

Wim Vereecken  
Michiel Steyaert

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Analog Circuits And Signal Processing

# Ultra-Wideband Pulse-based Radio

Reliable Communication  
over a Wideband Channel

 Springer

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**ANALOG CIRCUITS AND SIGNAL PROCESSING SERIES**

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Reliable Communication  
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ISBN 978-90-481-2449-7 e-ISBN 978-90-481-2450-3

DOI 10.1007/978-90-481-2450-3

Springer Dordrecht Heidelberg London New York

Library of Congress Control Number: 2009926324

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## Preface

Today's booming expanse of personal wireless radio communications is a rich source of new challenges for the designer of the underlying enabling technologies. Personal communication networks are designed from a fundamentally different perspective than broadcast service networks, such as radio and television. While the focus of the latter is on reliability and user comfort, the emphasis of personal communication devices is on throughput and mobility. However, because the wireless channel is a shared transmission medium with only very limited resources, a trade-off has to be made between mobility and the number of simultaneous users in a confined geographical area. According to Shannon's theorem on channel capacity,<sup>1</sup> the overall data throughput of a communication channel benefits from either a linear increase of the transmission bandwidth, or an (equivalent) exponential increase in signal quality. Consequently, it is more beneficial to think in terms of channel bandwidth than it is to pursue a high transmission power. All the above elements are embodied in the concept of *spatial efficiency*. By describing the throughput of a system in terms of bits/s/Hz/m<sup>2</sup>, spatial efficiency takes into account that the use of a low transmission power reduces the operational range of a radio transmission, and as such enables a higher reuse rate of the same frequency spectrum.

What is not accounted for in the above high-level theoretical perspective, is that a wide transmission bandwidth opens up a Pandora's box of many complications at receiver side. Shannon's theorem is indeed valid for an AWGN channel, but the environment where network devices are operated in, usually refuses to fit this idealized model. A real-world channel, for example, will suffer from multipath reflections: multiple, delayed versions of the same trans-

---

<sup>1</sup>Channel capacity = bandwidth  $\times$   $\log_2(1 + \text{signal quality})$ .

mission arrive at the receive antenna and start to interfere with one another, an effect that is known as *intersymbol interference*. Apart from this form of self-interference, a wide transmission band is also a wide open door for in-band interfering signals. It is not the presence of the interferer itself that causes the problem, but the sometimes very large difference in the power balance between the unwanted component and the signal-of-interest. By putting considerable stress on the linearity requirements of the receiver, high-powered interferers indirectly impact the battery lifetime of portable devices.

This work lays the foundations of a new radio architecture, based on the pulse-based radio principle. As will become clear throughout this book, using short pulses with a wide spectral footprint has considerable advantages for the reliability of a wireless transmission under indoor channel conditions. Notwithstanding being described as a pulse-based system, the presented architecture is also a direct descendant of single-carrier QPSK modulated radio. This genealogical line ensures the system can enjoy the best of both worlds: a high reliability and a fairly uncomplicated modulation technique.

However, simplicity does not preclude powerful capabilities. From the very early stages on, the high-level system design was conceived with the above described complications of the wideband radio channel in mind. Issues that come with the unpredictable nature of the wireless medium, such as interference and varying channel conditions, are dealt with at multiple levels in the system hierarchy. For example, a specially crafted *interferer suppression and signal reconstruction* algorithm has been developed (chapter 3). Without active intervention from the transmitter, the ISSR system – which is located entirely at receiver side – is capable of on-the-fly cleaning of frequency bands which have fallen victim to multipath fading or narrowband interference. The unique blend of pulse-based radio, a simple modulation scheme and a powerful signal reconstruction system in the back-end make the presented pulse-based radio system a viable and promising alternative for the high-end (but highly complex) modulation schemes such as the OFDM-system currently widely adopted by WLAN applications.

As a proof of concept, the theoretical underpinnings of this work are supported by the implementation of an analog front-end for pulse-based radio in  $0.18\ \mu\text{m}$  CMOS. The quadrature RF front-end comprises a wideband RF input stage, an I/Q pulse-to-baseband downconversion mixer and a variable gain amplifier (the latter based on a novel highly-linear open-loop topology). The prototype chip has drawn attention to some subtle technical issues inherent to pulse-based radio. For example, the sensitivity of the receiver may be adversely affected by leakage of clock signals into the sensitive signal chain. While this effect does not come to the surface in high-level system simulations, it can be easily prevented by some simple precautions in the early stages of the design process.

As a conclusion, the chip-level realization did not only prove the feasibility of a quadrature pulse-based transceiver system, but has also marked some key points that need special attention from a developer's viewpoint during the design of a pulse-based radio chipset.

Leuven, Belgium  
October 2008

*Wim Vereecken*

# List of Abbreviations and Symbols

## Abbreviations

|        |  |
|--------|--|
| AC     | Alternating current (commonly used in a small-signal context)  |
| ADC    | Analog-to-digital converter                                    |
| AFC    | Automatic frequency control                                    |
| AGC    | Automatic gain control   |
| AM     | Amplitude modulation   |
| AM-SSB | Single sideband AM   |
| AM-VSB | Amplitude modulation with a vestigial sideband (TV broadcast)  |
| AWGN   | Additive white Gaussian noise                                  |
| BALUN  | Balanced to unbalanced transformer                             |
| BER    | Bit error rate   |
| BICM   | Bit interleaved coded modulation                               |
| BPF    | Band-pass filter   |
| BPSK   | Binary phase shift keying                                      |
| BW     | Bandwidth  |
| C/A    | Coarse acquisition code (GPS related)                          |
| CCITT  | Comité Consultatif International Téléphonique et Télégraphique |
| CCK    | Complementary code keying                                      |
| CDF    | Cumulative distribution function                               |
| CDMA   | Code division multiple access                                  |
| CF     | Crest factor   |
| CL     | Closed-loop  |
| CMFB   | Common-mode feedback   |

|                                  |   |
|----------------------------------|---|
| CML                              | Current mode logic                                  |
| CMOS                             | Complementary metal oxide semiconductor             |
| CMRR                             | Common mode rejection ratio                         |
| CNR                              | Carrier-to-noise ratio                              |
| CSMA/CA                          | Carrier sense multiple access/collision avoidance   |
| CT                               | Confidence threshold                                |
| DAC                              | Digital-to-analog converter                         |
| DC                               | Direct current                                      |
| DFT                              | Discrete Fourier transform                          |
| DIFS                             | Distributed interframe spacing (IEEE802.11 related) |
| DLL                              | Data link layer of the OSI model                    |
| DLL                              | Delay locked loop (PLL related)                     |
| DSP                              | Digital signal processing                           |
| DSSS                             | Direct sequence spread spectrum                     |
| $E_b/N_0$                        | Bit energy over noise density ratio                 |
| EGC                              | Equal gain combining                                |
| EIRP                             | Effective isotropic radiated power                  |
| ENOB                             | Effective number of bits                            |
| ERBW                             | Effective resolution bandwidth                      |
| ESD                              | Energy spectral density                             |
| ESD                              | Electrostatic discharge (protection circuit)        |
| EVM                              | Error vector magnitude                              |
| FCC                              | Federal Communications Commission                   |
| FDMA                             | Frequency division multiple access                  |
| FEC                              | Forward error coding                                |
| FFT                              | Fast Fourier transform                              |
| FHSS                             | Frequency-hopping spread spectrum                   |
| FIR                              | Finite impulse response                             |
| FM                               | Frequency modulation                                |
| FSK                              | Frequency shift keying                              |
| FUND <sub><math>x</math></sub>   | Fundamental component at node $x$                   |
| GBW                              | Gain-bandwidth product                              |
| GMSK                             | Gaussian minimum shift keying                       |
| GPS                              | Global Positioning System                           |
| GSM                              | Global System for Mobile communications             |
| HARM <sub><math>n,x</math></sub> | $n$ -th order harmonic component at node $x$        |
| HD                               | Harmonic distortion                                 |
| HD <sub>2</sub>                  | Second-order harmonic distortion                    |
| HD <sub>3</sub>                  | Third-order harmonic distortion                     |
| hop                              | Change of frequency in a FHSS transmission          |
| IC                               | Integrated circuit                                  |
| IDFT                             | Inverse discrete Fourier transform                  |

|                  |  |
|------------------|--|
| IF               | Intermediate frequency                             |
| IIP <sub>3</sub> | Input-referred IP <sub>3</sub>                     |
| IIR              | Infinite impulse response                          |
| IL               | Implementation loss                                |
| IM               | Intermodulation                                    |
| IM <sub>3</sub>  | Third-order intermodulation                        |
| IO               | Input/output communication                         |
| IP <sub>3</sub>  | Third-order interception point                     |
| I/Q              | In-phase/quadrature                                |
| ISI              | Intersymbol interference                           |
| ISM              | Industrial, Scientific and Medical radio bands     |
| ISSR             | Interferer suppression and signal reconstruction   |
| ITU              | International Telecommunication Union              |
| ITU-T            | ITU Telecommunication Standardization Sector       |
| L1               | GPS L1 frequency band (1,575.42 MHz)               |
| LAN              | Local area network                                 |
| LNA              | Low noise amplifier                                |
| LO               | Local oscillator                                   |
| LOS              | Line-of-sight                                      |
| LPF              | Low-pass filter                                    |
| LQFP-32          | Low-profile quad flat package (32 leads)           |
| LTI              | Linear time-invariant                              |
| LVDS             | Low-voltage differential signalling                |
| MAC              | Media access control layer of the OSI model        |
| MODEM            | Modulator–demodulator                              |
| MOS              | Metal oxide semiconductor                          |
| MP               | Multipath  |
| MRC              | Maximum ratio combining                            |
| MS               | Mobile station                                     |
| MSB              | Most significant bit                               |
| MSE              | Mean square error                                  |
| MSED             | Minimum squared euclidean distance                 |
| MSK              | Minimum shift keying                               |
| N-FM             | Narrowband FM                                      |
| NBI              | Narrowband interference                            |
| NLOS             | Non-line-of-sight                                  |
| NMOS             | n-channel MOS transistor                           |
| OFDM             | Orthogonal frequency division multiplexing         |
| OIP <sub>3</sub> | Output-referred IP <sub>3</sub>                    |
| OL               | Open-loop  |
| OSI              | Open Systems Interconnection basic reference model |
| OTA              | Operational transconductance amplifier             |

|                  |   |
|------------------|---|
| PAE              | Power-added efficiency                                      |
| PAPR             | Peak-to-average power ratio                                 |
| PDF              | Probability density function                                |
| PDP              | Power delay profile   |
| PHY              | Physical layer of the OSI model                             |
| PL               | Path loss   |
| PL <sub>d0</sub> | Path loss at d <sub>0</sub> meter distance                  |
| PLL              | Phase locked loop   |
| PMOS             | p-channel MOS transistor                                    |
| POTS             | Plain old telephone service                                 |
| PPM              | Pulse position modulation                                   |
| PRN              | Pseudorandom noise  |
| PSD              | Power spectral density                                      |
| PSK              | Phase shift keying  |
| PSO              | Particle swarm optimization                                 |
| PSTN             | Public switched telephone network                           |
| QAM              | Quadrature amplitude modulation                             |
| QPSK             | Quadrature phase shift keying                               |
| rake             | Rake receiver: a radio receiver using several sub-receivers |
| RDS              | Radio Data Service (on FM 57 kHz subcarrier)                |
| RF               | Radio frequency   |
| RFID             | Radio-frequency identification                              |
| RMS              | Root mean square  |
| RPE-LTP          | Regular Pulse Excitation with Long-Term Prediction          |
| RS-232           | IEEE recommended standard 232 for serial interfacing        |
| RX               | Receive   |
| RZ               | Return-to-zero (related to line codes)                      |
| SAW              | Surface acoustic wave                                       |
| SDC              | Selection diversity combining                               |
| SDR              | Software defined radio                                      |
| SIFS             | Short interframe spacing (IEEE802.11 related)               |
| SNR              | Signal-to-noise ratio                                       |
| SoC              | System-on-a-chip  |
| TCM              | Trellis coded modulation                                    |
| TCP/IP           | Transmission control protocol/Internet protocol             |
| TF               | Transfer function   |
| THD              | Total harmonic distortion                                   |
| TSP              | True single phase (related to dynamic logic circuits)       |
| TDMA             | Time division multiple access                               |
| TX               | Transmit  |
| UMTS             | Universal Mobile Telecommunications System (3G)             |
| USB              | Universal Serial Bus  |