
Ultra-Low Power FM-UWB Transceivers for IoT

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Ultra-Low Power FM-UWB Transceivers for IoT

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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 circuit 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.

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Neuchatel, Switzerland
November 2019

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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)

