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Reliable Communication over a Wideband Channel

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ANALOG CIRCUITS AND SIGNAL PROCESSING SERIES

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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

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Contents

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,[1] 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^2, 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-

[1]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 μm 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 *Wim Vereecken*
October 2008

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_x	Fundamental component at node x
GBW	Gain-bandwidth product
GMSK	Gaussian minimum shift keying
GPS	Global Positioning System
GSM	Global System for Mobile communications
$\text{HARM}_{n,x}$	n-th order harmonic component at node x
HD	Harmonic distortion
HD_2	Second-order harmonic distortion
HD_3	Third-order harmonic distortion
hop	Change of frequency in a FHSS transmission
IC	Integrated circuit
IDFT	Inverse discrete Fourier transform

IF	Intermediate frequency
IIP_3	Input-referred IP_3
IIR	Infinite impulse response
IL	Implementation loss
IM	Intermodulation
IM_3	Third-order intermodulation
IO	Input/output communication
IP_3	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_3	Output-referred IP_3
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_{d0}	Path loss at d_0 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