

Optical Adaptive Precoding for Visible Light Communications

Hanaa Marshoud, *Student Member, IEEE*, Paschalis C. Sofotasios, *Senior Member, IEEE*, Sami Muhaidat, *Senior Member, IEEE*, Bayan S. Sharif, *Senior Member, IEEE*, and George K. Karagiannidis, *Fellow, IEEE*

Abstract—Multiple-input multiple-output (MIMO) techniques have recently demonstrated significant potentials in visible light communications (VLC), as they can overcome the modulation bandwidth limitation and provide substantial improvement in terms of spectral efficiency and link reliability. However, MIMO systems typically suffer from inter-channel interference, which causes severe degradation to the system performance. In this context, we propose a novel optical adaptive precoding (OAP) scheme for the downlink of MIMO VLC systems, which exploits the knowledge of transmitted symbols to enhance the effective signal-to-interference-plus-noise ratio. Furthermore, we derive bit-error-rate expressions for the proposed OAP scheme under perfect and outdated channel state information (CSI). Our results demonstrate that the proposed scheme is more robust to both CSI error and channel correlation, compared to conventional channel inversion precoding. These results are expected to provide useful insights in the effective design and efficient operation of VLC networks.

Index Terms—Visible light communications, MIMO, precoding, constructive interference, CSI error.

I. INTRODUCTION

With the explosive growth of broadband applications and Internet services, the consumer demands for seamless mobile data connectivity increase rapidly. Given that the majority of wireless data traffic is generated indoors [1], service providers are constantly looking for innovative solutions to provide robust indoor wireless coverage. In this context, the concept of small cells and heterogeneous networks has been proposed as a potential solution to this problem. Nevertheless, the imminent shortage of radio frequency (RF) resources at large, along with the evidenced spectral efficiency saturation, has revealed the need for larger bandwidth and spectral relief.

To address some of the aforementioned challenges, visible light communication (VLC) has recently emerged as a promising solution to support and complement traditional RF communication systems, owing to its capability to overcome the

currently witnessed scarcity of the radio spectrum resources. To this effect, VLC is an optical wireless communication (OWC) paradigm [2]–[4] that is opening a new pathway for connecting indoor users to the Internet by practically unlocking the untapped electromagnetic spectrum in the visible light region [5]–[7]. The interest in this technology is driven by several factors as it offers high degree of spatial reuse, enhanced communication security and increased energy efficiency. Moreover, unlike RF signals, VLC does not interfere with electromagnetic radiations, which makes it safe to be used in places with high electromagnetic interference (EMI), such as hospitals and industrial plants [8], [9].

VLC uses light emitting diodes (LEDs) as transmitters and photo detectors (PDs) as receivers. Due to the relatively high modulation bandwidth of the LEDs, the amplitude of the optical signals can be modulated at sufficiently high switching rate that cannot be perceived by the human eye. As a result, the illumination function of the LEDs is not affected. This process is known as intensity modulation (IM), and it is feasible due to the incoherent light emitted by the LEDs, where photons have different wavelengths and phases, unlike coherent light sources such as lasers. At the receiver site, direct detection (DD) of the arriving signals is performed to convert the received optical signal into electric current. It is recalled that direct detection is substantially simpler than coherent detection used in RF, where an oscillator is required to extract the baseband signal from the carrier. Also, the diameters of the PDs are typically several hundred times the wavelength of light signals and thus, spatial multi-path interference is mitigated by the integrating effect at the PDs' surfaces [10]–[12].

It has been recently shown that multiple-input-multiple-output (MIMO) systems can contribute towards enhancing the spectral efficiency of indoor VLC systems and networks [13]–[18] and the references therein. Motivated by the fact that indoor spaces are typically equipped by multiple LEDs, several optical MIMO techniques have been devised to facilitate high data rate transmission over VLC channels [18]. Yet, the implementation of MIMO schemes in multi-user (MU) scenarios creates MU interference, which has a detrimental impact on the overall system performance. Hence, interference mitigation techniques are needed, of which transmit precoding that constitutes an effective interference cancellation method for downlink transmissions [19].

Various transmit precoding schemes have been recently proposed aiming to eliminate the incurred inter-channel interference (ICI) in indoor MU-MIMO VLC systems [20], [21]. Motivated by this, in the present contribution we propose a

H. Marshoud and B. S. Sharif are with the Department of Electrical and Computer Engineering, Khalifa University, PO Box 127788, Abu Dhabi, UAE (email: {hanaa.marshoud; bayan.sharif}@kustar.ac.ae).

P. C. Sofotasios is with the Department of Electrical and Computer Engineering, Khalifa University, PO Box 127788, Abu Dhabi, UAE, and with the Department of Electronics and Communications Engineering, Tampere University of Technology, Tampere FI-33101, Finland (e-mail: p.sofotasios@ieee.org).

S. Muhaidat is with the Department of Electrical and Computer Engineering, Khalifa University, PO Box 127788, Abu Dhabi, UAE and with the Institute for Communication Systems, University of Surrey, GU2 7XH, Guildford, UK (email: muhaidat@ieee.org).

G. K. Karagiannidis is with the Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, 54 124 Thessaloniki, Greece (email: geokarag@auth.gr).

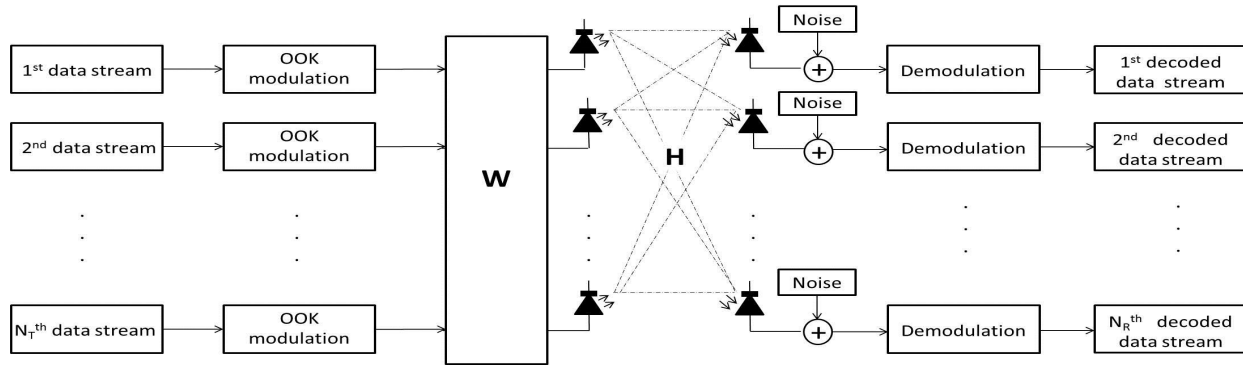


Fig. 1: MIMO-VLC system.

design framework for a novel and effective optical adaptive precoding (OAP) scheme. Specifically, unlike most existing approaches, where precoding is employed to completely eliminate interference, the proposed precoder exploits the knowledge of constructive interference between spatial streams in order to enhance the overall system performance. This scheme is based on on-off keying (OOK) modulation, which is widely considered in VLC systems [22]. Note that a similar concept was considered in the context of radio frequency (RF) MIMO networks [23], [24], where it led to performance gains compared to conventional channel inversion (CI) precoding. It is evident that OAP is particularly suitable in the context of VLC systems for the following reasons:

- The channel coefficients in indoor VLC remain constant, unless a change in the user position occurs. Thus, given that the indoor mobility velocity is relatively low, we can assume that the precoder calculation can be performed once per symbol, which leads to lower complexity overhead, compared to conventional RF systems.
- Optical channels are real and positive, which allows the estimation of the received interference, based only on the transmitted symbols. Hence, adaptive precoding in VLC becomes robust to channel state information (CSI) errors.
- Given that ICI is not completely eliminated, the high correlation between the optical subchannels is practically beneficial, when the transmitted symbols are equal.

To the best of our knowledge, this is the first work that proposes the exploitation of constructive interference to enhance the performance of VLC systems. In addition, it quantifies the impact of outdated CSI which results from the movement of indoor users in the proximity of the LEDs, leading to erroneous generation of the precoding matrix at the transmitter and, thus, to inaccurate detection at the receiver [25]. The contribution of the present paper is summarized below:

- We propose an optical adaptive precoding scheme that utilizes the knowledge of the transmitted symbols to constructively correlate the interference in an indoor MU-MIMO VLC downlink network.
- We investigate the bit-error-rate (BER) performance of the proposed scheme assuming perfect and outdated CSI,

where we derive a closed-form expression for the former and an upper bound for the latter.

- We provide extensive simulation results to verify the validity of the derived analytic expressions and extract useful insights on the performance of the proposed scheme under different realistic scenarios.
- We show that the fundamental classification of interference into constructive and destructive is independent of CSI.

The remainder of the paper is organized as follows: Section II introduces the system and channel model of MU-MIMO VLC. Section III presents the conventional channel inversion and the proposed OAP, along with the corresponding BER analysis for both schemes under perfect and outdated CSI. The respective numerical results are presented in Section IV, while closing remarks are provided in Section V.

II. SYSTEM AND CHANNEL MODEL

A. System Model

We consider a generic VLC system [26] with N_T transmitting LEDs and N_R receiving PDs, with $N_T = N_R = N$, as illustrated in Fig. 1. N_T independent data streams are simultaneously transmitted, and the N_R PDs may correspond to single or multi users with no impact on the presented analysis. Based on this, the received signal can be represented as

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{DC} + \mathbf{n} \quad (1)$$

where $\mathbf{y} \in \mathbb{R}^{N \times 1}$ and $\mathbf{x} \in \mathbb{R}^{N \times 1}$ are the received and transmitted signal vectors, respectively, \mathbf{DC} is the DC bias matrix added to ensure that the transmitted signal is positive, $\mathbf{n} \in \mathbb{R}^{N \times 1}$ is the noise vector and the square matrix $\mathbf{H} \in \mathbb{R}^{N \times N}$ represents the MIMO channel, namely

$$\mathbf{H} = \begin{bmatrix} h_{11D} & h_{12I} & \cdots & h_{1NI} \\ h_{21I} & h_{22D} & \cdots & h_{2NI} \\ \vdots & \vdots & \vdots & \vdots \\ h_{N1I} & h_{N2I} & \cdots & h_{NN D} \end{bmatrix} \quad (2)$$

where h_{ijD} and h_{ijI} indicate the desired and interference channel paths, respectively. Hence, the received signal at the i^{th} PD can be expressed as

$$y_i = \gamma P \mathbf{h}_i^T \mathbf{x} + n_i \quad (3)$$

where γ is the detector responsivity, P is the LED transmitting power, \mathbf{h}_i^T denotes the i^{th} row in \mathbf{H} and \mathbf{x} is the transmitted signal. Also, n_i represents the receiver noise with statistically independent and identically distributed entries drawn from a circularly-symmetric Gaussian distribution of zero mean and variance, namely

$$\sigma_i^2 = \sigma_{sh_i}^2 + \sigma_{th_i}^2 \quad (4)$$

with $\sigma_{sh_i}^2$ and $\sigma_{th_i}^2$ denoting the variances of the shot noise and the thermal noise, respectively. The shot noise variance at the i^{th} PD can be expressed as

$$\sigma_{sh_i}^2 = 2qB \left(\gamma P \sum_{j=1}^N h_{ij} x_j + I_{bg} I_2 \right) \quad (5)$$

where q is the electronic charge, B is the bandwidth, I_{bg} is background current, and I_2 is the noise bandwidth factor [27]. Moreover, the thermal noise is generated within the transimpedance receiver circuitry, and its variance can be determined by

$$\sigma_{th_i}^2 = \frac{8\pi k T_k}{G} \eta A_i I_2 B^2 + \frac{16\pi^2 k T_k \Gamma}{g_m} \eta^2 A_i^2 I_3 B^3. \quad (6)$$

In (6), k is Boltzmann's constant, T_k is the absolute temperature, G is the open-loop voltage gain, A_i is the PD area, η is the fixed capacitance of the PD per unit area, Γ is the field-effect transistor (FET) channel noise factor, g_m is the FET transconductance, and $I_3 = 0.0868$ is weighting function that depends on the input optical pulse shape [27].

Based on the above, the corresponding signal-to-interference-plus-noise ratio (SINR) at the i^{th} PD is expressed as

$$\text{SINR}_i = \frac{(\gamma P h_{ii})^2}{\left(\gamma^2 P^2 \sum_{j=1, j \neq i}^N h_{ij}^2 \right) + \sigma_i^2} \quad (7)$$

which constitutes a core metric in VLC systems and networks.

B. Channel Model

A line of sight (LOS) VLC channel is naturally assumed and the coefficients of the channel matrix \mathbf{H} are given by

$$h_{ij} = \begin{cases} \frac{A_i}{d_{ij}^2} R_o(\varphi_{ij}) T_s(\phi_{ij}) g(\phi_{ij}) \cos(\phi_{ij}) & 0 \leq \phi_{ij} \leq \phi_c \\ 0 & \phi_{ij} > \phi_c \end{cases} \quad (8)$$

where $i = 1, 2, 3, \dots, N$, $j = 1, 2, 3, \dots, N$, A_i denotes the receiver PD area, d_{ij} is the distance between j^{th} transmitting LED and i^{th} receiving PD, φ_{ij} is the angle of emergence with respect to the transmitter axis, ϕ_{ij} is the angle of incidence with respect to the receiver axis, ϕ_c is the field of view (FOV) of the PD, $T_s(\phi_{ij})$ is the gain of optical filter and $g(\phi_{ij})$ is the gain of the optical concentrator, which is expressed as

$$g(\phi_{ij}) = \begin{cases} \frac{n^2}{\sin^2(\phi_c)} & 0 \leq \phi_{ij} \leq \phi_c \\ 0 & \phi_{ij} > \phi_c \end{cases} \quad (9)$$

where n denotes the corresponding refractive index. Moreover,

$$R_o(\varphi_{ij}) = \frac{m+1}{2\pi} \cos^m(\varphi_{ij}) \quad (10)$$

denotes the Lambertian radiant intensity of the transmitting LEDs, where

$$m = \frac{-\ln(2)}{\ln(\cos(\varphi_{1/2}))} \quad (11)$$

with $\varphi_{1/2}$ representing the corresponding transmitter semi-angle at half power [27].

C. Outdated CSI

Although the indoor VLC channel is considered deterministic for given transmitter-receiver specifications and fixed locations, the assumption of perfect CSI at the transmitters is not in fact realistic. This is because the mobility of users in indoor places, such as museums, libraries or large offices, can change the channel coefficients of the users. Thus, it is evident that if this change occurs between CSI updates, it results to outdated CSI error. Based on this, in order to quantify and develop insights on the effect of imperfect CSI on the performance of VLC systems, we assume additive stochastic error for the CSI at the transmitter, namely

$$\hat{h}_{ij} = h_{ij} + \epsilon_o. \quad (12)$$

In the above, \hat{h}_{ij} denotes the estimate of h_{ij} available at the transmitter and $\epsilon_o \leq \mathcal{E}$, with \mathcal{E} denoting the error bound that occurs when the mobile user moves with maximum velocity between the reception of channel update and data signals [25].

In order to determine the value of \mathcal{E} , we substitute (9) and (10) into (8). Also, we substitute $\cos \varphi_i$ with z/d_{ij} , where z denotes the height between the LEDs' and the PDs' planes, which is assumed to be fixed. It follows that the corresponding channel gain h_{ij} can be expressed as

$$h_{ij} = \frac{\varpi}{d_{ij}^{m+3}} \quad (13)$$

where

$$\varpi = \frac{(m+1)A_i T_s(\phi_{ij}) g(\phi_{ij})}{2\pi}. \quad (14)$$

Assuming that a user U_i moves along the horizontal plane from (x_1, y_1) to (x_2, y_2) , with maximum velocity v_{max} as illustrated in Fig. 2, the error bound \mathcal{E} can be determined by

$$\mathcal{E} = \varpi \left| \frac{1}{d_2^{m+3}} - \frac{1}{d_1^{m+3}} \right| \quad (15)$$

where d_1 and d_2 denote d_{ij} at the locations (x_1, y_1) and (x_2, y_2) , respectively, calculated as

$$d_1^2 = x_1^2 + y_1^2 + z^2, \quad (16)$$

$$d_2^2 = x_2^2 + y_2^2 + z^2 \quad (17)$$

and

$$v_{max} = \frac{l_{max}}{t} = \frac{\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}}{t} \quad (18)$$

where l_{max} is the maximum displacement that the user can move between two channel updates, and t denotes the time elapsed since the last CSI update at the receiver.

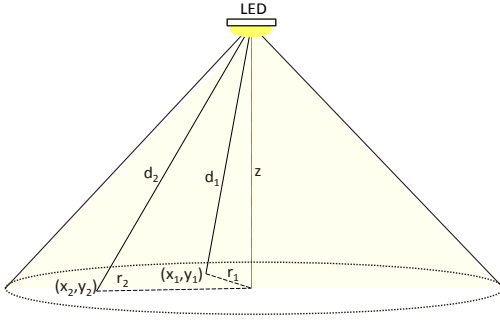


Fig. 2: Outdated CSI due to user mobility.

III. LINEAR PRECODING FOR MU-MIMO VLC

It is recalled that the main objective of transmit precoding is to mitigate the ICI between the different users, in order to establish parallel channels. In the following, we discuss the design of CI precoding in MU-MIMO VLC systems. Then, it is shown that exploiting the knowledge of the ICI results to benefits from the constructive part of this interference that ultimately lead to considerable performance enhancement.

A. Conventional Channel Inversion Precoding

CI precoding is a relatively simple approach to eliminate ICI in MIMO downlink communications and it results to independent subchannels for each receiving terminal. This can be achieved by multiplying the transmitted signal with a precoder $\mathbf{W} \in \mathbb{R}^{N \times N}$, which is obtained by means of the generalized inverse of the channel matrix, namely

$$\mathbf{W} = \beta \mathbf{H}^* (\mathbf{H} \mathbf{H}^*)^{-1} \quad (19)$$

where the $*$ symbol denotes Hermitian transpose and

$$\beta = \sqrt{\frac{1}{\mathbf{x}^* (\mathbf{H} \mathbf{H}^*)^{-1} \mathbf{x}}} \quad (20)$$

is a scaling factor that ensures instantaneous normalization of the transmit power [23]. Based on this, the inversion of the channel crosscorrelation matrix $\mathbf{R} = \mathbf{H} \mathbf{H}^*$ in (19) nulls all the off-diagonal components, which results to interference free subchannels. Based on this, the received signal at PD_i , $i = 1, 2, \dots, N$ after removing the DC bias is represented as

$$y_i = \gamma P \mathbf{h}_i^T \mathbf{w}_i x_i + z_i \quad (21)$$

and the signal-to-noise ratio (SNR) at the i^{th} PD can be represented as

$$\text{SNR}_i = \frac{(\gamma P \mathbf{h}_i^T \mathbf{w}_i)^2}{\sigma_i^2} \quad (22)$$

where \mathbf{w}_i denotes the i^{th} column vector in \mathbf{W} . Nevertheless, this leads to significant noise enhancement at the receiving

PDs, which constitutes the main limitation of CI precoding. Consequently, the normalized overall achievable throughput of the MIMO VLC system can be expressed as:

$$\text{Th}_{CI} = \sum_{i=1}^N \log_2 \left(1 + \frac{(\gamma P \mathbf{h}_i^T \mathbf{w}_i)^2}{2\sigma_i^2} \right). \quad (23)$$

1) *CI BER Performance Under Perfect CSI:* The error probability at the i^{th} PD can be expressed as

$$\begin{aligned} \text{Pr}_{e_i} &= \int_{-\infty}^{\frac{1}{2} \gamma P \mathbf{h}_i^T \mathbf{w}_i} \mathcal{N}_{y_i}(\gamma P \mathbf{h}_i^T \mathbf{w}_i, \sigma_i^2) dy_i \\ &+ \int_{\frac{1}{2} \gamma P \mathbf{h}_i^T \mathbf{w}_i}^{\infty} \mathcal{N}_{y_i}(0, \sigma_i^2) dy_i \end{aligned} \quad (24)$$

where $\mathcal{N}(\mu, \sigma^2)$ denotes the probability density function (PDF) of Gaussian distribution with mean μ and variance σ^2 . It is evident that (24) can be expressed in terms of the one dimensional Gaussian Q -function, $Q(\cdot)$, yielding

$$\text{Pr}_{e_i} = Q \left(\frac{\gamma P \mathbf{h}_i^T \mathbf{w}_i}{2\sigma_i} \right). \quad (25)$$

2) *CI BER Performance Under Outdated CSI:* Assuming outdated CSI which results from the mobility of users between consecutive CSI updates, the calculated precoding matrix does not lead to perfect cancellation of the destructive interference. As a result, the received signal at PD_i , $i = 1, 2, \dots, N$ after removing the DC bias is represented as

$$y_i = \gamma P \mathbf{h}_i^T \mathbf{w}_i x_i + \gamma P \sum_{k=1}^N \Upsilon_{ik} x_k + z_i \quad (26)$$

where $\Upsilon \in \mathbb{R}^{N \times N}$ is the residual error matrix, due to the movement of a user between two channel updates, namely

$$\Upsilon_{ik} = \mathbf{h}_i^T \times \hat{\mathbf{w}}_k. \quad (27)$$

Accordingly, the error probability at the i^{th} PD can be upper bounded by (28), at the top of the next page, where, $\hat{\mathbf{w}}_k$ is the k^{th} column vector in $\hat{\mathbf{W}}$, that is determined based on the estimate $\hat{\mathbf{H}} = \mathbf{H} + \mathcal{E}$, with \mathcal{E} denoting the error bound. Finally, δ_{sk} is in

$$\Delta = \begin{bmatrix} \delta_{11} & \dots & \delta_{1N} \\ \delta_{21} & \dots & \delta_{2N} \\ \vdots & \vdots & \vdots \\ \delta_{2N1} & \dots & \delta_{2NN} \end{bmatrix} = \begin{bmatrix} 0 & 0 & \dots & 0 & 0 \\ 0 & 0 & \dots & 0 & 1 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & 1 & \dots & 1 & 0 \\ 1 & 1 & \dots & 1 & 1 \end{bmatrix} \quad (29)$$

where the rows of $\Delta \in \mathbb{R}^{2N \times N}$ demonstrate the possible combinations of the transmitted OOK symbols from the N transmitting LEDs at any bit duration.

B. Optical Adaptive Precoding

It is evident that when the interference between the different users is constructive, not all off-diagonal components of \mathbf{H} need to be nulled. Thus, eliminating only the destructive interference can provide diversity gain for the receivers to avert

$$\Pr_{e_i} \leq \frac{1}{2^{N+1}} \sum_{s=1}^{2^N} \mathcal{Q} \left(\frac{\gamma^P \mathbf{h}_i^T \mathbf{w}_i}{2\sigma_i} - \frac{\gamma^P}{\sigma_i} \sum_{k \neq i} \Upsilon_{ik} \delta_{sk} \right) + \frac{1}{2^{N+1}} \sum_{s=1}^{2^N} \mathcal{Q} \left(\frac{\gamma^P \mathbf{h}_i^T \mathbf{w}_i}{2\sigma_i} + \frac{\gamma^P}{\sigma_i} \Upsilon_{ii} + \frac{\gamma^P}{\sigma_i} \sum_{k \neq i} \Upsilon_{ik} \delta_{sk} \right) \quad (28)$$

from the noise enhancement effect. We refer to this as optical adaptive precoding (OAP). More specifically, the constructive interference denotes the ICI that adds to the energy of the symbol of interest, yielding favorable increase in its distance from the constellation thresholds. By also considering OOK and recalling that the channel matrix \mathbf{H} in VLC is always positive, it follows that ICI is constructive when the instantaneous symbols are equal. Thus, using the knowledge of transmitted data, the interference can be evaluated symbol by symbol and a constructive adaptive matrix \mathbf{T} can be constructed as shown in Algorithm 1, where the the new adaptive precoding matrix $\mathbf{W}_d = \mathbf{W} \cdot \mathbf{T}$ consists of a fixed user-level precoding matrix \mathbf{W} , which is calculated based on the channel gains of the individual users, as well as a symbol-level adaptive precoding matrix \mathbf{T} that only depends on the symbols to be transmitted to each user. This ultimately allows the cancellation of the interference signals that carry different transmitted bits with respect to the receiving terminal, while keeping the signals that carry the same information bit. Furthermore, since the values of \mathbf{T} are either zeros or ones, we can use the same scaling factor as in (20).

```

for all symbols  $s=1:N_{symbols}$  do
  Compare the transmitted symbols of all users
  for  $k=1:N$  do
    for  $l=k+1:N$  do
      if  $x_k == x_l$  then
        Set the corresponding adaptive matrix
        element to 1,  $T_{kl}=T_{lk}=1$ 
      end
      else
        Set the corresponding adaptive matrix
        element to 0,  $T_{kl}=T_{lk}=0$ 
      end
    end
  end
  Transmit  $\beta \mathbf{W} \mathbf{T} x$ 
end

```

Algorithm 1: Design of adaptive precoding matrix

It is evident that the received signal at each PD is a summation of its desired signal and the signals of the LEDs with constructive ICI. Based on this, the received signal at PD_i , $i = 1, 2, \dots, N$ after removing the DC bias is represented as

$$y_i = \gamma^P \sum_{j \in G(i)} \mathbf{h}_i^T \mathbf{w}_{dj} x_j + z_i \quad (30)$$

where \mathbf{w}_{dj} is the j^{th} column vector in the adaptive precoding matrix \mathbf{W}_d , and $G(i)$ is the group of LEDs from which PD_i receives the desired data and the constructive ICI, which is in fact entirely wasted in conventional CI. Based on this, it

follows that the corresponding SNR can now be expressed as

$$\text{SNR}_i = \frac{\left(\gamma^P \sum_{j \in G(i)} \mathbf{h}_i^T \mathbf{w}_{dj} x_j \right)^2}{\sigma_i^2}. \quad (31)$$

Consequently, the normalized overall achievable throughput of the MIMO VLC system under OAP can be expressed as:

$$\text{Th}_{OAP} = \sum_{i=1}^N \log_2 \left(1 + \frac{\left(\gamma^P \sum_{j \in G(i)} \mathbf{h}_i^T \mathbf{w}_{dj} \right)^2}{2\sigma_i^2} \right). \quad (32)$$

1) *OAP BER Performance Under Perfect CSI:* The error probability at the i^{th} PD can be expressed by (33), at the top of the next page, which can be expressed in closed-form in terms of the one dimensional Gaussian Q -function, namely

$$\Pr_{e_i} = \frac{1}{2^{N+1}} \sum_{s=1}^{2^N} \mathcal{Q} \left(\frac{\gamma^P \mathbf{h}_i^T \mathbf{w}_{di}}{2\sigma_i} + \frac{\gamma^P}{\sigma_i} \sum_{j \in G(i), j \neq i} \mathbf{h}_i^T \mathbf{w}_{dj} \right) + \frac{1}{2^{N+1}} \sum_{s=1}^{2^N} \mathcal{Q} \left(\frac{\gamma^P \mathbf{h}_i^T \mathbf{w}_{di}}{2\sigma_i} \right). \quad (34)$$

2) *OAP BER Performance Under Outdated CSI:* By following the same methodology as in the case of CI, it follows that the BER of OAP under outdated CSI, can be upper bounded by the inequality in (35), at the top of the next page.

C. Complexity Analysis

In order to determine the complexity overhead associated with the proposed OAP scheme, we calculate the total number of operations involved in the construction of the conventional CI precoding matrix and in the proposed OAP. As shown in Table I, OAP adds relative complexity overhead of

$$\frac{O(N^3) + O(N^2)}{3 \cdot O(N^3)}. \quad (36)$$

As will be shown in the next section, the trade-off between performance and complexity is favourable for OAP.

IV. NUMERICAL AND SIMULATION RESULTS

In this section, we analyze the corresponding results for the conventional CI and the proposed adaptive precoding. This is realized by both analytic (solid lines) and respective computer simulation (markers) results. To this end, we consider a $4.0m \times 4.0m \times 3.0m$ indoor room scenario and an indicative 4×4 MIMO setup with different LEDs' spacing on the x -

$$\Pr_{e_i} = \frac{1}{2^{N+1}} \sum_{s=1}^{2^N} \left(\int_{-\infty}^{\frac{1}{2}\gamma P \mathbf{h}_i^T \mathbf{w}_{d_j}} \mathcal{N}_{y_i} \left(\gamma P \sum_{j \in G(i)} \mathbf{h}_i^T \mathbf{w}_{d_j}, \sigma_i^2 \right) dy_i + \frac{1}{2^{N+1}} \sum_{s=1}^{2^N} \int_{\frac{1}{2}\gamma P \mathbf{h}_i^T \mathbf{w}_{d_j}}^{\infty} \mathcal{N}_{y_i} (0, \sigma_i^2) dy_i \right) \quad (33)$$

$$\Pr_{e_i} \leq \frac{1}{2^{N+1}} \sum_{s=1}^{2^N} \left(\mathcal{Q} \left(\frac{\gamma P}{\sigma_i} \left(\frac{1}{2} \mathbf{h}_i^T \mathbf{w}_{d_i} - \sum_{k \neq i} \Upsilon_{ik} \delta_{sk} \right) \right) + \mathcal{Q} \left(\frac{\gamma P}{\sigma_i} \left(\frac{1}{2} \mathbf{h}_i^T \mathbf{w}_{d_i} + \sum_{j \in G(i)} \mathbf{h}_i^T \mathbf{w}_{d_j} + \Upsilon_{ii} + \sum_{k \neq i} \Upsilon_{ik} \delta_{sk} \right) \right) \right) \quad (35)$$

TABLE I: NUMBER OF OPERATIONS

Conventional Channel Inversion	
multiply $\mathbf{H}\mathbf{H}^*$	$O(N^3)$
invert $\mathbf{H}\mathbf{H}^*$	$O(N^2)$
multiply with \mathbf{H}^*	$O(N^3)$
Optical Adaptive Precoding	
multiply $\mathbf{H}\mathbf{H}^*$	$O(N^3)$
invert $\mathbf{H}\mathbf{H}^*$	$O(N^2)$
multiply with \mathbf{H}^*	$O(N^3)$
construct \mathbf{T}	$O(N^2)$
multiply \mathbf{T}	$O(N^3)$

TABLE II: SIMULATION PARAMETERS

Transmitters Parameters	
Number of LEDs per luminary	60×60
Transmitted power per LED	10 mW
Transmitter semi-angle $\varphi_{1/2}$	15°
Receivers Parameters	
Receiver FOV	15°
Physical area of PD	1.0 cm^2
PD responsivity γ	1 A/W
Refractive index of PD Lens	1.5
Gain of optical filter $T_s(\phi)$	1.0
Background current I_{bg}	$100 \mu\text{A}$
Noise bandwidth factor I_2	0.562

and y-axis of 0.25m, 0.5m and 1.0m¹. The corresponding channel gains across the room for the three different setups are shown in Fig. 3 for a receiver plane $z = 0.75$ m. Also, the locations of the users are assumed to be fixed and aligned with their respective transmitters and unless otherwise specified, the system parameters in Table II are used in the computer simulations.

Fig. 4 illustrates the BER of CI and OAP for the three considered scenarios. It is shown that the proposed OAP outperforms the conventional CI regardless of the transmitters spacing. In fact, it is noticed that CI requires an SNR increase of about 8 dB to achieve the BER of the OAP counterpart. Furthermore, the highest error rate occurs at the smallest spacing, which is due to the highly correlated links that increase the severity of the noise enhancement induced at the

¹It is noted here that the considered specifications are indicative of a practical application in realistic indoor environments, while the proposed results are generic and not subject to any physical dimensional restrictions.

receivers. It is also shown that the analytical and simulation results are in tight agreement, which verifies the validity of the derived expressions.

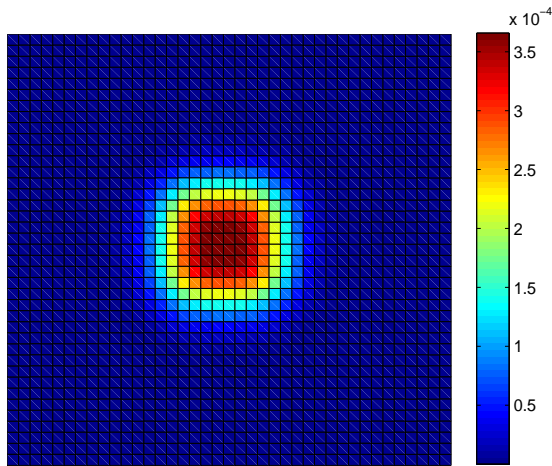
Next, we investigate the effect of changing the transmitters semi-angle at half power, $\varphi_{1/2}$, where fixed transmitters spacing of 1.0m is assumed. Larger $\varphi_{1/2}$ alleviates the transmitted beam concentration. In the case of conventional CI, this has a detrimental effect on the system performance for two reasons: i) it reduces the channel gains of the users leading to lower received power; and ii) it increases the ICI that needs to be cancelled, which practically creates more noise enhancement at the receivers. Fig. 5 demonstrates the performance degradation of CI when larger transmitting angles are used, which indicates that the effect of increasing $\varphi_{1/2}$ is less significant in the case of adaptive precoding. This is mainly because the effect of the reduction of the channel gains of the users is offset by the constructive interference that adds to the SNR at the receivers.

Next, Fig. 6 illustrates the effect of outdated CSI on the system performance, where the proposed error bound is computed assuming maximum velocity of users between two channel updates, $v = 0.2$ m/s. It is evident that adaptive precoding is more robust to CSI error, especially in the low SNR region. On the contrary, the effect of imperfect CSI becomes more significant at high SNR as the noise is no longer dominating, and thus channel uncertainty becomes a limiting factor.

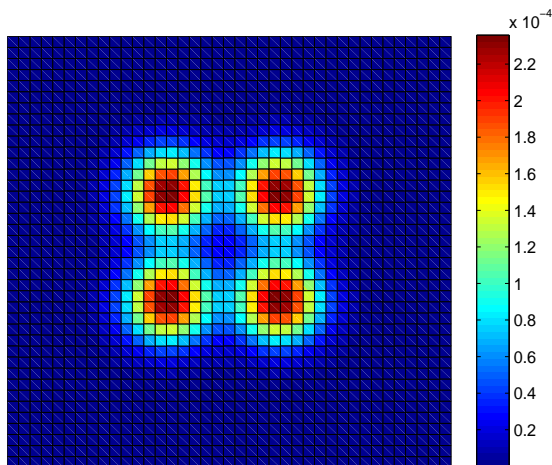
In the following, we examine the performance of the VLC MIMO system under different number of transmitting LEDs. To this end, Fig. 7 shows the BER performance for 2×2 , 4×4 and 8×8 MIMO configurations. As expected, the BER performance degrades as the number of transmitters increases, which is due to the severity of the noise enhancement caused by the high correlation between the spatial subchannels. It is evident that OAP provides noticeable performance enhancement compared to conventional CI for the different MIMO configurations.

V. CONCLUSIONS

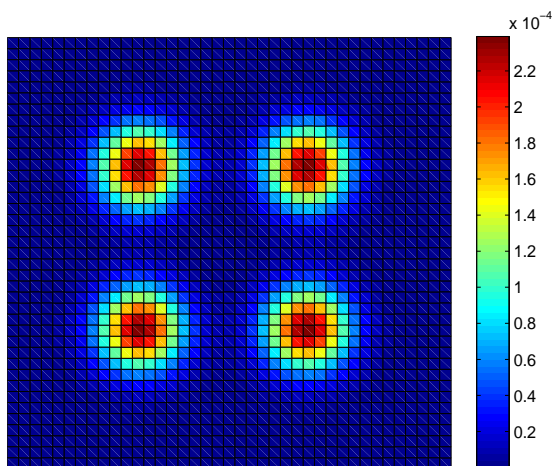
In this paper, the knowledge of transmitted data was exploited to design a low-complexity adaptive precoder based on channel inversion. The presented analysis and respective simulations showed that the proposed precoding scheme provides considerable performance enhancement compared to conventional channel inversion. In this context, it was shown that the concept of adaptive precoding creates new opportunities in VLC systems, as the classification of interference into



(a)



(b)



(c)

Fig. 3: VLC channel gains for four transmitting LEDs with $\varphi_{1/2} = 15^\circ$ and spacing of (a) 0.25 m, (b) 0.5 m and (c) 1.0 m.

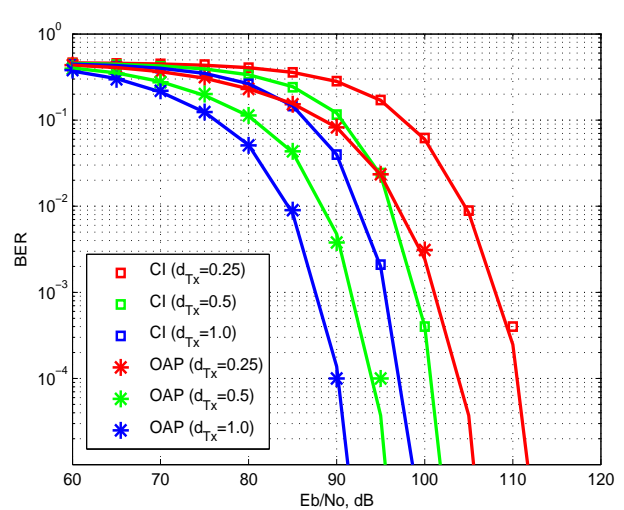


Fig. 4: Effect of channel correlation on the BER performance of CI and OAP.

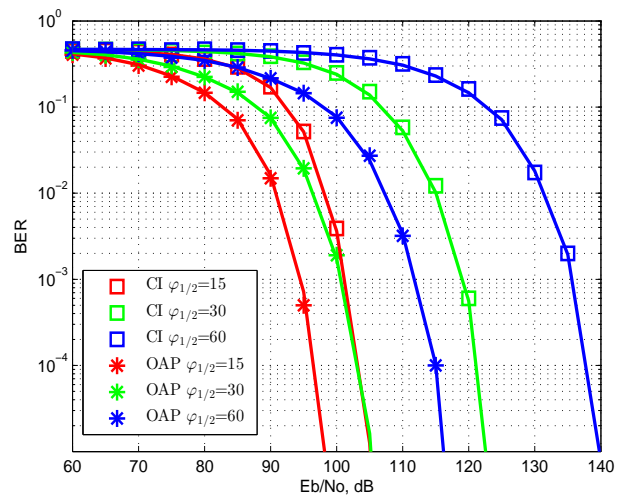


Fig. 5: Effect of varying the LED transmitting angle $\varphi_{1/2}$ on the BER performance of CI and OAP.

constructive and destructive is independent of CSI due to the nature of the optical channel. Future work will attempt extensions to higher-order modulations, which is a non-trivial task as it requires a thorough design of the precoding matrix.

REFERENCES

- [1] "Cisco service provider wi-fi: A platform for business innovation and revenue generation, Cisco, San Jose, CA, USA, 2012." <http://www.cisco.com/en/US/solutions/collateral/ns341/ns524/ns673/solution-overview-c22-642482.html/>, accessed: 2016-01-16.
- [2] M. A. Kashani, M. Safari, and M. Uysal, "Optimal relay placement and diversity analysis of relay-assisted free-space optical communication systems," *IEEE/OSA IEEE J. Opt. Commun. Netw.*, vol. 5, no. 1, pp. 37–47, Jan. 2013.
- [3] M. Karimi and M. Uysal, "Novel adaptive transmission algorithms for free-space optical links," *IEEE Trans. Commun.*, vol. 60, no. 12, pp. 3808–3815, Dec. 2012.
- [4] M. A. Kashani, M. M. Rad, M. Safari, and M. Uysal, "All-optical amplify-and-forward relaying system for atmospheric channels," *IEEE Commun. Lett.*, vol. 16, no. 10, pp. 1684–1687, Oct. 2012.

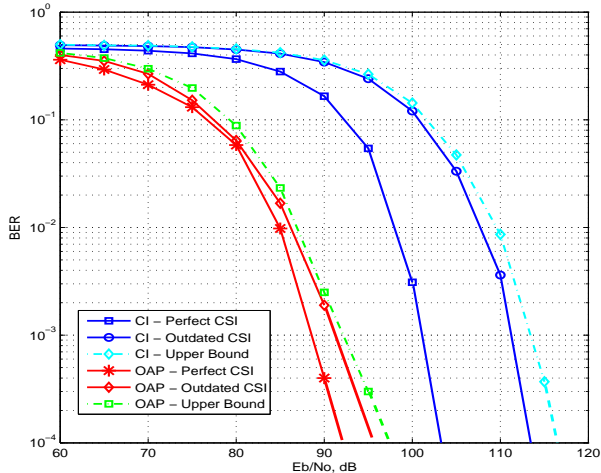


Fig. 6: BER vs transmit SNR with outdated CSI.

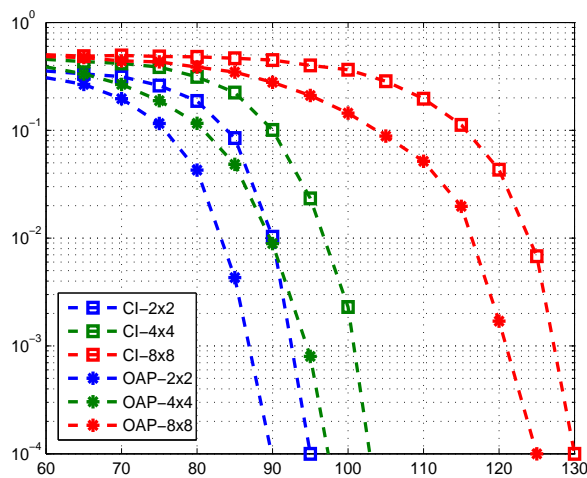


Fig. 7: BER vs transmit SNR for different MIMO configurations.

- [5] H. Burchardt, N. Serafimovski, D. Tsonev, S. Videv, and H. Haas, "VLC: Beyond point-to-point communication," *IEEE Commun. Mag.*, vol. 52, no. 7, pp. 98–105, July 2014.
- [6] S. Shao, A. Khreishah, and I. Khalil, "Joint link scheduling and brightness control for greening VLC-based indoor access networks," *IEEE J. Opt. Commun. Netw.*, vol. 8, no. 3, pp. 148–161, Mar. 2016.
- [7] J. Armstrong, "Optical domain digital-to-analog converter for visible light communications using LED arrays [invited]," *Photon. Res.*, vol. 1, no. 2, pp. 92–95, Aug. 2013. [Online]. Available: <http://www.osapublishing.org/prj/abstract.cfm?URI=prj-1-2-92>
- [8] A. Jovicic, J. Li, and T. Richardson, "Visible light communication: opportunities, challenges and the path to market," *IEEE Commun. Mag.*, vol. 51, no. 12, pp. 26–32, Dec. 2013.
- [9] P. H. Pathak, X. Feng, P. Hu, and P. Mohapatra, "Visible light communication, networking, and sensing: A survey, potential and challenges," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 4, pp. 2047–2077, Fourthquarter 2015.
- [10] S. Dimitrov and H. Haas, *Principles of LED Light Communications: Towards Networked Li-Fi*. Cambridge University Press, 2015.
- [11] F. Miramirkhani and M. Uysal, "Channel modeling and characterization for visible light communications," *IEEE Photon. J.*, vol. 7, no. 6, pp. 1–16, Dec. 2015.
- [12] D. Karunatilaka, F. Zafar, V. Kalavally, and R. Parthiban, "LED based

indoor visible light communications: State of the art," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 3, pp. 1649–1678, thirdquarter 2015.

- [13] M. Safari, *MIMO Free-Space Optical Communication*. Cham: Springer International Publishing, 2016, pp. 231–253.
- [14] S. Navidpour, M. Uysal, and M. Kavehrad, "BER performance of free-space optical transmission with spatial diversity," *IEEE Trans. Wireless Commun.*, vol. 6, no. 8, pp. 2813–2819, Aug. 2007.
- [15] W. Popoola, E. Poves, and H. Haas, "Spatial pulse position modulation for optical communications," *J. Lightw. Technol.*, vol. 30, no. 18, pp. 2948–2954, Sep. 2012.
- [16] Y.-J. Zhu, W.-F. Liang, J.-K. Zhang, and Y.-Y. Zhang, "Space-collaborative constellation designs for MIMO indoor visible light communications," *IEEE Photon. Technol. Lett.*, vol. 27, no. 15, pp. 1667–1670, Aug. 2015.
- [17] A. Nuwanpriya, S. Ho, and C. Chen, "Indoor MIMO visible light communications: Novel angle diversity receivers for mobile users," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 9, pp. 1780–1792, Sep. 2015.
- [18] T. Fath and H. Haas, "Performance comparison of MIMO techniques for optical wireless communications in indoor environments," *IEEE Trans. Commun.*, vol. 61, no. 2, pp. 733–742, Feb. 2013.
- [19] H. Marshoud, D. Dawoud, V. Kapinas, G. Karagiannidis, S. Muhaidat, and B. Sharif, "MU-MIMO precoding for VLC with imperfect CSI," in *Proc. IEEE 4th International Workshop on Optical Wireless Communications (IWOW)*, Sep. 2015, pp. 93–97.
- [20] Y. Hong, J. Chen, Z. Wang, and C. Yu, "Performance of a precoding MIMO system for decentralized multiuser indoor visible light communications," *IEEE Photon. J.*, vol. 5, no. 4, pp. 7 800 211–7 800 211, Aug. 2013.
- [21] J. Chen, N. Ma, Y. Hong, and C. Yu, "On the performance of MU-MIMO indoor visible light communication system based on THP algorithm," in *Proc. IEEE International Conference on Communications in China (ICCC)*, Oct. 2014, pp. 136–140.
- [22] "IEEE standard for local and metropolitan area networks—part 15.7: Short-range wireless optical communication using visible light," in *IEEE Std 802.15.7-2011*, pp. 1–309, Sep. 2011.
- [23] C. Masouros and E. Alsusa, "Dynamic linear precoding for the exploitation of known interference in MIMO broadcast systems," *IEEE Trans. Wireless Commun.*, vol. 8, no. 3, pp. 1396–1404, Mar. 2009.
- [24] C. Masouros, "Correlation rotation linear precoding for MIMO broadcast communications," *IEEE Trans. Signal Process.*, vol. 59, no. 1, pp. 252–262, Jan. 2011.
- [25] H. Ma, L. Lampe, and S. Hranilovic, "Coordinated broadcasting for multiuser indoor visible light communication systems," *IEEE Trans. Commun.*, vol. 63, no. 9, pp. 3313–3324, Sep. 2015.
- [26] H. Marshoud, P. C. Sofotasios, S. Muhaidat, G. K. Karagiannidis, and B. S. Sharif, "On the performance of visible light communications systems with non-orthogonal multiple access," *IEEE Trans. Wireless Commun.*, vol. PP, no. 99, pp. 1–1, 2017.
- [27] T. Komine and M. Nakagawa, "Fundamental analysis for visible-light communication system using LED lights," *IEEE Trans. Consum. Electron.*, vol. 50, no. 1, pp. 100–107, Feb. 2004.



Hanaa Marshoud received the Bachelor's degree in Electrical Engineering from Ajman University of Science and Technology, UAE, in 2011 and the M.Sc. and Ph.D. degrees in Electrical and Computer Engineering from Khalifa University, UAE, in 2013 and 2017. Her research interests include signal processing for wireless and optical wireless communications with a particular focus on visible light communication systems.



Paschalis C. Sofotasios (S'07-M'12-SM'16) was born in Volos, Greece in 1978. He received the MEng degree from Newcastle University, UK, in 2004, the MSc degree from the University of Surrey, UK, in 2006, and the PhD degree from the University of Leeds, UK, in 2011. His MSc studies were funded by a scholarship from UK-EPSC and his Doctoral studies were sponsored by UK-EPSC and Pace plc. He has held academic positions at the University of Leeds, UK, the University of California, Los Angeles, USA, Tampere University of Technology, Finland, Khalifa University, UAE and the Aristotle University of Thessaloniki, Greece. His research interests are in the broad areas of digital and optical wireless communications as well as in topics relating to special functions and statistics.

Dr. Sofotasios serves as a regular reviewer for several international journals and has been a Member of the Technical Program Committee of numerous IEEE conferences. He currently serves as an Editor of the IEEE COMMUNICATIONS LETTERS and he has received an Exemplary Reviewer award by IEEE COMMUNICATIONS LETTERS in 2012 and by IEEE TRANSACTIONS ON COMMUNICATIONS in 2015 and 2016. He is a Senior Member IEEE and a co-recipient of the best paper award at ICUFN '13.



Sami Muhaidat (S'01-M'08-SM'11) received the Ph.D. degree in electrical and computer engineering from the University of Waterloo, Waterloo, ON, Canada, in 2006. From 2007 to 2008, he was an NSERC Postdoctoral Fellow with the Department of Electrical and Computer Engineering, University of Toronto, ON, Canada. From 2008 to 2012, he was an Assistant Professor with the School of Engineering Science, Simon Fraser University, Burnaby, BC, Canada. He is currently an Associate Professor with Khalifa University, Abu Dhabi, United Arab Emirates, and a Visiting Professor at the Department of Electrical and Computer Engineering, University of Western Ontario, London, ON, Canada. He is also a Visiting Reader at the Faculty of Engineering, University of Surrey, Surrey, U.K. His research interests include advanced digital signal processing techniques for communications, cooperative communications, vehicular communications, MIMO systems and machine learning. He has authored more than 100 journal and conference papers on these topics.

Dr. Muhaidat currently serves as a Senior Editor for the IEEE COMMUNICATIONS LETTERS, an Editor for the IEEE TRANSACTIONS ON COMMUNICATIONS, and an Associate Editor for the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY. He was the recipient of several scholarships during his undergraduate and graduate studies and the winner of the 2006 NSERC postdoctoral fellowship competition.



Bayan Sharif (M'92-SM'01) received the B.Sc. degree from Queen's University of Belfast, U.K., in 1984, the Ph.D. degree from Ulster University, U.K., in 1988 and the D.Sc. degree from Newcastle University, U.K., in 2013. He is currently Dean of the College of Engineering at Khalifa University, Abu Dhabi, UAE. Prior to this appointment in 2012, and since 1990 he was on the faculty at Newcastle University, U.K., where he held a number of appointments including Professor of digital Communications, Head of Communications and Signal Processing Research and Head of the School of Electrical, Electronic and Computer Engineering. His main research interests are in digital communications with a focus on wireless receiver structures and optimization of wireless networks. Dr. Sharif is a Chartered Engineer and Fellow of the IET, U.K.



George K. Karagiannidis (M'96-SM'03-F'14) was born in Pithagorion, Samos Island, Greece. He received the University Diploma (5 years) and PhD degree, both in electrical and computer engineering from the University of Patras, in 1987 and 1999, respectively. From 2000 to 2004, he was a Senior Researcher at the Institute for Space Applications and Remote Sensing, National Observatory of Athens, Greece. In June 2004, he joined the faculty of Aristotle University of Thessaloniki, Greece where he is currently Professor in the Electrical and Computer Engineering Dept. and Director of Digital Telecommunications Systems and Networks Laboratory. He is also Honorary Professor at South West Jiaotong University, Chengdu, China. His research interests are in the broad area of Digital Communications Systems and Signal processing, with emphasis on Wireless Communications, Optical Wireless Communications, Wireless Power Transfer and Applications, Molecular Communications, Communications and Robotics and Wireless Security. He is the author or co-author of more than 400 technical papers published in scientific journals and presented at international conferences. He is also author of the Greek edition of a book on Telecommunications Systems and co-author of the book Advanced Optical Wireless Communications Systems, Cambridge Publications, 2012.

Dr. Karagiannidis has been involved as General Chair, Technical Program Chair and member of Technical Program Committees in several IEEE and non-IEEE conferences. In the past he was Editor in IEEE TRANSACTIONS ON COMMUNICATIONS, Senior Editor of IEEE COMMUNICATIONS LETTERS, Editor of the EURASIP JOURNAL OF WIRELESS COMMUNICATIONS AND NETWORKS and several times Guest Editor in IEEE SELECTED AREAS IN COMMUNICATIONS. From 2012 to 2015 he was the Editor-in Chief of IEEE COMMUNICATIONS LETTERS.

Dr. Karagiannidis is one of the highly-cited authors across all areas of Electrical Engineering, recognized as 2015 and 2016 Thomson Reuters highly-cited researcher.