Principles of LED Light Communications

Towards Networked Li-Fi

Balancing theoretical analysis and practical advice, this book describes all the underlying principles required to build high-performance indoor optical wireless communication (OWC) systems based on visible and infrared light, alongside essential techniques for optimizing systems by maximizing throughput, reducing hardware complexity, and measuring performance effectively.

It provides a comprehensive analysis of information rate-, spectral-, and power-efficiencies for single- and multi-carrier transmission schemes, and novel analysis of non-linear signal distortion, enabling the use of off-the-shelf LED technology. Other topics covered include cellular network throughput and coverage, static resource partitioning and dynamic interference-aware scheduling, realistic light propagation modeling, OFDM, optical MIMO transmission, and non-linearity modeling.

Covering practical techniques for building indoor optical wireless cellular networks supporting multiple users, and guidelines for 5G cellular system studies, in addition to physical layer issues, this is an indispensable resource for academic researchers, professional engineers, and graduate students working in optical communications.

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CAMBRIDGE
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University Printing House, Cambridge CB2 8BS, United Kingdom

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of
education, learning and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/9781107049420

First published 2015

Printed in the United Kingdom by TJ International Ltd. Padstow Cornwall

A catalogue record for this publication is available from the British Library

Library of Congress Cataloguing in Publication data
Dimitrov, Svilen.
Principles of LED light communications: towards networked Li-Fi / Svilen Dimitrov, Harald Haas.
pages cm
Includes bibliographical references and index.
ISBN 978-1-107-04942-0 (Hardback)
1. Optical communications. 2. Wireless LANs. 3. Light emitting diodes. I. Haas, Harald. II. Title.
TK5103.59.D56 2015
621.382′7–dc23 2014034786

ISBN 978-1-107-04942-0 Hardback

Cambridge University Press
978-1-107-04942-0 - Principles of LED Light Communications: Towards Networked Li-Fi
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Acronyms

3D	3-dimensional
4G	4th generation
AC	alternating current
ACI	adjacent channel interference
ACO-OFDM	asymmetrically clipped optical orthogonal frequency division multiplexing
ADC	analog-to-digital converter
AGC	automatic gain control
AMC	adaptive modulation and coding
AP	access point
AWGN	additive white Gaussian noise
AZ	azimuth
BB	busy burst
BER	bit-error ratio
BPSK	binary phase shift keying
BRDF	bi-directional reflectance distribution function
CAD	computer-aided design
CCDF	complementary cumulative distribution function
CCI	co-channel interference
CDMA	code division multiple access
CESAR	cellular slot access and reservation
CLT	central limit theorem
CP	cyclic prefix
CSMA/CD	carrier sense multiple access with collision detection
DAC	digital-to-analog converter
DC	direct current
DCO-OFDM	direct-current-biased optical orthogonal frequency division multiplexing
DFE	decision-feedback equalizer
DMT	discrete multi-tone
DSL	digital subscriber line
DSP	digital signal processor
E/O	electrical-to-optical

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EL	elevation
FDD	frequency division duplexing
FDMA	frequency division multiple access
FEC	forward error correction
FFE	feed-forward equalizer
FFT	fast Fourier transform
FOV	field of view
FSO	free-space optical
HPA	high-power amplifier
ICI	inter-carrier interference
IEEE	Institute of Electrical and Electronics Engineers
IFFT	inverse fast Fourier transform
IM/DD	intensity modulation and direct detection
IP	Internet protocol
IR	infrared
IrDA	Infrared Data Association
ISI	inter-symbol interference
LDPC	low density parity check
LED	light emitting diode
Li-Fi	light fidelity
LOS	line-of-sight
LTE	long term evolution
M-PAM	multi-level pulse amplitude modulation
M-PAPM	multi-level pulse amplitude and position modulation
M-PPM	multi-level pulse position modulation
M-QAM	multi-level quadrature amplitude modulation
MAC	medium access control
Mbps	megabits per second
MCRT	Monte Carlo ray-tracing
MIMO	multiple-input–multiple-output
MLSD	maximum likelihood sequence detection
MMSE	minimum mean squared error
MRC	maximum ratio combining
NIR	near infrared
NLOS	non-line-of-sight
O/E	optical-to-electrical
O-OFDM	optical orthogonal frequency division multiplexing
OFDM	orthogonal frequency division multiplexing
OFDM-TDMA	OFDM time division multiple access
OFDMA	orthogonal frequency division multiple access
OFDMA-TDD	OFDMA time division duplexing
OOK	on–off keying
OSTBC	orthogonal space-time block codes
OWC	optical wireless communication

P/S	parallel-to-serial
PAM-DMT	pulse amplitude modulation discrete multi-tone
PAPR	peak-to-average-power ratio
PD	photodiode
PDF	probability density function
PDU	protocol data unit
PEP	pairwise error probability
PIM	pulse interval modulation
PIN	positive–intrinsic–negative
PLC	power line communication
PoE	power-over-Ethernet
PSD	power spectral density
PSU	passenger service unit
PWM	pulse width modulation
QoS	quality of service
RC	repetition coding
RF	radio frequency
RGB	red, green, and blue
RMS	root mean square
Rx	receiver
S/P	serial-to-parallel
SE	spectral efficiency
SER	symbol-error rate
SFO-OFDM	spectrally factorized O-OFDM
SIMO	single-input–multiple-output
SINR	signal-to-interference-and-noise ratio
SIR	signal-to-interference ratio
SISO	single-input–single-output
SM	spatial modulation
SMP	spatial multiplexing
SNR	signal-to-noise ratio
TDD	time division duplexing
TDMA	time division multiple access
TIA	transimpedance amplifier
Tx	transmitter
UE	user equipment
U-OFDM	unipolar orthogonal frequency division multiplexing
VLC	visible light communication
VLCC	Visible Light Communications Consortium
WDD	wavelength division duplexing
WDM	wavelength division multiplexing
WDMA	wavelength division multiple access
Wi-Fi	wireless fidelity
WLAN	wireless local area network
ZF	zero forcing

Notation

$*$	linear convolution operator
$\star$	linear discrete convolution operator
$[\cdot]^T$	transpose operator
$\|\cdot\|_{\mathrm{F}}$	Frobenius norm
$\lfloor\cdot\rfloor$	floor operator
$\lceil\cdot\rceil$	ceiling operator
$\mathrm{mod}(\cdot,\cdot)$	modulus of a congruence
a	variable related to the RMS delay spread of the channel, D
A	photosensitive area of the PD
A_0	reference area of 1 m^2
b	bit sequence, reservation indicator
$\mathbf{b}$	bit loading vector in OFDM
B	signal bandwidth
B_{c}	coherence bandwidth of the optical wireless channel
BER	generalized BER of M-PAM and M-QAM O-OFDM
$\mathrm{BER}_{\mathrm{PAM}}$	BER of M-PAM
$\mathrm{BER}_{\mathrm{RC}}$	BER of RC
$\mathrm{BER}_{\mathrm{SM}}$	BER of SM
$\mathrm{BER}_{\mathrm{SMP}}$	BER of SMP
BOTTOM	shifted bottom clipping level
c	speed of light
$c(t)$	chip
$\mathbf{c}$	chip vector
C	mutual information/information rate
$\mathrm{Cov}[\cdot]$	covariance operator
d	distance between the transmitter and the receiver on the direct path
d_1	distance between the transmitter and the reflective surface
d_2	distance between the receiver and the reflective surface
$d_{\mathrm{H}}(\cdot,\cdot)$	Hamming distance of two bit sequences
d_{ref}	reference distance
d_{s}	distance between an intended symbol and the closest interfering symbol

d_{tot}	total distance (including the reflections) a ray travels
d_{Tx}	spacing of the individual transmitters in the optical array
D	RMS delay spread of the channel
$\mathrm{E}[\cdot]$	expectation operator
$E(d_{\mathrm{ref}})$	irradiance at a reference distance d_{ref}
$E_{\mathrm{b(elec)}}$	average electrical bit energy
E_{eye}	irradiance of the eye
$E_{\mathrm{s(elec)}}$	average electrical symbol energy
f	frequency variable
$\mathbf{f}$	OFDM frame vector
$\widetilde{\mathbf{f}}$	distorted replica of the OFDM frame vector at the receiver
$\mathbf{f}_{\mathrm{info}}$	vector with the information-carrying subcarriers
$\widetilde{\mathbf{f}}_{\mathrm{info}}$	distorted replica of the vector with the information-carrying subcarriers
$F(\cdot)$	non-linear transfer function of the transmitter
F_{OE}	O/E conversion factor for the intended signal
$F_{\mathrm{OE,I}}$	O/E conversion factor for the interfering signal
$F_{\mathrm{O,S}}$	factor for the useful optical symbol power in the intended signal
$g_{\mathrm{h(elec)}}$	electrical path gain
$g_{\mathrm{h(opt)}}$	optical path gain
g_{I}	optical path gain between an interfering transmitter and the receiver
g_{S}	optical path gain between the intended transmitter and the receiver
G_{B}	bandwidth utilization factor
G_{DC}	DC-bias gain
G_{EQ}	equalizer gain
G_{GC}	Gray coding gain
G_{OC}	gain of the optical concentrator
G_{T}	utilization factor for the information-carrying time
G_{TIA}	gain of the TIA
$\mathbf{h}$	impulse response vector of the optical wireless channel
$h(t)$	impulse response of the optical wireless channel
$h_{\mathrm{norm}}(t)$	normalized impulse response of the optical wireless channel
$h_{n_{\mathrm{r}}n_{\mathrm{t}}}$	optical channel gain between transmitter n_{t} and receiver n_{r}
$\mathbf{H}$	optical channel matrix in a MIMO setup
$\mathbf{H}_{d_{\mathrm{Tx}}}$	optical channel matrix for a given spacing of transmitters
$\widehat{\mathbf{H}}_{d_{\mathrm{Tx}}}$	optical channel matrix for a given spacing of transmitters with induced link blockage
$H(f)$	Fourier transform of $h(t)$
$H_{\mathrm{norm}}(f)$	Fourier transform of $h_{\mathrm{norm}}(t)$
i	imaginary unit $i = \sqrt{-1}$, index of a direct ray, index of an interfering transmitter
I_{f}	forward current

I_{in}	input current
I_{max}	maximum forward current
$I_{\text{max,norm}}$	normalized maximum forward current
I_{min}	minimum forward current
$I_{\text{min,norm}}$	normalized minimum forward current
I_{out}	output current
j	index of a polynomial function $\psi(\cdot)$, index of a reflecting ray
$\hat{j}$	index of a normalized clipping level, λ
J	number of normalized clipping levels
k	time-domain sample index in OFDM, index of a ray reflection
k_{B}	Boltzmann's constant
k_{c}	chunk time index
K	attenuation factor of the non-linear distortion for the information-carrying subcarriers
K_{C}	size of coordination cluster of adjacent APs
l	symbol index
L	number of symbols per transmission vector
m	subcarrier index
m_{c}	chunk frequency index
M	modulation order
M_{SE}	modulation and coding scheme
$\hat{M}_{\text{SE}}$	modulation scheme associated with an *a priori* SINR estimate
$\bar{M}_{\text{SE}}$	modulation scheme of higher order to be used in the next frame
n	integer polynomial order
n_{os}	number of OFDM symbols per chunk
n_{r}	index of a receiver/PD in the optical array
n_{sc}	number of subcarriers per chunk
n_{spec}	Lambertian mode number of the specular reflection
n_{t}	index of a transmitter/LED in the optical array
n_{Tx}	Lambertian mode number of the transmitter
N	number of subcarriers, FFT size
N_0	power spectral density of the AWGN
N_{A}	number of APs
N_{C}	number of chunks
N_{CP}	number of CP samples in OFDM
N_{LOS}	number of rays directly impinging on the PD
N_{NLOS}	number of rays which undergo one or multiple reflections
N_{r}	number of receivers/PDs in the optical front-end
N_{rays}	number of rays
N_{refl}	number of reflections
N_{s}	average number of neighboring symbols
N_{t}	number of transmitters/LEDs in the optical front-end
p	scaling factor for the current/optical power levels in M-PAM
$\mathbf{p}$	power loading vector in OFDM

$p_S(s)$	PDF of the clipped OFDM symbol
$p_{\hat{S}}(\hat{s})$	PDF of the unfolded clipped ACO-OFDM symbol
$p_{\mathbf{y}}$	probability density function of the received signal $\mathbf{y}$
$P_{\text{avg,norm}}$	normalized average optical power constraint
$P_{\text{bb,elec}}$	electrical power of the BB signal at a receiver
$P_{\text{b(elec)}}$	average electrical bit power
P_{bg}	optical power of the background illumination
P_{elec}	dissipated electrical power
P_{eye}	optical power irradiating the eye pupil
$P_{\text{I,elec}}$	total interference electrical power
$P_{\text{I,elec,th}}$	threshold interference electrical power
$P_{\text{I,opt}}$	optical power of an interfering transmitter
P_{LOS}	received optical power from the direct rays
$P_{\text{max,norm}}$	normalized maximum optical power constraint
$P_{\text{min,norm}}$	normalized minimum optical power constraint
$P_{\text{N,elec}}$	electrical noise power
P_{NLOS}	received optical power from the reflecting rays
P_{opt}	radiated optical power
$P_{\text{opt}}^{\text{bb}}$	radiated optical power of the BB signal
$P_{\text{opt}}^{\text{PAM}}$	optical power level of an M-PAM symbol for an infinite non-negative linear dynamic range
$P_{\text{opt}}^{\text{SM}}$	optical power level in SM for an infinite non-negative linear dynamic range
P_{R}	optical power at receiver
$P_{\text{S,elec}}$	intended electrical symbol power
$P_{\text{S,opt}}$	optical power of the intended transmitter
$P_{\text{s(elec)}}$	average electrical symbol power
$P_{\text{s(opt)}}$	average optical symbol power
$P_{\tilde{\text{s}}\text{(opt)}}$	effective received optical symbol power in a MIMO setup
$\widetilde{P}_{\text{s(opt)},n_{\text{t}}}$	average optical power assigned to transmitter n_{t} in a MIMO setup with power imbalance
PEP_{SM}	PEP of SM
PEP_{SMP}	PEP of SMP
$\text{PL}(d)$	path loss at distance d
P_{T}	optical power of the transmitter
q	elementary electric charge, i.e. $q = 1.6 \times 10^{-19}$ C
$Q(\cdot)$	CCDF of a standard normal distribution
r	radius in a spherical coordinate system
r_{eye}	radius of the eye pupil
r_{FOV}	FOV radius at distance of 20 cm
R	coding rate
R_{b}	bit rate
R_{load}	load resistance

$R_{\mathrm{LED}}(\theta, n_{\mathrm{Tx}})$	generalized Lambertian radiation pattern of the LED
R_{s}	symbol rate
R_{th}	user reservation threshold
s	user score for fair resource reservation
$s(t)$	symbol
$\hat{s}(t)$	unfolded ACO-OFDM symbol
$\bar{s}(t)$	unfolded and debiased ACO-OFDM symbol
$\mathbf{s}$	symbol vector
$\widetilde{\mathbf{s}}$	distorted replica of the symbol vector at the receiver
S	number of subbands of subcarriers, number of groups of cells
S_{PD}	responsivity of the PD
SE	spectral efficiency of the modulation schemes for OWC
SE_M	spectral efficiency of a modulation and coding scheme
SINR	electrical SINR in O-OFDM
SNR	electrical SNR in O-OFDM
$\mathrm{SNR}_{\mathrm{Rx}}$	electrical SNR at the receiver side in a MIMO setup
$\mathrm{SNR}_{\mathrm{Tx}}$	electrical SNR at the transmitter side in a MIMO setup
t	time variable
T	absolute temperature
T_{s}	symbol duration in PPM and PAM
T_{OF}	transmittance of the optical filter
TOP	shifted top clipping level
u	dummy integration variable
U	number of users
U_{A}	number of users served by an AP
$U(t)$	unit step function
$v(t)$	impulse response of the pulse shaping filter
$V(f)$	Fourier transform of $v(f)$
V_{f}	forward voltage
$w(t)$	AWGN at the receiver
$\mathbf{w}$	AWGN vector at the receiver
$w_{\mathrm{clip}}(t)$	uncorrelated non-Gaussian time-domain non-linear distortion noise
$\mathbf{W}$	AWGN vector at the frequency domain subcarriers
$\mathbf{W}_{\mathrm{clip}}$	additive Gaussian non-linear distortion noise at the information-carrying subcarriers
$x(t)$	biased information-carrying signal
$\mathbf{x}$	biased information-carrying signal vector
$\widehat{\mathbf{x}}$	decoded signal vector at the receiver
x_{Rx}	position offset of the receiver array on the X-axis
X	direction in a Cartesian coordinate system
$y(t)$	received signal
$\mathbf{y}$	received signal vector
y_{Rx}	position offset of the receiver array on the Y-axis

Y	direction in a Cartesian coordinate system
z	counter in summation of $W(f)$
Z	direction in a Cartesian coordinate system
$Z_{\mathbf{x}}$	length of the biased information-carrying signal vector
$Z_{\mathbf{h}}$	length of the impulse response vector of the optical wireless channel
α	scaling factor for the signal power
α_{A}	AP associated with UE μ_{U}
β_{A}	AP associated with UE ν_{U}
β_{DC}	DC-bias current
γ	electrical SINR at receiver
$\hat{\gamma}$	*a priori* estimate of the electrical SINR at receiver
$\gamma_{\mathrm{b(elec)}}$	undistorted electrical SNR per bit at the transmitter
Γ	electrical SINR target
$\Gamma_{\mathrm{b(elec)}}$	effective electrical SNR per bit at the receiver
$\Gamma_{\min}$	minimum electrical SINR target
δ	optical power imbalance factor between the individual transmitters
$\delta(t)$	Dirac delta function
$\Delta_{d_{\mathrm{Tx}}}^{\mathrm{SNR_{Rx}}}$	penalty on the received electrical SNR for a given spacing of transmitters
$\widehat{\Delta}_{d_{\mathrm{Tx}}}^{\mathrm{SNR_{Rx}}}$	penalty on the received electrical SNR for a given spacing of transmitters with induced link blockage
ϵ	user indicator for access of an idle chunk
ζ	shadowing component, index of user
η	fraction of the light reflected in a diffuse Lambertian fashion
θ	zenith angle in a spherical coordinate system
θ_{eye}	angle subtended by the eye pupil and the origin at d = 20 cm
$\theta_{\mathrm{FOV,Rx}}$	FOV semi-angle of receiver
$\theta_{\mathrm{FOV,Tx}}$	FOV semi-angle of transmitter
θ_{inc}	incident angle of the incoming light/ray at the reflective surface
θ_{obs}	observation angle of the outgoing light/ray from the reflective surface
θ_{Rx}	incident angle of the receiver from the reflective surface
$\theta_{\mathrm{Rx,d}}$	incident angle of the receiver on the direct path
θ_{Tx}	observation angle of the transmitter towards the reflective surface
$\theta_{\mathrm{Tx,d}}$	observation angle of the transmitter on the direct path
κ	factor of standard deviations quantifying the DC bias in DCO-OFDM
λ	normalized clipping level, wavelength
$\lambda_{\mathrm{bottom}}$	normalized bottom clipping level

λ_{top}	normalized top clipping level
$\Lambda(f)$	variable related to $V(f)$ and $H(f)$ by (2.20)
μ	mean of the clipped DCO-OFDM symbol
μ_{U}	UE associated with AP α_{A}
ν_{U}	UE associated with AP β_{A}
ξ	path loss exponent
$\Xi(\cdot)$	piecewise polynomial transfer function of the transmitter
π	number pi, $\pi \approx 3.14$
ρ	reflection coefficient of the reflective surface
σ	standard deviation of the OFDM time-domain signal
σ_{AWGN}	standard deviation of the AWGN
σ_{clip}	standard deviation of the non-linear distortion noise
σ_{shad}	standard deviation of log-normal shadowing
τ	dummy integration variable
ϕ	azimuth angle in a spherical coordinate system
$\phi(\cdot)$	PDF of a standard normal distribution
$\Phi(\cdot)$	linearized transfer function of the transmitter denoting the double-sided signal clipping
$\psi(\cdot)$	polynomial function of non-negative integer order, n
Ψ	user priority penalty factor
$\Psi(\cdot)$	normalized non-linear transfer function of the transmitter
$\hat{\Psi}(\cdot)$	unfolded normalized non-linear transfer function in ACO-OFDM
$\mathcal{A}$	set of chunks assigned to a user
$\#\mathcal{A}$	number of chunks assigned to a user
$\mathcal{G}$	group of APs/cells
$\mathcal{G}_{\beta_{\text{A}}}$	group of APs β_{A}
$\mathcal{I}$	integral structure for calculation of the non-linear distortion parameters
$\mathcal{M}$	set of supported modulation schemes
$\#\mathcal{M}$	cardinality of $\mathcal{M}$
$\mathcal{N}(\mu, \sigma^2)$	normal distribution with mean μ and variance σ^2 of the unclipped OFDM symbol
$\mathcal{R}(\theta, \phi)$	BRDF
$\mathcal{R}_{\text{in}}(\theta, \phi, \lambda)$	portion of the BRDF related to the incoming light