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 powerefficiencies 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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Towards Networked Li-Fi

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1

2

Contents

| | 'nyms | page 1x |
|---|---|--|
| Note | ition | xii |
| Intro | duction | 1 |
| 1.1 | History of OWC | 1 |
| 1.2 | Advantages of OWC | 3 |
| 1.3 | Application areas | 4 |
| 1.4 | Li-Fi | 5 |
| | 1.4.1 Modulation | 5 |
| | 1.4.2 Multiple access | 6 |
| | 1.4.3 Uplink | 7 |
| | 1.4.4 The attocell | 8 |
| | 1.4.5 Cellular network | 9 |
| 1.5 | Challenges for OWC | 9 |
| 1.6 | Summary | 11 |
| Opti | cal wireless communication | 12 |
| 2.1 | Introduction | 12 |
| 2.2 | System setup | 13 |
| 2.3 | Communication scenarios | 14 |
| | 2.3.1 Line-of-sight communication | 15 |
| | | |
| | 2.3.2 Non-line-of-sight communication | 15 |
| 2.4 | 2.3.2 Non-line-of-sight communication Optical front-ends | 15 16 |
| 2.4 | 2.3.2 Non-line-of-sight communicationOptical front-ends2.4.1 Transmitter | 15 16 16 |
| 2.4 | 2.3.2 Non-line-of-sight communicationOptical front-ends2.4.1 Transmitter2.4.2 Receiver | 15 16 16 18 |
| 2.4 2.5 | 2.3.2 Non-line-of-sight communicationOptical front-ends2.4.1 Transmitter2.4.2 ReceiverOptical wireless channel | 15 16 16 18 20 |
| 2.4 2.5 | 2.3.2 Non-line-of-sight communication Optical front-ends 2.4.1 Transmitter 2.4.2 Receiver Optical wireless channel 2.5.1 Channel model | 15 16 16 18 20 21 |
| 2.4 2.5 | 2.3.2 Non-line-of-sight communication Optical front-ends 2.4.1 Transmitter 2.4.2 Receiver Optical wireless channel 2.5.1 Channel model 2.5.2 Path loss | 15 16 16 18 20 21 21 |
| 2.4 2.5 | 2.3.2 Non-line-of-sight communication Optical front-ends 2.4.1 Transmitter 2.4.2 Receiver Optical wireless channel 2.5.1 Channel model 2.5.2 Path loss 2.5.3 Delay spread and coherence bandwidth | 15 16 16 18 20 21 21 21 26 |
| 2.4 2.5 | 2.3.2 Non-line-of-sight communication Optical front-ends 2.4.1 Transmitter 2.4.2 Receiver Optical wireless channel 2.5.1 Channel model 2.5.2 Path loss 2.5.3 Delay spread and coherence bandwidth 2.5.4 Channel equalization | 15 16 16 18 20 21 21 21 26 27 |
| 2.42.52.6 | 2.3.2 Non-line-of-sight communication Optical front-ends 2.4.1 Transmitter 2.4.2 Receiver Optical wireless channel 2.5.1 Channel model 2.5.2 Path loss 2.5.3 Delay spread and coherence bandwidth 2.5.4 Channel equalization Cellular network: a case study in an aircraft cabin | 15 16 18 20 21 21 21 26 27 29 |

V

| vi | Contents | |
|----|---|----------|
| | | |
| | 2.6.2 Cabin setup: propagation paths, cellular configuration, and | 22 |
| | wavelength reuse | 32 |
| | 2.6.5 Cabin geometry and materials | 36 |
| | 2.6.5 Photobiological safety | 38 |
| | 2.6.6 Estimation of line-of-sight path loss and shadowing | 39 |
| | 2.6.7 Estimation of non-line-of-sight path loss and shadowing | 42 |
| | 2.6.8 Signal-to-interference ratio maps | 49 |
| | 2.7 Summary | 55 |
| 3 | Front-end non-linearity | 57 |
| | 3.1 Introduction | 57 |
| | 3.2 Generalized non-linear transfer function | 58 |
| | 3.3 Pre-distortion | 59 |
| | 3.4 Non-linear distortion of Gaussian signals | 61 |
| | 3.4.1 Analysis of generalized non-linear distortion | 61 |
| | 3.4.2 Analysis of double-sided signal clipping distortion | 65 |
| | 3.5 Summary | 71 |
| 4 | Digital modulation schemes | 72 |
| | 4.1 Introduction | 72 |
| | 4.2 Optical signals | 72 |
| | 4.3 Single-carrier modulation | 77 |
| | 4.3.1 Pulse position modulation: <i>M</i> -PPM | 78 |
| | 4.3.2 Pulse amplitude modulation: <i>M</i> -PAM | 80 |
| | 4.3.3 BER performance with pre-distortion in AWGN | 82 |
| | 4.4 Multi-carlier modulation $4.4.1$ Optical OEDM with M OAM: DCO OEDM and ACO OEDM | 04 84 |
| | 4.4.2 BER performance with generalized non-linear distortion in AWG | N 89 |
| | 4.4.3 BER performance with pre-distortion in AWGN | 91 |
| | 4.5 Summary | 94 |
| 5 | Spectral efficiency and information rate | 95 |
| | 5.1 Introduction | 95 |
| | 5.2 Constraints on the information rate in OWC | 96 |
| | 5.2.1 Link impairments | 97 |
| | 5.2.2 On the maximization of information rate | 98 |
| | 5.3 Modulation schemes in the flat fading channel with AWGN | 99 |
| | 5.3.1 Biasing optimization of Gaussian signals | 100 |
| | 5.3.2 Maximum spectral efficiency without an average optical power | |
| | constraint | 103 |
| | 5.3.3 Spectral efficiency with an average optical power constraint | 106 |
| | | |

| | | Contents | vii |
|---|------|---|------------|
| | | | |
| | 5.4 | Information rate of OFDM-based modulation with non-linear distortion | 110 |
| | | 5.4.1 Biasing optimization of Gaussian signals | 111 |
| | | 5.4.2 Maximum information rate without an average optical power | |
| | | constraint | 113 |
| | | 5.4.3 Information rate with an average optical power constraint | 115 |
| | 5.5 | Modulation schemes in the dispersive channel with AWGN | 120 |
| | | 5.5.1 Biasing optimization of Gaussian signals | 121 |
| | | 5.5.2 DC-bias penalty | 122 |
| | | 5.5.3 Equalizer penalty | 124 |
| | | 5.5.4 Maximum spectral efficiency without an average optical power | 105 |
| | 5.6 | constraint | 125 |
| | 5.6 | Summary | 127 |
| 6 | MIN | 10 transmission | 130 |
| | 6.1 | Introduction | 130 |
| | 6.2 | System model | 131 |
| | 6.3 | MIMO techniques | 133 |
| | | 6.3.1 Repetition coding | 133 |
| | | 6.3.2 Spatial multiplexing | 135 |
| | | 6.3.3 Spatial modulation | 136 |
| | | 6.3.4 Computational complexity | 138 |
| | 6.4 | BER performance | 139 |
| | | 6.4.1 Varying the separation of transmitters | 139 |
| | | 6.4.2 Varying the position of receivers | 145 |
| | | 6.4.3 Power imbalance between transmitters | 146 |
| | | 6.4.4 Link blockage | 147 |
| | 6.5 | Summary | 150 |
| 7 | Thro | oughput of cellular OWC networks | 151 |
| | 7.1 | Introduction | 151 |
| | 7.2 | System throughput using static resource partitioning | 152 |
| | | 7.2.1 Signal-to-interference-and-noise ratio modeling | 153 |
| | | 7.2.2 Adaptive modulation and coding | 156 |
| | | 7.2.3 System throughput of optical OFDM in an aircraft cabin | 157 |
| | 7.3 | Interference coordination in optical cells using busy burst signaling | 160 |
| | | 7.3.1 System model | 161 |
| | | 7.3.2 Interference coordination in optical cells | 162 |
| | | 7.3.3 Busy burst principle | 164 |
| | | | 165 |
| | | 7.3.4 Contention avoidance among neighboring cells | 165 |
| | | 7.3.4 Contention avoidance among neighboring cells7.3.5 User scheduling and fair reservation mechanism | 165 168 |

| Contents | | |
|-----------|--|--|
| 7.3 | 7 System throughput with busy burst signaling | 170 |
| 7.3. | 8 System throughput with busy burst signaling and fair reservation | 110 |
| | mechanism | 178 |
| 7.4 Sur | nmary | 181 |
| Reference | es | 183 |
| Index | | 197 |
| | Contents 7.3. 7.4 Sur Reference Index | Contents 7.3.7 System throughput with busy burst signaling 7.3.8 System throughput with busy burst signaling and fair reservation mechanism 7.4 Summary References Index |

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 |
| СР | 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 |

iх

| X | Acronyms | |
|---|---------------|---|
| | | |
| | 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 |
| | <i>M</i> -PAM | multi-level pulse amplitude modulation |
| | M-PAPM | multi-level pulse amplitude and position modulation |
| | M-PPM | multi-level pulse position modulation |
| | <i>M</i> -OAM | 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 | ontical-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 keving |
| | OSTRC | orthogonal space-time block codes |
| | OWC | ontical wireless communication |
| | Unc | opucar whereas communication |

Acronyms

| 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 |
|--------------------------------|---|
| * | linear discrete convolution operator |
| $\left[\cdot\right]^{T}$ | transpose operator |
| $\ \cdot\ _{F}$ | Frobenius norm |
| [·] | floor operator |
| [·] | ceiling operator |
| $mod(\cdot, \cdot)$ | modulus of a congruence |
| а | variable related to the RMS delay spread of the channel, D |
| Α | photosensitive area of the PD |
| A_0 | reference area of 1 m ² |
| b | bit sequence, reservation indicator |
| b | bit loading vector in OFDM |
| В | signal bandwidth |
| B _c | coherence bandwidth of the optical wireless channel |
| BER | generalized BER of M-PAM and M-QAM O-OFDM |
| BER _{PAM} | BER of <i>M</i> -PAM |
| BER _{RC} | BER of RC |
| BER _{SM} | BER of SM |
| BER _{SMP} | BER of SMP |
| BOTTOM | shifted bottom clipping level |
| С | speed of light |
| c(t) | chip |
| c | chip vector |
| С | mutual information/information rate |
| Cov [·] | 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 |
| $d_{\rm ref}$ | reference distance |
| $d_{\rm s}$ | distance between an intended symbol and the closest interfering |
| | symbol |

| Notation |
|----------|
|----------|

xiii

| $d_{\rm tot}$ | 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 |
| E[·] | expectation operator |
| $E(d_{\rm ref})$ | irradiance at a reference distance d_{ref} |
| $E_{\rm b(elec)}$ | average electrical bit energy |
| Eeve | irradiance of the eye |
| $E_{\rm s(elec)}$ | average electrical symbol energy |
| f | frequency variable |
| f | OFDM frame vector |
| Ĩ | distorted replica of the OFDM frame vector at the receiver |
| f _{info} | vector with the information-carrying subcarriers |
| $\widetilde{\mathbf{f}}_{info}$ | 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 |
| $F_{\text{OE,I}}$ | O/E conversion factor for the interfering signal |
| $F_{O,S}$ | factor for the useful optical symbol power in the intended signal |
| gh(elec) | electrical path gain |
| gh(opt) | optical path gain |
| g_{I} | optical path gain between an interfering transmitter and the |
| | receiver |
| gs | optical path gain between the intended transmitter and the |
| | receiver |
| $G_{\rm B}$ | bandwidth utilization factor |
| $G_{\rm DC}$ | DC-bias gain |
| $G_{\rm EQ}$ | equalizer gain |
| $G_{\rm GC}$ | 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 |
| h | impulse response vector of the optical wireless channel |
| h(t) | impulse response of the optical wireless channel |
| $h_{\rm norm}(t)$ | normalized impulse response of the optical wireless channel |
| $h_{n_{\rm r}n_{\rm t}}$ | optical channel gain between transmitter $n_{\rm t}$ and receiver $n_{\rm r}$ |
| H H | optical channel matrix in a MIMO setup |
| $\mathbf{H}_{d_{\mathrm{Tx}}}$ | optical channel matrix for a given spacing of transmitters |
| $\mathbf{H}_{d_{\mathrm{Tx}}}$ | induced link blocks |
| H(f) | Induced link blockage |
| $\Pi(J)$ | Fourier transform of $h_{(1)}$ |
| $n_{\text{norm}}(J)$ | Fourier mailstorial of $n_{\text{norm}}(l)$ |
| ı | an interfering transmitter |
| Ic | forward current |
| *I | for ward current |

| xiv No | tation |
|--------|--------|
|--------|--------|

| Iin | input current |
|-------------------------|--|
| Imax | maximum forward current |
| Imax norm | normalized maximum forward current |
| Imin | minimum forward current |
| Imin norm | normalized minimum forward current |
| Iout | output current |
| i | index of a polynomial function $\psi(\cdot)$, index of a reflecting ray |
| ĵ | 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 |
| $k_{\rm c}$ | chunk time index |
| ĸ | 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 |
| т | subcarrier index |
| m _c | chunk frequency index |
| М | modulation order |
| $M_{\rm SE}$ | modulation and coding scheme |
| $\hat{M}_{\rm SE}$ | modulation scheme associated with an <i>a priori</i> SINR estimate |
| \bar{M}_{SE} | modulation scheme of higher order to be used in the next frame |
| n | integer polynomial order |
| nos | 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 |
| Ν | number of subcarriers, FFT size |
| N_0 | power spectral density of the AWGN |
| NA | number of APs |
| N _C | number of chunks |
| N _{CP} | number of CP samples in OFDM |
| NLOS | number of rays directly impinging on the PD |
| N _{NLOS} | number of rays which undergo one or multiple reflections |
| Nr | number of receivers/PDs in the optical front-end |
| N _{rays} | number of rays |
| N _{refl} | number of reflections |
| IV _S | average number of neighboring symbols |
| /v _t | number of transmitters/LEDs in the optical front-end |
| р | scanng factor for the current/optical power levels in <i>M</i> -PAM |
| р | power loading vector in OFDM |

Rb R_{load}

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

Notation

bit rate

load resistance

| (vi | Notation | |
|-----|---|--|
| | | |
| | $R_{\text{LED}}(\theta, n_{\text{Tx}})$ | generalized Lambertian radiation pattern of the LED |
| | $R_{\rm s}$ | symbol rate |
| | $R_{ m th}$ | user reservation threshold |
| | S | user score for fair resource reservation |
| | s(t) | symbol |
| | $\hat{s}(t)$ | unfolded ACO-OFDM symbol |
| | $\overline{s}(t)$ | unfolded and debiased ACO-OFDM symbol |
| | 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 |
| | $S_{\rm PD}$ | 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 |
| | SNR _{Rx} | electrical SNR at the receiver side in a MIMO setup |
| | SNR _{Tx} | electrical SNR at the transmitter side in a MIMO setup |
| | t | time variable |
| | Т | absolute temperature |
| | $T_{\rm s}$ | symbol duration in PPM and PAM |
| | $T_{\rm OF}$ | 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 $v(f)$ |
| | $V_{ m f}$ | forward voltage |
| | w(t) | AWGN at the receiver |
| | W | AWGN vector at the receiver |
| | $w_{\rm clip}(t)$ | uncorrelated non-Gaussian time-domain non-linear |
| | | distortion noise |
| | W | AWGN vector at the frequency domain subcarriers |
| | \mathbf{W}_{clip} | additive Gaussian non-linear distortion noise at the |
| | × | information-carrying subcarriers |
| | x(t) | biased information-carrying signal |
| | Х | biased information-carrying signal vector |
| | x | decoded signal vector at the receiver |
| | $x_{\rm Rx}$ | position offset of the receiver array on the X-axis |
| | Х | direction in a Cartesian coordinate system |
| | y(t) | received signal |
| | У | received signal vector |
| | <i>y</i> _{Rx} | position offset of the receiver array on the Y-axis |
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| | Notation | xvii |
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| | | |
| Y | direction in a Cartesian coordinate system | |
| Z. | counter in summation of $W(f)$ | |
| Ζ | direction in a Cartesian coordinate system | |
| $Z_{\mathbf{x}}$ | length of the biased information-carrying signal vector | |
| Z _h | length of the impulse response vector of the optical wireless channel | |
| α | scaling factor for the signal power | |
| $lpha_{ m A}$ | AP associated with UE $\mu_{\rm U}$ | |
| $\beta_{\rm A}$ | AP associated with UE $v_{\rm U}$ | |
| $\beta_{\rm DC}$ | DC-bias current | |
| γ | electrical SINR at receiver | |
| Ŷ | a priori estimate of the electrical SINR at receiver | |
| $\gamma_{b(elec)}$ | undistorted electrical SNR per bit at the transmitter | |
| Γ | electrical SINR target | |
| $\Gamma_{b(elec)}$ | effective electrical SNR per bit at the receiver | |
| Γ_{\min} | minimum electrical SINR target | |
| δ | optical power imbalance factor between the individual | |
| | transmitters | |
| $\delta(t)$ | Dirac delta function | |
| $\Delta_{d_{\mathrm{Tx}}}^{\mathrm{SNR}_{\mathrm{Rx}}}$ | penalty on the received electrical SNR for a given spacing of transmitters | |
| $\widehat{\Lambda}^{SNR_{Rx}}$ | penalty on the received electrical SNR for a given spacing of | |
| Δd_{Tx} | transmitters with induced link blockage | |
| C | user indicator for access of an idle chunk | |
| د ۲ | shadowing component index of user | |
| 5 n | fraction of the light reflected in a diffuse I ambertian fashion | |
| n A | zenith angle in a spherical coordinate system | |
| 0 A | angle subtended by the even pupil and the origin at $d = 20$ cm | |
| deve decivities | FOV semi-angle of receiver | |
| $\theta_{\rm FOV,KX}$ | FOV semi-angle of transmitter | |
| $\theta_{\rm inc}$ | incident angle of the incoming light/ray at the reflective | |
| ine | surface | |
| $\theta_{\rm obs}$ | observation angle of the outgoing light/ray from the | |
| | reflective surface | |
| θ_{Rx} | incident angle of the receiver from the reflective surface | |
| $\theta_{\rm Rx,d}$ | 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 | |
| ĸ | factor of standard deviations quantifying the DC bias in | |
| | DCO-OFDM | |
| λ | normalized clipping level, wavelength | |
| λ_{bottom} | normalized bottom clipping level | |
| | * | |

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| xviii | Notation | |
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| | | |
| | 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 |
| | $\mu_{ m U}$ | UE associated with AP α_A |
| | $\nu_{\rm U}$ | 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 |
| | $\sigma_{ m AWGN}$ | standard deviation of the AWGN |
| | $\sigma_{ m clip}$ | standard deviation of the non-linear distortion noise |
| | $\sigma_{ m shad}$ | 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 |
| | ${\cal G}$ | group of APs/cells |
| | $\mathcal{G}_{eta_{A}}$ | 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 |
| | $\mathcal{R}(heta, oldsymbol{\phi})$ | BRDF |
| | $\mathcal{R}_{in}(\theta,\phi,\lambda)$ | portion of the BRDF related to the incoming light |