to expand their knowledge of low power transceivers.

The authors would like to acknowledge the members of the staff, present and past, of the Integrated and Wireless Systems Division at CSEM for their valuable contribution to this research work. It was through collaboration and many insightful discussions that the authors could benefit from their knowledge and immense experience in RF circuit design. Their helpful advice, both theoretical and practical, has proven to be crucial for the success of this work, hence special thanks go to: David Barras, David Ruffieux, Franz Pengg, Erwan Le Roux, Alexandre Vouilloz, Nicola Scolari, Nicolas Raemy, Pascal Persechini, John Farserotu, Ricardo Caseiro and Pierre-Alain Beuchat of CSEM.

The authors would also like to thank the staff at River Publishers, particularly Junko Nakajima, for the support in making this book.

Vladimir Kopta<br>Neuchatel, Switzerland<br>November 2019

# List of Figures

# List of Tables

# List of Abbreviations

| | |
|---|---|
| ACLR | Adjacent Channel Leakage Ratio |
| ACPR | Adjacent Channel Power Ratio |
| ADC | Analog to Digital Converter |
| AM | Amplitude Modulation |
| AWG | Arbitrary Waveform Generator |
| AWGN | Additive White Gaussian Noise |
| AZ-IF | Approximate Zero Intermediary Frequency |
| BAN | Body Area Network |
| BAW | Bulk Acoustic Wave |
| BB | Baseband |
| BER | Bit Error Rate |
| BLE | Bluetooth Low Energy |
| BT | Bluetooth |
| C-UWB | Chirp Ultra Wideband |
| CH | Cherry-Hooper |
| Clk | Clock |
| CDMA | Code Division Multiple Access |
| CMOS | Complementary Metal Oxide Semiconductor |
| CP | Continuous Phase |
| DAC | Digital to Analog Converter |
| DBPF | Dual Band-Pass Filter |
| DCO | Digitally Controlled Oscillator |
| DDS | Direct Digital Synthesis |
| DL | Delay Line |
| DPSK | Differential Phase Shift Keying |
| DQPSK | Differential Quadrature Phase Shift Keying |
| ED | Envelope Detector |
| EDR | Enhanced Data Rate |
| FCC | Federal Communications Commission |
| FDMA | Frequency Division Multiple Access |
| FH | Frequency Hopping |

| | |
|---|---|
| FLL | Frequency Locked Loop |
| FM | Frequency Modulation |
| FPGA | Field Programmable Gate Array |
| FSK | Frequency Shift Keying |
| GFSK | Gaussian Minimum Shift Keying |
| HD | High Density |
| I/Q | In-phase/Quadrature |
| IEEE | Institute of Electrical and Electronic Engineers |
| IF | Intermediary Frequency |
| IFA | Intermediary Frequency Amplifier |
| IO | Input-Output |
| IoT | Internet of Things |
| IR | Impulse Radio |
| ISM | Industrial Scientific Medical |
| LAN | Local Area Network |
| LF | Low Frequency |
| LNA | Low Noise Amplifier |
| LO | Local Oscillator |
| LP | Low Power |
| MEMS | Micro Electro-Mechanical System |
| MFC | Microbial Fuel Cell |
| MOS | Metal-Oxide Semiconductor |
| MPP | Maximum Power Point |
| MSO | Mixed Signal Oscilloscope |
| MU | Multi-User |
| NB | Narrowband |
| NF | Noise Figure |
| NFC | Near Field Communication |
| OFDM | Orthogonal Frequency Division Multiplex |
| OOK | On-Off Keying |
| PA | Power Amplifier |
| PCB | Printed Circuit Board |
| PDF | Probability Density Function |
| PHY | Physical Layer |
| PLL | Phase Locked Loop |
| PPA | Preamplifier |
| PPM | Pulse Position modulation |
| ppm | parts per million |
| PRR | Pulse Repetition Ratio |

| | |
|---|---|
| PSD | Power Spectral Density |
| PSK | Phase Shift keying |
| PTAT | Proportional to Absolute Temperature |
| PVC | Photovoltaic Cell |
| PVT | Process Voltage Temperature |
| QPSK | Quadrature Phase Shift Keying |
| RA-OOK | Random Alternate On-Off Keying |
| RF | Radio Frequency |
| RFID | Radio Frequency Identification |
| S-OOK | Synchronous On-Off Keying |
| SAR | Successive Approximation Register |
| SAW | Surface Acoustic Wave |
| SC | Sub-Carrier |
| SIF | Sliding Intermediary Frequency |
| SIR | Signal to Interference Ratio |
| SMA | Sub-Miniature version-A |
| SNIR | Signal to Noise and Interference Ratio |
| SNR | Signal to Noise Ratio |
| SPI | Serial Peripheral Interface |
| TDMA | Time Division Multiple Access |
| TEG | Thermoelectric Generator |
| UNB | Ultra Narrowband |
| UWB | Ultra-Wideband |
| VCO | Voltage Controlled Oscillator |
| WBAN | Wireless Body Area Network |
| WLAN | Wireless Local Area Network |
| WSN | Wireless Sensor Network |
| WU | Wake-Up (Receiver) |