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Temperature- and Supply Voltage-Independent Time References for Wireless Sensor Networks

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The only reason for time is so that everything doesn't happen at once.

–A. Einstein

Preface

"Most of what makes a book 'good' is that we are reading it at the right moment for us" is a quote from the Swiss-British philosopher Alain De Botton. The quote is right on top for a book where timing is the central given. Read this book about timing if at this moment your design is in need of an accurate yet efficient timing reference!

The book you are holding is the result of several years of Ph.D. research that started with the ambition to set important steps toward the implementation of batteryless wireless sensor nodes. Relatively soon it became clear that accurate timing is one of the key points in realizing this. Therefore the focus shifted to the construction of a low power, supply, and/or temperature independent timing reference. This topic in its turn surpasses the world of wireless sensor networks as it is much wider applicable.

We are convinced that the results we present here can help you in several ways. You can have a look at the circuits and concepts and adapt them for your system. More importantly the book can act as a source of inspiration for all those that are involved in sensor network design and the hardware for the Internet of Things. We dare to hope that the book brings you as much research inspiration as it brought us research joy while creating it.

Leuven, September 2014

Valentijn De Smedt
Georges Gielen
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Contents

Abstract

Back in 2000, the Nobel prize committee recognized the invention of the integrated circuit in 1958 by Jack Kilby as one of the most far-reaching steps forward in modern technology. Today, almost 60 years after this invention, electronics are found everywhere in our society. This is mainly caused by the characteristic exponential growth factors in the electronics industry (Moore's law), which result in an exponential miniaturization and cost decrease. This evolution goes hand in hand with a similar growth of wireless communication technology: devices become smaller, frequencies and data rates higher. As a result, the wearability and functionality of wireless electronic devices drastically increase.

This ongoing technological progress is a direct cause of the appearance of Wireless Sensor Networks (WSN). An increasing number of autonomously operating devices is wirelessly connected to a network and/or to the Internet, an evolution which will eventually result in the so-called Internet of Things. Since both the miniaturization as well as the cost decrease of these wireless sensor nodes is necessary to become economically feasible, a growing need for fully-integrated, single-chip wireless devices is observed. The use of modern deep-submicron CMOS technologies in analog electronics, however, has several drawbacks in terms of temperature sensitivity and linearity.

This work elaborately investigates the possible circuit techniques to overcome the temperature and supply voltage sensitivity of fully integrated time references for ultra-low-power wireless communication in WSN. In a first step, the basic needs to build a frequency reference are studied. Furthermore, a closer look at the short-term as well as the long-term frequency stability of integrated oscillators is taken. This results in a design strategy, which is applied to six different oscillator design cases. All six implementations are subject to a study of phase noise and long-term frequency stability.

The first two implementations are respectively a temperature- and a supply voltage-independent Wien bridge oscillator. The temperature independence is obtained by using a novel feedback amplifier topology of which the output resistance only depends on a temperature stable resistor. This requires advanced circuit techniques and a highly-stable amplitude regulation circuit. The second Wien bridge implementation makes use of two nested regulators, resulting in an ultra-high supply voltage stability over a wide voltage range.

The third design case makes use of a high-quality bondwire LC tank. A novel pulsed driving technique is developed to decrease the power consumption of the high-frequency oscillator circuit. This driving technique reduces the impact of the oscillator circuitry on the output frequency and therefore also on the temperature- and supply voltage stability of the oscillator. To better understand the application field of the pulsed oscillator topology, the noise performance is analyzed as well. The processed implementation is a unique combination of power consumption and long-term frequency stability.

Next, two injection-locked oscillator implementations are discussed. Apart from a stable output frequency, a high absolute accuracy is also obtained due to the locking to a wirelessly received RF signal. The first design uses the received 2.4 GHz carrier frequency as a time reference. Despite its simple system topology, this approach has several drawbacks in terms of selectivity and power consumption. The second implementation locks to the envelope of the received RF signal. Therefore, the oscillator can run at a low frequency, drastically diminishing the power consumption. A second improvement is the addition of a network coordination receiver. For this purpose, a novel ultra-low-power receiver topology and demodulation technique are developed. As a result of the addressability, the overall power consumption in the network is reduced.

The last design case is a temperature- and supply voltage-independent oscillator-based sensor interface. Since the challenge in this design is rather the stability of the output value than the frequency stability, a different design strategy is used. It is shown that the matching of different oscillator delay stages can be applied to obtain a stable and highly-linear digitalization of a sensor input.

The wirelessly injection-locked oscillator, the coordination receiver, the sensor interface, and a transmitter are combined into one highly-flexible wireless tag. The content, the scrambling code, and the length of the transmitted data burst can be adapted freely, depending on the application. The developed tag can therefore be used in a wide range of applications, with different accuracy requirements and energy constraints.

Finally, an elaborate comparison between the developed oscillator designs and the state of the art is performed. It is shown that the free-running implementations as well as the injection-locked designs improve the state of the art. This discussion results in several suggestions for possible future work.

About the Authors

Valentijn De Smedt (S'08) was born in Lubbeek, Belgium, in 1984. He received the M.Sc. degree in electrical engineering from the Katholieke Universiteit Leuven in 2007. The subject of his Master thesis was the design of an accurate integrated frequency reference. From 2007 to 2014 he was working as a research assistant at the MICAS laboratories of the Katholieke Universiteit Leuven towards a Ph.D. degree on the design of ultra-low-power time-based building blocks for wireless sensor networks, which he received in April 2014. At KU Leuven, he was involved in and has set up several extra-curricular educational projects, some of them in co-operation with the IEEE Student Branch of Leuven.

He has been vice-chair technical activities of the IEEE student branch of Leuven between 2009 and 2013 and chaired the IEEE Student Branch and GOLD congress 2010 (SBC 2010). Since 2011, he is IEEE Benelux GOLD (Young Professionals) chair and co-chair of the IEEE SSCS Benelux chapter. Since 2009 he is a guest lecturer at ACE Group-T on UWB standards and Zigbee.

Georges G.E. Gielen received the M.Sc. and Ph.D. degrees in Electrical Engineering from the Katholieke Universiteit Leuven (KU Leuven), Belgium, in 1986 and 1990, respectively. He is a full professor at the Department of Electrical Engineering (ESAT). From August 2013, Georges Gielen is also appointed as vice-rector for the Group Science, Engineering and Technology and Academic Personnel of the KU Leuven.

His research interests are in the design of analog and mixed-signal integrated circuits, and especially in analog and mixed-signal CAD tools and design automation. He is a coordinator or partner of several (industrial) research projects in this area, including several European projects. He has authored or coauthored seven books and more than 450 papers in edited books, international journals, and conference proceedings. He is a Fellow of the IEEE since 2002.

Wim Dehaene was born in Nijmegen, The Netherlands, in 1967. He received the M.Sc. degree in electrical and mechanical engineering in 1991 from the Katholieke Universiteit Leuven. In November 1996, he received the Ph.D. degree at the Katholieke Universiteit Leuven. His thesis is entitled "CMOS integrated circuits for analog signal processing in hard disk systems."

After receiving the M.Sc. Degree, Wim Dehaene was a research assistant at the ESAT-MICAS Laboratory of the Katholieke Universiteit Leuven. His research involved the design of novel CMOS building blocks for hard disk systems. The research was first sponsored by the IWONL (Belgian Institute for Science and Research in Industry and Agriculture) and later by the IWT (the Flemish institute for Scientific Research in the Industry). In November 1996, Wim Dehaene joined Alcatel Microelectronics, Belgium. There he was a senior project leader for the feasibility, design and development of mixed mode systems on chip. The application domains were telephony, xDSL, and high-speed wireless LAN. In July 2002, Wim Dehaene joined the staff of the ESAT-MICAS Laboratory of the Katholieke Universiteit Leuven where he is now a full professor. His research domain is circuit level design of digital circuits. The current focus is on ultra low power signal processing and memories in advanced CMOS technologies. Part of this research is performed in cooperation with IMEC, Belgium where he is also a part-time principal scientist.

Wim Dehaene is teaching several classes on electrical engineering and digital circuit and system design. He is also very interested in the didactics of engineering. As such, he is guiding several projects aiming to bring engineering to youngsters and he is a teacher in the teacher education program of the KU Leuven.

Wim Dehaene is a senior member of the IEEE. Wim Dehaene is a member of the technical program committee of ESSCIRC and ISSCC.

Abbreviations

A-ISF	Amplitude Impulse Sensitivity Function
AC	Alternating Current
AM	Amplitude Modulation
BBPLL	Bang–Bang Phase-Locked Loop
BER	Bit Error Rate
BJT	Bipolar Junction Transistor
CMB	Cosmic Microwave Background
DAC	Digital-to-Analog Converter
EEF	Energy Enhancement Factor
ELP	Extremely-Low Power
ENOB	Effective Number of Bits
ETF	Electro-Thermal Filter
FET	Field-Effect Transistor
FLL	Frequency-Locked Loop
FoM	Figure of Merit
FRS	Fellow of the Royal Society
FSM	Finite State Machine
IFF	Identification Friend or Foe
IoT	Internet of Things
IR-UWB	Impulse Radio Ultra-Wideband
ISF	Impulse Sensitivity Function
JFET	Junction Field-Effect Transistor
LDO	Low-DropOut
LFSR	Linear Feedback Shift Register
LTI	Linear Time-Invariant
LTV	Linear Time-Variant
MEMS	Microelectromechanical systems
MiM	Metal-insulator-Metal

MoI	Moment of Impact
MoM	Metal-oxide-Metal
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
OCXO	Oven-Compensated Crystal Oscillator
P-UWB	Pulsed Ultra-Wideband
PC	Personal Computer
pcb	Printed Circuit Board
PDF	Probability Density Function
ppb	Parts per billion
ppm	Parts per million
PSD	Power Spectral Density
PVT	Process, Temperature and (Supply) Voltage
PW	Pulse Width
RF	Radio Frequency
RFID	Radio Frequency Identification
rms	Root mean square
SNDR	Signal to Noise and Distortion Ratio
SNR	Signal to Noise Ratio
TANSTAAFL	There Ain't No Such Thing As A Free Lunch
TCXO	Temperature-Compensated Crystal Oscillator
ULP	Ultra-Low Power
VCO	Voltage-Controlled Oscillator
VCXO	Voltage-Controlled Crystal Oscillator
WSN	Wireless Sensor Network
XO	Crystal Oscillator

Symbols

$\alpha(\omega \cdot t)$	Deterministic, periodic function with period 2π
α_k	Phase shift of the k-th harmonic of a voltage oscillator signal
α_{μ_n}	Temperature coefficient of the electron mobility
$\alpha_{V_{th}}$	Temperature coefficient of the transistor threshold voltage
β	Phase modulation index
β_k	Phase shift of the k-th harmonic of a voltage oscillator signal
$\Delta\omega_{3dB}$	-3 dB width of a resonant peak in a transfer function
Δf_{-3dB}	Half-power width of an oscillator output spectrum
ΔT_n	Delay error induced by noise
ΔV_n	Output voltage error induced by noise
ΔV_{rel}	Relative supply voltage span, as defined in Sect. 4.3.2
$\mathscr{A}(\Delta\omega)$	Amplitude noise density at frequency offset $\Delta\omega$, relative to the carrier
$\Delta\omega_0$	Difference between the fundamental frequency ω_0 and the natural frequency ω_n of the tuned network
$\Delta\omega_n$	Angular frequency difference between the natural oscillator frequency ω_n and the frequency of an injected signal ω_i
$\Delta\omega_{inj}$	Frequency perturbation on the injected signal i_{inj}, equal to $d\phi_{inj}(t)/dt$
$\Delta\omega_{nn}$	Frequency perturbation on the free-running oscillator signal (not the injection-locked oscillator signal), equal to $d\phi_{nn}(t)/dt$
$\Delta\phi_i(t)$	Perturbation of the phase shift between an oscillator current and an injected current (due to noise), equal to $\Delta\phi_{inj}(t) - \Delta\phi_{osc}$
$\Delta\phi_{inj}(t)$	Perturbation on the phase of the injected signal i_{inj}
$\Delta\phi_{osc}$	Perturbation on the phase of the (locked) oscillator signal

δ_k	Relative amplitude of the *k*-th harmonic of the voltage waveform, compared to the amplitude of the fundamental frequency
δ_{Xx}	Skin-depth of a conducting material *Xx* (for instance Silver, *Ag*)
ε	Parameter equal to A_{inj}/A_{osc}
$\varepsilon(t)$	Random amplitude variation of an oscillator signal
γ	Constant parameter used to determine the bandwidth of a Lorentzian spectrum, equal to $\pi \cdot f_0^2 \cdot c$
$\Gamma(x)$	The Impulse Sensitivity Function (ISF) with period $2 \cdot \pi$
$\Gamma_i(x)$	Impulse Sensitivity Function (ISF) on node *i* with period $2 \cdot \pi$
γ_k	Relative amplitude of the *k*-th harmonic of the voltage waveform, compared to the amplitude of the fundamental frequency
$\Gamma_{eff}(x)$	Effective Impulse Sensitivity Function (ISF), taking cyclo-stationary noise sources into account
Γ_{rms}	Root mean square (rms) value of the Impulse Sensitivity Function (ISF)
$\Lambda(x)$	Amplitude Impulse Sensitivity function (A-ISF), with period $2 \cdot \pi$
λ_i	Eigenvalue with corresponding eigenvector $\mathbf{u_i}$
$\Lambda_i(x)$	Amplitude Impulse Sensitivity function (A-ISF) on node *i*, with period $2 \cdot \pi$
$\boldsymbol{\rho}$	Generalized eigenvector with corresponding eigenvalue λ
μ	Scalar nonlinearity parameter in the *van der Pol* equation
μ_{Xx}	Magnetic permeability of a conducting material *Xx* (for instance Silver, *Ag*)
Ω	Unit of electrical resistance
ω	Instantaneous angular frequency, pulsation, $2\pi f$
$\omega(t)$	Instantaneous angular frequency over time
ω_0	Constant mean angular frequency of an oscillator, often used as the angular frequency in standard conditions
ω_B	Beating frequency of an injected oscillator
ω_i	Angular frequency of an injected signal
ω_L	One-sided lock range of an injection-locked oscillator
ω_m	Angular frequency of a motor
ω_n	Natural angular frequency of an electrical (tuned) network, natural angular frequency of an oscillator, $2\pi f_n$
Φ	magnetic flux due to the magnetic poles in a motor
$\Phi(t)$	Instantaneous phase of an oscillator signal
$\phi(t)$	Random variations of noise in the phase function, also called excess phase function
ϕ_∞	Steady-state phase shift between the oscillator current and the injected current

$\phi_i(t)$	Phase shift between the oscillator current and the injected current
ϕ_{ETF}	Phase shift of an Electro-Thermal Filter
$\phi_{i,0}$	Initial phase shift between the oscillator current and the injected current
$\phi_{inj}(s)$	Phase shift of the injected signal in the frequency domain
$\phi_{nn}(s)$	Phase shift of the free-running oscillator signal in the frequency domain
$\phi_{nn}(t)$	Phase shift of the free-running oscillator signal (not the injection-locked oscillator signal)
$\phi_{osc}(s)$	Phase shift of the locked oscillator signal in the frequency domain
ψ	Phase shift between the injected signal and the relaxation oscillator current
$\Psi(t)$	Systematic or deterministic variations in the phase function
ρ_{Xx}	Conductivity of a conducting material *Xx* (for instance Silver, *Ag*)
$\sigma(A, f, \tau)$	Allan variance of the output of a function *f* with dead time τ between the subsequent samples
$\sigma(T_h, T_l)$	Covariance between two stochastic periods
σ_c	Cycle-to-cycle jitter of an oscillator output signal
$\sigma_{A,h,l}$	Allan covariance between two variables T_h and T_l (with dead time τ)
$\sigma_{abs}(t = N \cdot \tau_{avg})$	Standard deviation of the absolute jitter after *N* oscillation cycles, sometimes also called the absolute jitter
σ_{cc}	Alternative definition of the cycle-to-cycle jitter, calculated using the difference between subsequent periods
$\sigma_{LC,Cte}$	Average cycle-to-cycle jitter of the output waveform of a resonant tank with constant output amplitude
$\sigma_{LC,Pulsed,N}$	Standard deviation of the length of the pulsed period of an LC tank, normalized to $T_{LC}/2$
σ_{LC}	Average cycle-to-cycle jitter of the output waveform of a resonant tank with decaying output amplitude
σ_{T_n}	Standard deviation (rms) of the time noise on a stage delay
σ_{V_n}	Standard deviation (rms) of the voltage noise
τ	An arbitrary moment in time
τ_i	Period of the *i*-th oscillation cycle
τ_{avg}	Average period of an oscillator output signal
$\theta(t)$	Phase shift of an oscillation over time (compared to $\omega_n \cdot t$)
θ_0	Initial phase shift of an oscillation
θ_i	Phase shift induced by a small injected signal in the oscillator, angle between the oscillator signal and the resulting signal
θ_n	Phase shift of a tuned network at $\omega \neq \omega_n$

$\Upsilon(t)$	Deterministic and systematic amplitude variations of an oscillator signal
A	Voltage gain of a generic amplifier
A_0	Ideal constant amplitude of an oscillator signal
A_1	Linear gain of a voltage dependent transconductance amplifier
A	Ampère, unit of electrical current
A_D	Area or size of a diode junction
A_{ds}	Amplitude of the drain-source current in an oscillator
$A_{env,DC}$	DC approximation of the complex envelope of an oscillator output signal
$A_{env}(t)$	Complex envelope of an oscillator output signal
A_i	i-th-order gain of a voltage dependent transconductance amplifier
A_{inj}	Amplitude of a signal injected in an oscillator
A_{osc}	Amplitude of an oscillator signal current
A_R	Area or size of a resistor
A_r	Amplitude of the resulting oscillator signal, sum of the injected current and the oscillator current
$A(t)$	Instantaneous amplitude of an oscillator signal
A_t	Minimum attenuation of a feedback network
A_v	Voltage gain of an amplifier
B	Bandwidth of a modulating signal
C	Capacitance, a capacitor
c	Motor constant, speed of light
c	Constant parameter used to determine the bandwidth of a Lorentzian spectrum
C_{ds}	Drain-source capacitor of a MOS transistor
C_{gd}	Gate-drain capacitor of a MOS transistor
C_{gs}	Gate-source capacitor of a MOS transistor
c_i	Complex i-th pole frequency
C_{ox}	Gate-oxide capacitance per unit area of a MOS transistor
C_p	Parallel capacitor in the equivalent quartz crystal model
C_s	Series capacitor in the equivalent quartz crystal model
DC	Duty cycle of a digital signal
e	Euler's constant
$E_{Decay}(N)$	Energy loss over N oscillation cycles in a resonant tank with exponentially decaying output amplitude
E_M	Back electromotive force
$E_{Osc}(N)$	Energy loss over N oscillation cycles in a resonant tank with constant output amplitude
$f(\Phi(t))$	Periodic function of $\Phi(t)$ with period $2 \cdot \pi$
F	Device excess noise factor
F_{amp}	Noise factor of an amplifier

F	Farad, unit of electrical capacitance
f_i	State variable of an oscillation on node i, normalized to amplitude and frequency
$f_i(x_1, \ldots, x_n)$	A smooth real-valued function of $x_1, \ldots, x_n$
FoM_{AD}	Figure of Merit for Analog to Digital converters
FoM_{JT}	Jitter and Temperature-dependency Figure of Merit (FoM) of an oscillator
FoM_{PN}	Phase noise Figure of Merit (FoM) of an oscillator
$FoM_{PN,tuned}$	Phase noise Figure of Merit (FoM) of an oscillator, taking the tuning sensitivity into account
FoM_{PNT}	Phase noise and Temperature-dependency Figure of Merit (FoM) of an oscillator
FoM_{PNTV}	Phase noise, Temperature-dependency and Voltage-dependency Figure of Merit (FoM) of an oscillator
FoM_{TV}	Temperature- and Voltage-dependency Figure of Merit (FoM) of an oscillator
FoM_V	Voltage-dependency Figure of Merit (FoM) of an oscillator
G	Transconductance of a generic amplifier
g_m	Transconductance of a transistor
g_{mb}	Transconductance of the bulk of a transistor
$G_m(v)$	Gain of a nonlinear negative resistance or amplifier
$g_{m,wi}$	Transconductance of a MOS transistor in weak-inversion
$G(s)$	Transconductance of a generic amplifier, dependent on the Laplace variable (representing the frequency)
$G(v)$	Input-amplitude-dependent transconductance of a generic amplifier
$h_\phi(t, \tau)$	Unit impulse response for the excess phase for a charge injected at time τ
$h_A(t, \tau)$	Unit amplitude impulse response for a charge injected at time τ
H	Henry, unit of electrical inductance
$H_{inj}(j \cdot \Delta\omega)$	Transfer function of the phase perturbations on the injected signal i_{inj} to the injection-locked oscillator output
$H_n(j \cdot \Delta\omega)$	Transfer function of the phase perturbations on the free-running oscillator signal i_{osc} to the injection-locked oscillator output
$h_n(t)$	Normalized impulse response of a resonant network
$H(s)$	Transfer function of a linear system or network
$h(t)$	Impulse response of a linear system or network
I	Unity matrix, symbol of electrical current, mechanical moment of inertia
I_A	Current amplitude through an inductor
I_b	Biasing current of an oscillator or an oscillator stage

I_{D0}	Technology dependent parameter determining the weak-inversion current of a MOS transistor
$i_{d,n}(t)$	Small-signal differential noise current
I_{ds}	Large-signal drain-source current of a MOS transistor
i_{ds}	Small-signal drain-source current of a MOS transistor
$I_{ds,f}$	Zero-temperature-coefficient DC biasing current of a transistor
$I_{ds,wi}$	Large-signal drain-source current of a MOS transistor in weak-inversion
$i_{inj}(t)$	Injected current in an oscillator
$I_{i,reg}$	Regulated output current of a current regulation circuit
$I_{i,reg,rep}$	Regulated output current through the oscillator replica when the regulator is loaded with a resistor
I_k	Fourier coefficient of a current oscillator signal
$\Im(x)$	The imaginary part of x
I_n	Amplitude of a noise current
$i_{n0}(t)$	Stationary current noise source
$i_n(t)$	Injected small-signal noise current
i_{osc}	Oscillator signal current
$i_r(t)$	Resulting current in an oscillator, sum of the injected current and the oscillator current
$I(s)$	Laplace transform of a current waveform
$i(t)$	Small-signal current
j	Imaginary unit, $\sqrt{-1}$
$j_{abs}(t = N \cdot \tau_{avg})$	Absolute jitter after N oscillation cycles
$J(d)$	Current density in a conductor, depending on the distance d from the surface
J	Joule, unit of energy
J_s	Current density in a conductor at the surface
k	The Boltzmann constant, approximately equal to $1.38\ \mathrm{m}^2 \cdot \mathrm{kg} \cdot \mathrm{s}^{-1} \cdot \mathrm{K}^{-1}$
k_{100}	Conversion gain of an envelope detector for an input signal with 100 % modulation depth
k_{30}	Conversion gain of an envelope detector for an input signal with 30 % modulation depth
k_{DC}	Conversion gain of an envelope detector for a DC (low-frequency) input signal
K_{fD}	Technology dependent $1/f$ noise fitting parameter of a diode
K_{fR}	Technology dependent $1/f$ noise fitting parameter of a resistor
K_{fT}	Technology dependent $1/f$ noise fitting parameter of a transistor
K_{ij}	Residue of a partial fraction corresponding to real pole i with j-th degree denominator

K_{ILO}	Injection-locked oscillator gain
K_{mix}	Mixing gain of a mixer circuit
K_{VCO}	Integration constant or sensitivity of a VCO to its control voltage v_c
L	Inductance, an inductor
L	Length of a MOS transistor
$\mathscr{L}(\Delta\omega)$	Phase noise density at frequency offset $\Delta\omega$, relative to the carrier
L_{ij}	Residue of a partial fraction corresponding to complex pole i with j-th degree denominator
$\mathscr{L}_{total}(\Delta\omega)$	Total noise power density at frequency offset $\Delta\omega$, relative to the carrier
MoI	Moment of Impact of a pulse applied to a resonant tank
MoI_N	Moment of Impact of a pulse applied to a resonant tank, normalized to $T_{LC}/2$
N	Number of free-running periods in a Pulsed-Harmonic oscillator
NF_{amp}	Noise figure of an amplifier
N_{LF}	Noise spectral density of the low-frequency noise at an amplifier output (expressed in V^2/Hz)
$N_{o,ED}$	Noise spectral density of the noise at the output of an envelope detector (expressed in V^2/Hz)
N_{src}	Noise spectral density of an input source (expressed in V^2/Hz)
p	Frequency of a single pole
p_i	Real i-th pole frequency
$P(s)$	Numerator of a transfer function $H(s)$
P_s	Average power dissipated in a resonant tank
$P_{sbc}(\Delta\omega)$	Single-sideband noise power at offset frequency $\Delta\omega$, relative to the carrier
$\mathscr{P}_{side}(f_0 + \Delta f, 1\text{ Hz})$	Single-sideband noise power in a 1 Hz interval at a frequency offset Δf from the carrier
PW	Pulse width of a pulse applied to a resonant tank
PW_N	Pulse width of a pulse applied to a resonant tank, normalized to $T_{LC}/2$
Q	Quality factor of a resonant (second order) network
q	Unit charge of a single charge carrier (electron or hole)
Q_C	Quality factor of a capacitor C
q_{Cte}	Maximum charge displacement (compared to equilibrium) in a resonant network with constant output amplitude during one period
q_{Decay}	Maximum charge displacement (compared to equilibrium) in a resonant network with exponentially decaying output amplitude during one period

Q_G	Generalized Q factor
Q_L	Quality factor of an inductor L
q_{max}	Maximum charge displacement from the equilibrium state on the output node of a resonant tank during one oscillation cycle
$Q(s)$	Denominator of a transfer function $H(s)$
R	Resistance, a resistor
r_0	Small signal output (drain) impedance of a MOS transistor (also called r_{ds})
R_B	Bulk resistance of a transistor
R_D	Drain resistance of a transistor
r_{ds}	Small signal output (drain) impedance of a MOS transistor (also called r_0)
R_{eff}	Effective noise resistance of a transistor
$\Re(x)$	The real part of x
R_G	Gate resistance of a transistor
R_p	Equivalent parallel resistance of an RLC network
R_S	Source resistance of a transistor
R_s	Series resistance of an inductor
s	Laplace variable, equal to $\sigma + j \cdot \omega$, in steady-state equal to $j \cdot \omega$
s	Second, unit of time
$S_{\phi,f}(f)$	Power Spectral Density of the phase fluctuations as a result of the $1/f$ noise component
$S_a(f)$	Power Spectral Density of a waveform a
$S_{i_n}(f)$	Power Spectral Density of a current noise source i_n
$S_{inj}(\omega)$	Power spectral density of the injected signal i_{inj}
$S_{nn}(\omega)$	Power spectral density of the free-running oscillator signal
$S_{osc}(\omega)$	Power spectral density of the locked oscillator signal i_{osc}
$S_{RF}(f)$	Power Spectral Density of a general RF signal
$S_{V_n}(f)$	Power Spectral Density of the voltage noise on a capacitor
$S_{v_n}(f)$	Power Spectral Density of a voltage noise source v_n
$S_x(f)$	Power Spectral Density of phase time fluctuations
$S_y(f)$	Power Spectral Density of fractional frequency fluctuations
$S_\phi(f)$	Power Spectral Density of phase fluctuations
$S_{\Delta f}(f)$	Power Spectral Density of frequency fluctuations
$S_{\Delta\omega}(f)$	Power Spectral Density of angular frequency fluctuations
T	Absolute temperature, expressed in Kelvin [K] or (depending on the context), the oscillation period
t	Time variable
T_0	Period of an oscillator
T_D	Delay of an oscillator stage
t_d	Delay of an inverter

T_h	Time span that a digital oscillator output is high during one period
$T_{h,0}$	Time span that a digital oscillator output is high during one period with a sensor input signal equal to zero
t_{hl}	Input-output delay of an amplifier for a falling edge at the output
$T_{i,reg}$	Loopgain of a current regulation circuit
T_l	Time span that a digital oscillator output is low during one period
t_L	Time needed for an injection-locked oscillator to lock, lock time of an injection-locked oscillator
$T_{l,0}$	Time span that a digital oscillator output is low during one period with a sensor input signal equal to zero
T_{LC}	Period of a free-running LC tank
t_{lh}	Input-output delay of an amplifier for a rising edge at the output
T_M	Motor torque
T_{Osc}	Complete period of a multi-stage oscillator
$T(s)$	Frequency dependent loopgain of a feedback system
T_{Sens}	Sensitivity of the output frequency f_0 to temperature
T_{Switch}	Time interval needed for a differential oscillator stage to switch
$T(t)$	Phase time
$T_{v,reg}$	Loopgain of a voltage regulation circuit
U	Symbol of electrical tension
$\mathbf{u_i}$	Eigenvector with corresponding eigenvalue λ_i
$u(t)$	The Heaviside function
V_A	Voltage amplitude over a capacitor
V_{bs}	Large-signal bulk-source voltage of a MOS transistor
v_{bs}	Small-signal bulk-source voltage of a MOS transistor
$v_c(t)$	Control voltage of a VCO
V_{Cte}	Constant input voltage
V_{ctrl}	Control voltage to control the gain of an amplifier
V_d	Differential voltage applied to the input of a differential pair
V_{dd}	Supply voltage
V_{ds}	Large-signal drain-source voltage of a MOS transistor
v_{ds}	Small-signal drain-source voltage of a MOS transistor
V_E	Early-voltage of a MOS transistor
V_{gs}	Large-signal gate-source voltage of a MOS transistor
v_{gs}	Small-signal gate-source voltage of a MOS transistor
$V_{gs,f}$	Zero-temperature-coefficient DC biasing voltage of a transistor
V_{gt}	Overdrive voltage of a MOS transistor, equal to $V_{gs} - V_{th}$
V_i	Output voltage of the i-th oscillator stage

$V_{i,reg}$	Regulated output voltage of a current regulation circuit
V_k	Fourier coefficient of a voltage oscillator signal
V_{max}	Maximum supply voltage at which a circuit can properly operate
v_{max}	Maximum output voltage (compared to equilibrium) of a resonant tank during one oscillation cycle
V_{min}	Minimum supply voltage at which a circuit can properly operate
$v_{n,diff}$	Differential noise voltage
$v_n(t)$	Small-signal noise voltage
V_{ref}	Output voltage of a voltage reference
V_{reg}	Output voltage of a voltage regulator
V_{rep}	Output biasing voltage coming from a replica circuit
$V(s)$	Laplace transform of a voltage waveform
V_S	Output voltage of a sensor, input voltage of a sensor interface
$V_{S,DC}$	DC value of the sensor output voltage
V_{Sens}	Sensitivity of the output frequency f_0 to the supply voltage
V_{S-}	Negative voltage output of a differential sensor
V_{S+}	Positive voltage output of a differential sensor
$v(t)$	Small-signal voltage
$v(t-\tau)$	Decay function of the excess amplitude
V_T	Threshold voltage of a relaxation oscillator
V_t	Thermal voltage, equal to $k \cdot T/q = 26$ mV at room temperature
V_{th}	Threshold voltage of a MOS transistor
V	Volt, unit of electrical tension
$V_{v,reg}$	Regulated output voltage of a voltage regulation circuit
$V_{v,reg,rep}$	Regulated output voltage over the oscillator replica when the regulator is loaded with a resistor
$V_{v,reg,res}$	Regulated output voltage of a voltage regulation circuit loaded with a resistor
W	Width of a MOS transistor
x	Normalized variable of the ISF $\Gamma(x)$, typically equal to $\omega_n \cdot t$
$\dot{x}_i$	Time-derivative of x_i
$x_i(t)$	A real-valued function of t
$x(t)$	Random instantaneous phase time variation, $\phi(t)/\omega_0$
$y(t)$	Instantaneous fractional frequency variation, $dx(t)/dt$
Z	Complex impedance
z	Scalar for which $z \in \mathbb{Z}$
Z_k	Impedance of a resonant network, seen by the k-th harmonic