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**JOINT PRECODING AND USER ASSOCIATION FOR
MULTIUSER HYBRID RF/VLC SYSTEMS UNDER
SECRECY CONSTRAINTS**

São João da Boa Vista - SP

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JOINT PRECODING AND USER ASSOCIATION FOR MULTIUSER HYBRID RF/VLC SYSTEMS UNDER SECURITY CONSTRAINTS

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Verônica Liberali Messias
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*À minha família, em especial aos meus pais Luciana e Mavíael, por todo amor, apoio,
confiança e incentivo em todos os momentos.*

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*“The future belongs to those
who believe in
the beauty of their dreams.”*

Eleanor Roosevelt

RESUMO

Neste trabalho, uma estratégia conjunta de pré-codificação e associação de usuários para o enlace direto de redes híbridas de comunicação por radiofrequência (RF) e luz visível (VLC, *visible light communications*) é investigada. Assumindo um sistema de múltiplas entradas e única saída (MISO, *multiple-input single-output*) com um ponto de acesso VLC, um ponto de acesso RF e múltiplos usuários, em que cada usuário pode se conectar apenas ao ponto de acesso de VLC ou RF, pretende-se maximizar a taxa de sigilo agregada na rede. Primeiramente, formula-se um problema de otimização com objetivo de projetar os precodificadores que maximizam a taxa de sigilo agregada para cada ponto de acesso. Este problema de otimização é não-convexo e apresenta difícil resolução. Por este motivo, o problema é reformulado utilizando o procedimento convexo-côncavo com restrições (CCCP, *constrained convex-concave procedure*). Esta reformulação apresenta baixa complexidade e é capaz de convergir à uma solução ótima de forma eficiente. Ademais, para garantir a máxima taxa agregada de sigilo para a rede, propõe-se também um algoritmo de associação de usuários baseado em teoria de jogos. Dos resultados numéricos, observa-se que a estratégia conjunta de pré-codificação e associação de usuários proposta é eficiente e permite obter ganhos de desempenho em termos da taxa agregada de sigilo comparada a outros esquemas tomados como referência. Além disso, o número de iterações necessárias para convergência do algoritmo de associação de usuários e o efeito de diferentes parâmetros do sistema, como a potência de transmissão e o número total de usuários conectados a rede, também foram avaliados, evidenciando os benefícios de combinar as tecnologias de RF e VLC.

Palavras-chave: Associação de usuários. Comunicação por luz visível. Comunicação por radiofrequência. Múltiplos usuários. Pré-codificação. Taxa de sigilo agregada.

ABSTRACT

In this work, a joint strategy of precoding and user association for the direct link of hybrid radio-frequency (RF) / visible light communication (VLC) networks is investigated. Assuming a multiple-input single-output (MISO) system with VLC and RF access points (APs), and multiple users, where each user can connect only to the VLC or RF AP, we aim to maximize the sum secrecy rate of the network. First, an optimization problem to design a precoder that maximizes the sum secrecy rate of each AP is formulated. The precoding design is a non-convex fractional programming problem, which is extremely challenging to solve. For this purpose, the original problem is reformulated using the constrained convex-concave procedure (CCCP). The reformulated problem shows to be low-complex and can efficiently converge to an optimal solution. In addition, a user association algorithm based on the coalitional game theory is also proposed, to guarantee the maximum sum secrecy rate of the network. Numerical results emphasize the efficiency of the proposed joint precoding and user association (JPUA) method and its gain in terms of the network sum secrecy rate in comparison to different baseline schemes. Moreover, the number of iterations of the user association algorithm, and the effect of various system parameters, such as the transmit power and the total number of users connected to the network are also evaluated, highlighting the advantage of combining RF and VLC technologies.

Keywords: Multiple users. Precoding design. User association. Radiofrequency communications. Sum secrecy rate. Visible light communications.

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LIST OF ACRONYMS

5G	Fifth Generation
6G	Sixth Generation
AC	Alternating Current
AP	Access Point
AWGN	Addictive White Gaussian Noise
CCCP	Constrained Convex Concave Procedure
CSI	Channel State Information
DC	Direct Current
DPC	Dirty Paper Coding
EPI	Entropy Power Inequality
FoV	Field-of-View
IM/DD	Intensity Modulation/Direct Detection
IPA	Interior Point Algorithm
IR-A	Infrared-A
JPUA	Joint Precoding and User Association
LD	Laser Diode
LED	Light Emitting Diode
LoS	Line of Sight
MIMO	Multiple-Input Multiple-Output
MISO	Multiple-Input Single-Output
ML	Maximum-Likelihood
MMSE	Minimum Mean Square Error
MUI	Multi-User Interference
NOMA	Non-Orthogonal Multiple Access
OWC	Optical Wireless Communication
PD	Photo-detector
PDF	Probability Density Function
PIN	Positive-Intrinsic-Negative
PLS	Physical Layer Security
RF	Radio Frequency
SDR	Semidefinite Relaxation

SEE	Secrecy Energy Efficiency
SIMO	Single-Input Multiple-Output
SINR	Signal-to-Interference-and-Noise ratio
SISO	Single-Input Single-Output
SOP	Secrecy Outage Probability
UV	Ultraviolet
VLC	Visible Light Communication
WIC	Wireless Infrared Communication
WUVC	Wireless Ultraviolet Communication
ZF	Zero-Forcing
ZFUA	Zero-Forcing plus User Association

LIST OF SYMBOLS

R_k	Achievable secrecy capacity for the k user
θ	Angle of irradiance with respect to the normal axis of the receiver plane
ψ	Angle of incidence with respect to the normal axis of the receiver plane
$b_k^i, i \in \{\text{RF}, \text{VLC}\}$	Binary connection variable
C_k^{RF}	Channel capacity of the k th user connected to the RF AP
C_k^{VLC}	Channel capacity of the k th user connected to the VLC AP
$\mathbf{h}_i^{\text{VLC}}$	Channel coefficient vector between the i th user and the VLC AP
$\mathbf{h}_i^{\text{RF}}$	Channel coefficient vector between the i th user and the RF AP
$S^i, i \in \{\text{RF}, \text{VLC}\}$	Coalition
$\Theta^i \in \{\text{RF}, \text{VLC}\}$	Complexity of Algorithm 1
ψ_{FOV}	Concentrator FOV
S_c	Current partition of the user association
$d_{n,i}$	Distance between the n th LED and i th user
E	Eavesdropper
ε	Error tolerance of Algorithm 1
A_{eff}	Effective area of the PD
$\mathbb{E}[\cdot]$	Expectation operator
S_f	Final user association partition
$\mathbf{I}_K$	Identity matrix with size K
S_{init}	Initial partition of the user association
s_n	Input electrical signal of the n th LED
$E_e(d)$	Irradiance
$\succsim_k$	k user coalition preference
η	LED conversion factor
$(\cdot)^H$	Matrix conjugate operation
$(\cdot)^T$	Matrix transpose operation
i_{max}	Maximum number of iterations of Algorithm 1
p_n^{VLC}	Nominal optical intensity of the n th LED
$\chi^i, i \in (\text{VLC}, \text{RF})$	Normalizing constant
M	Number of antennas of the RF AP
N	Number of LEDs of the VLC AP
$D(\psi)$	Optical filter gain
m	Order of Lambertian emission
φ	Path-loss exponent

A	PD physical area
$R(\theta)$	Radiant intensity
p^{VLC}	Received optical power of the VLC AP
y_i^{RF}	Received signal at the i th user by the RF AP
y_i^{VLC}	Received signal at the i th user by the VLC AP
r	Refractive index
$v^i, i \in (\text{VLC}, \text{RF})$	Regularization parameter
R	Responsitivity of the PD
$\mathbf{x}^{\text{RF}}$	RF data symbol vector
n_k^{RF}	RF AWGN component
$\mathbf{V}$	RF precoding matrix
Cs_k^{RF}	Secrecy capacity of the k th user connected to the RF AP
Cs_k^{VLC}	Secrecy capacity of the k th user connected to the VLC AP
$\phi_{1/2}$	Semi-angle at half illuminance of the LED
$\mathcal{T}^{\text{RF}}$	Set of transmit antennas at the RF AP
$\mathcal{T}^{\text{VLC}}$	Set of VLC transmitters
$\mathcal{K}_i, i \in \{k, E\}$	Shape factor of the Rice distribution
$P(\lambda)$	Spectral power distribution
$\mathcal{R}_k$	Target rate
P_{LED}	Total radiated power
K	Total number of users
K^{RF}	Total number of users connected to the RF AP
K^{VLC}	Total number of users connected to the VLC AP
$\text{Tr}(\cdot)$	Trace operator
p_s^{RF}	Transmit power limitation for the RF AP
$\bar{s}_n$	Transmitted signal by the n th LED unit
$\mathbf{s}^{\text{RF}}$	Transmitted signal vector by the RF AP
$U(S^i)$	Utility function of coalition S^i
u_k	Utility function of k th player
$\sigma_n^{\text{RF}^2}$	Variance of the RF AWGN component
$\sigma_x^{\text{RF}^2}$	Variance of the RF data symbol
$\sigma_n^{\text{VLC}^2}$	Variance of the VLC AWGN component
$\sigma_x^{\text{VLC}^2}$	Variance of the VLC data symbol
n_k^{VLC}	VLC AWGN component
$\mathbf{H}^{\text{VLC}}$	VLC channel gain matrix of the legitimate users
$\mathbf{h}_E^{\text{VLC}}$	VLC channel gain vector of the eavesdropper
$\mathbf{x}^{\text{VLC}}$	VLC data symbol vector
$\mathbf{W}$	VLC precoding matrix

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1 INTRODUCTION

In this chapter, hybrid radiofrequency (RF) and visible light communications (VLC) networks with multiple users are briefly conceptualized. Moreover, security constraints and possible approaches for future hybrid RF/VLC systems are presented. Specifically, in Section 1.1 the motivation of this work is introduced, followed by related works in Section 1.2, Section 1.3 lists the main contributions of this work, and finally, in Section 1.4, the outline is presented.

1.1 MOTIVATION

With the deployment of the fifth-generation (5G) of wireless communications starting in 2019, researchers are envisioning the requirements and applications of the sixth-generation (6G). As already predicted for 5G networks, the explosive growth of devices and increased data traffic remain an important issue that should be handled in future mobile networks. Since the RF spectrum is already congested, the increase in data traffic urges the use of new frequencies of the electromagnetic spectrum (ALWIS et al., 2021). On this matter, researchers are considering to explore part of the license-free optical spectrum (214 THz to 1500 THz, or equivalently, 1400 nm to 200 nm) as a complementary frequency range for wireless communications. Specifically, the use of visible light wavelengths (380 nm to 780 nm) for wireless communication has attracted special attention given the possibility of simultaneous illumination and data transmission via a single device (AL-KINANI et al., 2018).

The idea of transmitting information using a visible light source is not recent, with the first study on the topic dating from 1880 (HUTT; SNELL; BÉLANGER, 1993). Later, in 2000, researchers of Keio University employed white light-emitting diodes (LEDs) to transmit light and data simultaneously (TANAKA; HARUYAMA; NAKAGAWA, 2000). After that, academia focused on how to improve white LEDs' performance for communication purposes. Nowadays, given the advancement of white LEDs, VLC has attracted substantial attention, with promising advantages such as immunity to RF waves, a large unlicensed spectrum, longer lifespan, and high energy efficiency (CHI et al., 2020).

Despite the advantages of VLC, it still presents serious limitations that must be considered for practical scenarios, such as a strong dependence on line-of-sight (LoS), small coverage area, instability of the link quality, and interference of other sources of light (CHOWDHURY et al., 2020). Accordingly, even though RF-based communications suffer from interference and have a strictly regulated and narrower spectrum bandwidth, it is capable to support high mobility and

performs well in environments with non-LoS, which makes RF systems a good candidate to overcome those limitations of VLC. As shown in (ABUELLA et al., 2021), given that RF and VLC do not interfere with each other, combining both techniques is possible and can result in a remarkable gain in terms of system connectivity and throughput.

Furthermore, another important consideration is the extension of the study of hybrid RF/VLC networks for the multiuser case. Scenarios with multiple users suffer from multiuser interference (MUI). On this matter, stand-alone RF multiuser scenarios have been widely studied, and several techniques have been developed to reduce MUI and increase the system performance, such as beamforming and multiple access techniques (VU; PAULRAJ, 2007). Meanwhile, for VLC networks with multiple users, MUI can still severely affect the system performance. Methods such as angle-oriented receiver (AOR) (YAPICI; GUVENC, 2019) and precoding (PHAM; LE-MINH; PHAM, 2017) have been explored as a way to combat MUI. For hybrid RF/VLC networks, most works focus on single-input single-output (SISO) networks with only one user (PAN et al., 2020; NAMDAR et al., 2018). However, by extending hybrid RF/VLC scenarios to the multiuser case, if the correct techniques to reduce MUI are employed, it is possible to increase the system performance and guarantee the connectivity to a higher number of users with a fair resource allocation through user association (WANG; WU; HAAS, 2017; ABDALLA; RAHAIM; LITTLE, 2020).

On the other hand, with the increasing number of devices and novel technologies arising with 6G, security continues to be a paramount feature that should be considered to guarantee resilience and private communications. In this sense, as indicated in (PORAMBAGE et al., 2021), physical layer security (PLS), which takes advantage of the wireless medium to enhance the secrecy of wireless communications, may be one of the enablers of confidentiality in 6G. Pioneering works such as (WYNER, 1975) and (LEUNG-YAN-CHEONG; HELLMAN, 1978) proved that secure communications are possible without secret keys if the eavesdropping channel is degraded with respect to the legitimate channel. Particularly in (WYNER, 1975), the concepts of wiretap channel and secrecy capacity as a performance metric were first introduced. Hence, aligned with classic cryptography techniques, PLS can be used to enhance security or to meet quality-of-service (QoS) requirements for sensitive applications (YLIANTTILA et al., 2020). In this regard, PLS techniques have been extensively studied for RF broadcast channels, proving to be a promising resource to enhance the secrecy performance in the most diverse kind of scenarios (OSORIO et al., 2020; SILVA et al., 2022; CABEZAS; OSORIO; LATVA-AHO, 2021).. On the other hand, for VLC networks, a few adaptations should be considered before employing PLS due to illumination requirements and operational constraints of the LEDs, such as dimming control and peak-power constraint (ARFAOUI et al., 2020).

1.2 RELATED WORKS

In terms of hybrid RF/VLC networks with multiple users, (OBEED et al., 2018) investigates the system capacity and the fairness of a hybrid RF/VLC network. For this scenario, a joint power allocation and user association algorithm is proposed. Specifically, the users are first associated with the closest access point (AP), and the power allocation problem is solved, aiming to maximize the system's achievable rate. Then, users with lower data rates are reallocated from one AP to another to enhance the system's fairness and balance the load.

Moreover, (ABOAGYE et al., 2021) studies the downlink of a multiuser heterogeneous network formed by a macro base station, several pico base stations, and many office buildings equipped with VLC-enabled lamps, where the indoor users have the option to connect to any of the three sources for data transmission. Accordingly, a joint user association and power allocation optimization problem is formulated based on the College Admission model (GALE; SHAPLEY, 1962). The authors of that work demonstrated that the considered hybrid heterogeneous network significantly outperforms traditional heterogeneous networks and that the proposed optimization problem is effective even with such a complex network configuration.

In (PAPANIKOLAOU; DIAMANTOULAKIS; KARAGIANNIDIS, 2019), the user association problem of an indoor hybrid RF/VLC network performing non-orthogonal multiple access (NOMA) is studied. Specifically, to maximize the system achievable rate, the user association is approached as a coalitional game. First, all users are allocated to the RF AP and swapped between VLC and RF until the maximum capacity for both APs is achieved. After evaluating the proposed algorithm, it is possible to conclude that for hybrid RF/VLC networks, the user association problem presents better results if it is handled with a cooperative game over standard opportunistic schemes.

Note that the previous works do not address the secrecy performance in communications. In this respect, (DUONG et al., 2021) investigates the secrecy energy efficiency (SEE) of a multiuser multiple-input single-output (MISO) VLC network in which the message information intended for each user must be kept confidential. To maximize the SEE, authors propose a precoding scheme, assuming that the users' secrecy rate must be above a certain threshold. Beyond the originally proposed precoding algorithm, two suboptimal designs based on the semidefinite relaxation (SDR) technique and zero-forcing (ZF) are also evaluated. The algorithms showed to be of low complexity and effective to enhance the SEE. Besides, from the numerical results, it can be seen that system's parameters, such as the VLC transmit power, secrecy rate threshold, and number of users can impact the feasibility and convergence of the algorithm.

(SILVA et al., 2021a) assesses the secrecy outage probability (SOP) of an indoor SISO hybrid RF/VLC network in the presence of an eavesdropper. Both users are assumed to have multihoming capabilities, and the data is transmitted over the RF and VLC links following a

proposed multiplexing scheme. The authors of that work provided an integral-form and an asymptotic form expression for the SOP and were able to conclude that even though the VLC AP is capable to provide a higher secrecy rate to the legitimate user, the variation of the RF link's parameters can highly increase the secrecy performance of the network. Moreover, in (SILVA et al., 2021b), the effective capacity and the maximum average arrival rate of a hybrid RF/VLC network with secrecy constraints are evaluated. The transmission also follows a multiplexing scheme. However, in contrast to (SILVA et al., 2021a), the data is first stored in a buffer, and the splitting ratio between the VLC and RF links is based on the buffer service rate. Besides, it is also assumed that the buffer overflow probability acts as a QoS constraint. From the results, it can be seen that even under QoS constraints, the combination of RF and VLC is still beneficial.

Finally, in (QIAO; ZHAO; SUN, 2021) an indoor multiuser MISO hybrid RF/VLC network in the presence of an eavesdropper is evaluated in terms of the sum secrecy rate. The authors of that work assume that the users are able to aggregate information from the VLC and RF links and also that the channel state information (CSI) of all nodes is known. To maximize the secrecy performance, a precoding scheme based on ZF is proposed. Accordingly, an optimization problem aiming to maximize the secrecy capacity of the system constrained by the ZF restrictions is formulated and solved using classic optimization methods. By analyzing the optimization problem in terms of the sum secrecy rate, it is possible to conclude that the considered hybrid model is superior to a stand-alone VLC or RF network and also capable to accommodate a higher number of users.

1.3 CONTRIBUTIONS

Notwithstanding the research efforts carried out so far, several issues remain open to study on the topic of hybrid RF/VLC systems, and to the best of the authors' knowledge, aside from (QIAO; ZHAO; SUN, 2021), there is no previous study on the secrecy performance of hybrid RF/VLC networks with multiple users. Hence, we aim to contribute in this respect by evaluating an indoor multiuser MISO RF/VLC network in the presence of an eavesdropper in terms of the average sum secrecy rate, which is assumed as the summation of the attained secrecy capacity by each user connected to either VLC or RF. The transmission is made via a VLC or a RF AP, and all users are equipped with a photodetector (PD) and an RF antenna. Moreover, it is assumed that the legitimate users can only be associated with one of the APs. Next, the main contributions of this work are listed:

- A precoding design problem is formulated to maximize the sum secrecy rate, which is set in terms of the secrecy capacity achieved by the users, assuming that a minimum rate threshold must be satisfied by each user. The problem is shown to be non-convex and to tackle it, the original problem is transformed using the constrained convex-concave

procedure (CCCP), which converges to a local solution after a number of iterations.

- To associate the users to the VLC or RF AP, an algorithm based on coalitional game theory is proposed. Specifically, the users are randomly allocated to the APs and must be swapped between them until the maximum sum secrecy rate is achieved. The algorithm is proven to have low complexity and capable to enhance the sum secrecy rate of the system.
- The impact of important parameters of the system, e.g., number of users and total transmit power of the VLC and RF APs are evaluated, as well as the number of iterations for the considered precoding and user association strategy. Furthermore, a comparison between the proposed joint precoding and user association (JPUA) strategy with reference schemes is also provided.

1.4 OUTLINE

The remainder of this work is organized as follows:

- Chapter 2 presents an overview of some key concepts for the understanding of this work.
- Chapter 3 describes the system model and the channel model for the RF/VLC network.
- Chapter 4 provides a description of the strategy considered to maximize the sum secrecy rate.
- Chapter 5 illustrates the numerical results and discussions for the considered scenario and algorithms.
- Finally, chapter 6 concludes this work.

Notation. Throughout this work, $\mathbb{R}$ and $\mathbb{C}$ are the set of real-valued and complex-valued numbers, respectively; Bold upper-case letters denotes matrices whereas bold lower-case letter denotes vectors; $(\cdot)^T$ and $(\cdot)^H$ stands for the matrix transpose and conjugate operation, respectively; $\mathbf{I}_K$ is the identity matrix with size K ; $\|\cdot\|_\infty$, $\|\cdot\|$ and $|\cdot|$ are the infinity-norm, the Euclidian-norm and the absolute value operator; $\text{Tr}(\cdot)$ is the trace of a square matrix; $\mathbb{E}[\cdot]$ is the expectation operator; and $[x]^+ \triangleq \max(x, 0)$.

2 BASIC CONCEPTS

In this chapter, basic concepts related to the problem studied in this work will be presented. Specifically, Sections 2.1, 2.2, and 2.3 provide a brief description of visible light communications, multiple-input multiple-output systems, and game theory, respectively.

2.1 VISIBLE LIGHT COMMUNICATIONS

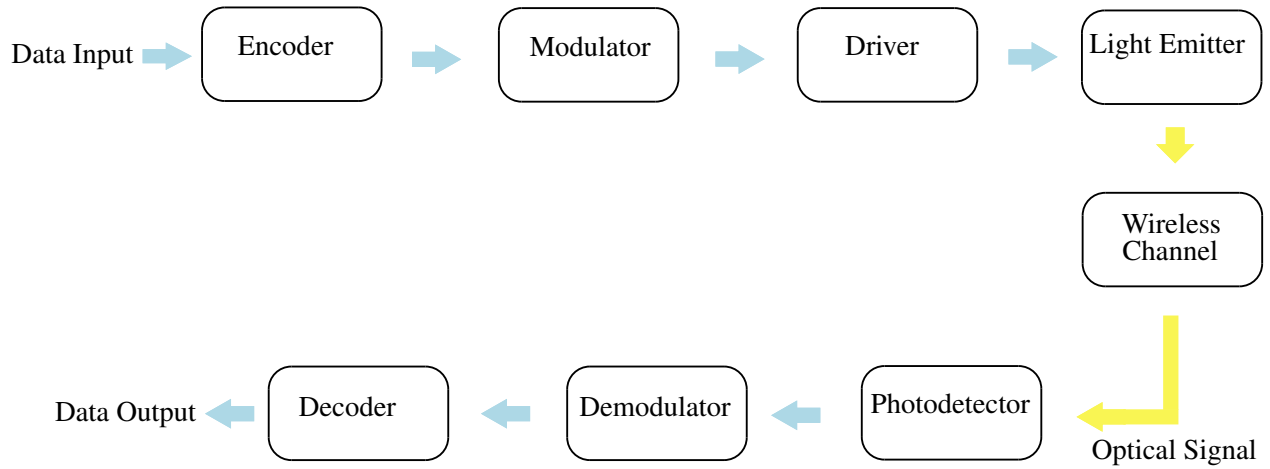
2.1.1 *Optical Wireless Communications*

Optical wireless communications (OWCs) comprehend all wireless communications through the optical wavelengths of the electromagnetic spectrum. Specifically, according to the region of the optical spectrum used for communication, OWC can be further classified as wireless ultraviolet communication (WUVC), VLC, and wireless infrared communication (WIC) (ALKINANI et al., 2018). Accordingly, WUVC occurs on a segment of the ultraviolet wavelength range called ultraviolet-C (UV-C), which varies from 200 nm to 280 nm. Next, for VLC, the entire range of visible light wavelengths, 380 nm to 780 nm, can be employed. Finally, WIC takes place in the infrared-A (IR-A) segment of the IR portion of the electromagnetic spectrum, which contains wavelengths going from 780 nm to 1400 nm. Under these considerations, for this work, we focus on the study of VLCs. Hence, next, an overview of the VLC system architecture is presented.

2.1.2 *VLC System Architecture*

VLC systems aim to provide simultaneous illumination and communication by taking advantage of part of the implemented lighting infrastructure. Even though the implementation of typical VLC systems employs intensity modulation and direct detection (IM/DD) schemes, they still follow the same principles as other communication setups, as can be seen in Fig. 1 (MEDINA; NEZ; NAVARRO, 2015). First, the data is encoded, and to achieve higher throughput in the given bandwidth, the data is modulated and sent to the driver, which is responsible to control the data output of the light emitter. On the other hand, on the receiver side, the transmitted signal is recovered using DD. In this process, the PD converts the received optical signal into an electrical signal. Finally, to retrieve the data, the signal is demodulated and decoded (CHI, 2018).

Figure 1 - System architecture of a VLC system.



Source: Author, adapted from (MEDINA; NEZ; NAVARRO, 2015)

2.1.2.1 Front-Ends

- **Transmission:** LEDs are the most common devices used as light emitters in VLC systems. Primarily, phosphor-converted LEDs and multi-chip LEDs are the two types of LEDs considered for VLC systems, especially for the low cost. The first type consists of a blue-colored LED with a phosphor layer coated on top of it, whereas the multi-chip type, is formed of three primary colored chips (RGB) that emit each color simultaneously, and at the output, the required colored/white light is produced. The phosphor white LED has the lowest cost compared with the multi-chip LED. However, the nature of phosphor light conversion makes it unsuitable for high-speed data communication due to phosphorous response time (ABUELLA et al., 2021). The selection of the appropriate type of LED largely depends on the specific applications of VLC systems.

Moreover, laser diodes (LDs) can also be used for VLC and present a very similar method to white light generation with LEDs. LDs can reach even higher data rates than LEDs. However, the major issue that might hamper LD-VLC technology is safety concerns involving the use of these devices. Since LEDs have a larger area in comparison to LDs, the IEC 60825, an international standard for laser devices in terms of eye and skin safety, indicates that depending on the wavelength of the source, the LED launch power can be in the range of 250 to 750 mW (IEC, 2014). However, for smaller area devices, such as LDs, it classifies the transmission power into three classes: Class 1 (up to 0.2 mW), Class 2 (0.2 to 1 mW), Class 3A (1 to 5 mW), and Class 3B (5 to 500 mW). To guarantee human safety when operating in indoor environments, LDs must be Class 1. Although it is possible to assure the eye safety requirement and reach a higher launch power by passing the beams of a Class 3B LD through diffusers, LDs still are less likely to be employed for VLC systems, especially due to the higher cost in comparison to LEDs-based

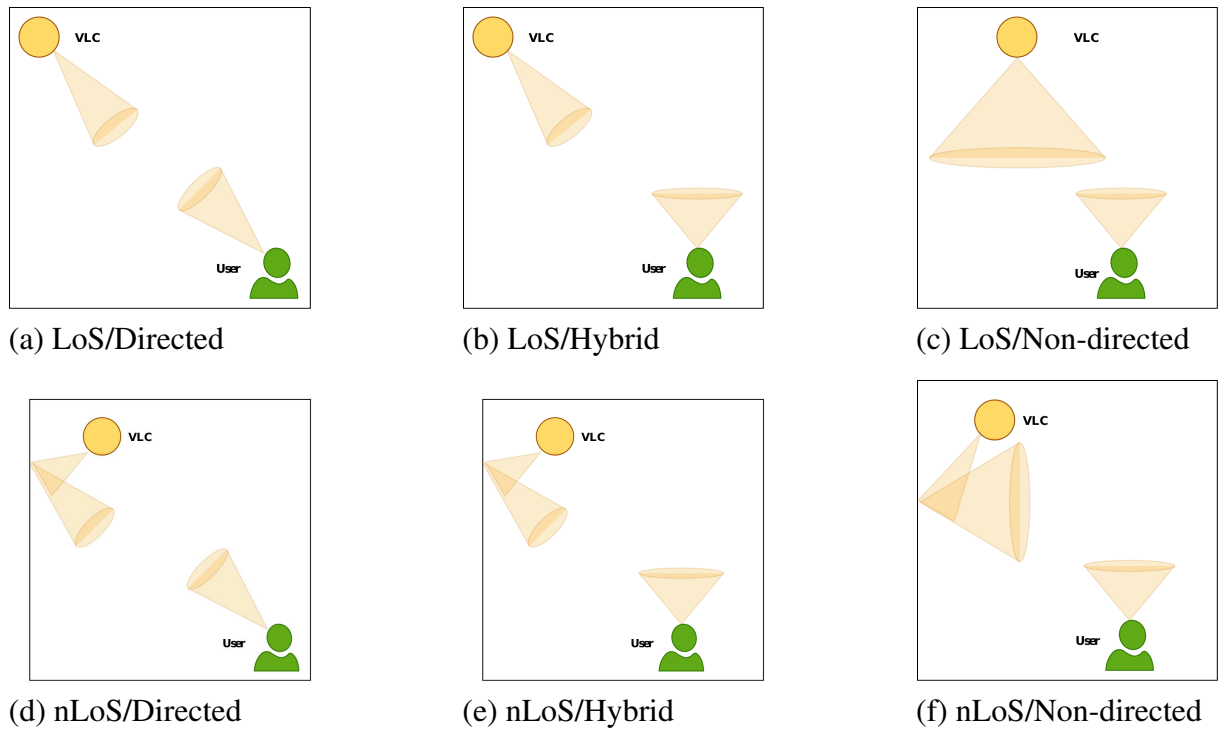
VLC (ZAFAR; BAKAUL; PARTHIBAN, 2017).

- **Reception:** PDs are employed to receive the transmitted data by the source. The main types of PDs are positive-intrinsic-negative (PIN), avalanche, and positive-negative (P-N) PDs. When the PD is exposed to the optical signal, the P-N junction produces the electrical current, which is linearly proportional to the optical signal. Along with the PD, the receiver unit often comprises an optical filter, an optical concentrator, an optical lens, and an amplifier connected to its rear end (ABUELLA et al., 2021).

2.1.3 Channel Model

The VLC propagation link is classified according to the presence of a direct path between the transmitter and receiver. It distinguishes the links between LoS and non-LoS links. Moreover, another parameter to consider for a VLC propagation link is the directionality of the nodes. Thus, the propagation link is further classified as direct, non-direct, and hybrid. As illustrated in Fig. 2, the combination of both classifications results in six possible scenarios for transmission.

Figure 2 - Geometries used in channel gain calculations.



Source: Author, adapted from (KAHN; BARRY, 1997).

2.1.3.1 LoS Links Description

Assuming the devices used for transmission are LEDs, the link model considers the generalized Lambertian cosine law, which states that the radiant intensity and the cosine of the angle θ between the direction of incident light and the normal of an ideal diffusely reflecting surface are directly proportional (PEDROTTI; PEDROTTI; PEDROTTI, 2017). Accordingly, the basic geometry of a VLC system is depicted in Figure 3. Under these circumstances, the radiant intensity, which measures the intensity of the light coming from the LED, is given, in Watts per steradian (W/sr) by (ZENG et al., 2009)

$$R(\theta) = \frac{m+1}{2\pi} \cos(\theta)^m P_{\text{LED}}, \quad (1)$$

where $m = -1 / \log_2(\cos(\phi_{1/2}))$ is the order of Lambertian emission, which depends on the semi-angle at half illuminance of the LED, $\phi_{1/2}$, and P_{LED} is the total radiated power, given by

$$P_{\text{LED}} = \int_{\lambda} P(\lambda) d\lambda, \quad (2)$$

with $P(\lambda)$ being the spectral density in the wavelength domain. Next, to obtain the received power, the irradiance and the photodetector effective area must be defined. Accordingly, for a given distance d , the irradiance is written as $E_e(d) = R(\theta)/d^2$, and the effective area is given by (KAHN; BARRY, 1997)

$$A_{\text{eff}} = \begin{cases} \frac{r^2}{\sin^2(\psi_{\text{FOV}})} AD(\psi), & |\psi| \leq \psi_{\text{FOV}}, \\ 0, & |\psi| > \psi_{\text{FOV}}, \end{cases} \quad (3)$$

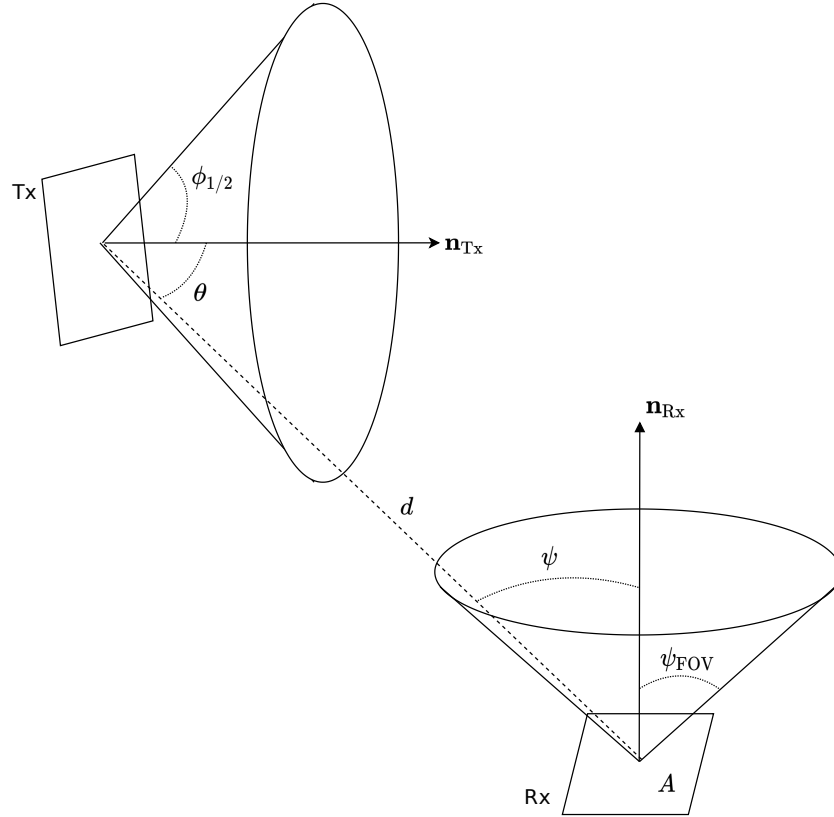
where r is the refractive index, ψ_{FOV} is the concentrator field-of-view (FOV), A is the photodetector physical area, ψ is the incident angle, and $D(\psi)$ is the optical filter gain in the direction of ψ . Thus, the received optical power and channel coefficient are written, respectively, as (KAHN; BARRY, 1997)

$$P^{\text{VLC}} = E_e(d) A_{\text{eff}}, \quad (4)$$

$$h_{\text{LoS}}^{\text{VLC}}(t) = \begin{cases} \frac{(m+1) \cos^m(\theta) r^2 AD(\psi) \cos(\psi)}{2\pi d^2 \sin^2(\psi_{\text{FOV}})} \delta(t - \frac{d}{c}), & |\psi| \geq \psi_{\text{FOV}}, \\ 0, & |\psi| < \psi_{\text{FOV}}, \end{cases} \quad (5)$$

where $\delta(\cdot)$ is the delta function, and c is the speed of light.

Figure 3 - Basic geometry for a VLC transmitter Tx, and receiver Rx.



Source: Author, adapted from (QIU; CHEN; MENG, 2016).

2.1.3.2 Non-LoS Links Description

For Non-LoS links, the gain is obtained through the multiple reflections from the surfaces of the environment. Accordingly, the impulse response of multiple bounces is given by

$$h(t) = \sum_{k=0}^{\infty} h^{(k)}(t, P(\lambda)), \quad (6)$$

with k being the number of bounces. Considering that the reflecting paths still obey the Lambertian Law, the channel coefficient at the k th bounce can be recursively calculated as (QIU; CHEN; MENG, 2016)

$$h_k^{\text{VLC}} = \frac{1}{P_{\text{LED}}} \int_S \left[L_1 L_2 \cdots L_{k+1} P_k^{\text{VLC}} \text{rect} \left(\frac{\psi_{k+1}}{\psi_{\text{FOV}}} \right) \delta \left(t - \frac{d_1 + d_2 + \cdots + d_{k+1}}{c} \right) \right] dA_S, \quad (7)$$

where S is the area of all reflection surfaces, dA_S is a small reflection area, $\text{rect}(\cdot)$ is the rectangular function, $d_i, \forall i = 1, 2, \dots, k+1$ is the distance of each path during the bounce, P_k^{VLC} is the optical power of the reflected light after k bounces, and $L_i, i \in [1, 2, \dots, k+1]$ is the path loss

gain of each path during k bounces¹, given by (WANG et al., 2018)

$$L_1 = \frac{(m+1)A_{\text{eff}}}{2\pi d_1^2} \cos^m(\theta_1) \cos(\psi_1), \quad (8)$$

$$L_2 = \frac{(m+1)A_{\text{eff}}}{2\pi d_2^2} \cos(\theta_2) \cos(\psi_2), \quad (9)$$

$\vdots$

$$L_{k+1} = \frac{A \cos(\theta_{k+1}) \cos(\psi_{k+1})}{\pi d_{k+1}^2}. \quad (10)$$

2.1.4 Channel Capacity

For a typical VLC system, the received signal at a instant t is written as (QIU; CHEN; MENG, 2016)

$$y(t) = x(t) * h(t) + n(t), \quad (11)$$

where $x(t)$ is the signal input, $h(t)$ is the channel coefficient, described in the previous subsection, and $n(t)$ is the noise component, modeled as additive white Gaussian noise (AWGN), with variance σ_n^2 , which includes the variance of the shot noise and the thermal noise. As previously presented in the architecture of VLC systems, most of VLC systems employ IM/DD, and as a consequence of IM, the input signal must be non-negative. Moreover, due to practical illumination requirements and eye safety standards, the average power, p^{VLC} , and peak amplitude, Amp , also must be constrained. Hence, it follows that (FARID; HRANILOVIC, 2009)

$$0 < x(t) < Amp, \quad (12)$$

$$\mathbb{E}(x(t)) \leq p^{\text{VLC}}. \quad (13)$$

Thus, the channel capacity of a VLC channel, C^{VLC} , is defined as the maximum mutual information between x and y over all possible input distributions, that is (MA et al., 2021),

$$C^{\text{VLC}} = \max_{P(x)} \{\mathbb{I}(x, y)\}, \quad (14)$$

$$= \max_{P(x)} \{z(y) - z(y|x)\}, \quad (15)$$

$$= \max_{P(x)} \left\{ - \int_{-\infty}^{\infty} f_y(y) \log_2 f_y(y) dy - \frac{1}{2} \log_2 2\pi e \sigma_n^2 \right\}, \quad (16)$$

where $z(y) \triangleq \int f(y) \log_2 f(y) dy$ is the the entropy function of y , and $P(x)$ and $f_y(y)$ are the distribution of x , and the probability density function (PDF) of y , respectively. As pointed out

¹Note that for $k=1$, the channel coefficient is described by L_1 and L_2 , that is, h_1^{VLC} is given in terms of the path loss gain between the light emitter and a reflective surface, and between the reflective surface and the receiver PD.

in (MA et al., 2021), the optimal input distribution $P(x)$ that solves (16) is a unique discrete distribution over a finite number of mass points. However, there is no efficient method to reach the optimal $P(x)$ except for exhaustive search. Therefore, most works on the literature approximates the VLC channel capacity by its lower bound, which can be reached via the entropy power inequality (EPI) as (CHAABAN; REZKI; ALOUINI, 2017)

$$\begin{aligned} z(y) + z(y|x) &\geq \frac{1}{2} \log_2 \left(2^{2z(hx)} + 2^{2z(n)} \right), \\ &= \frac{1}{2} \log_2 \left(2^{2z(x)} h^2 + 2\pi e \sigma_n^2 \right), \\ &= \frac{1}{2} \log_2 \left(1 + h^2 \frac{2^{2z(x)}}{2\pi e \sigma_n^2} \right), \end{aligned} \quad (17)$$

where $z(x)$ is the differential entropy of x .

2.2 MULTIPLE-INPUT MULTIPLE-OUTPUT (MIMO) WIRELESS SYSTEMS

As defined in (HAMPTON, 2013), MIMO communications refers to a collection of signal processing techniques developed to enhance the performance of wireless communications systems by employing multiple antennas at the transmitter, receiver, or both. Accordingly, as illustrated in Fig. 4, two particular cases of MIMO systems are MISO, in which the transmitter has multiple antennas, and the receiver employs only one antenna; and single-output multiple-output (SIMO), in this case, the transmitter is a single-antenna node, and the receiver has multiple antennas.

MIMO techniques aim to improve the performance of wireless communication systems by taking advantage of the multipath scattering in the communication channel. Accordingly, the main benefits of MIMO techniques in point-to-point and multiuser networks is described next.

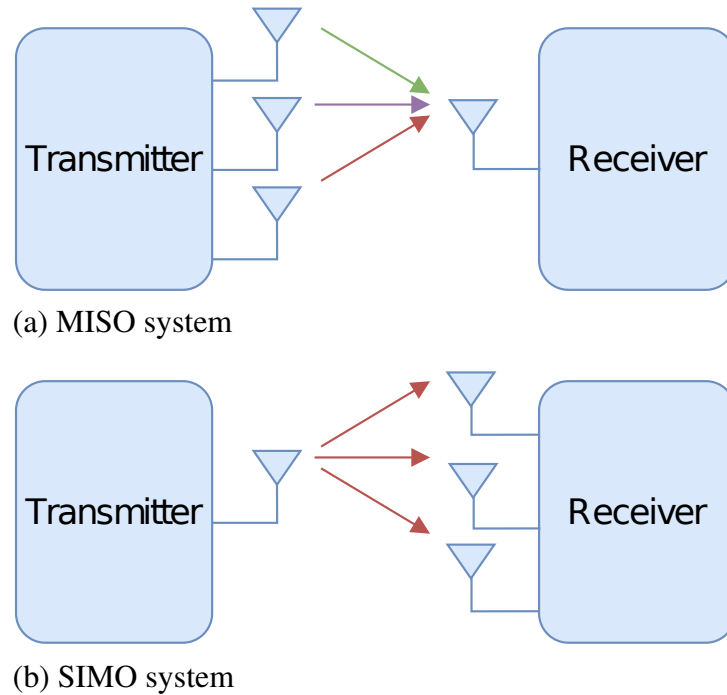
2.2.1 Point-to-point Communications

In point-to-point communications, under suitable fading channel conditions, MIMO is capable to provide spatial diversity and spatial multiplexing.

2.2.1.1 Spatial Diversity

For wireless communications, diversity implies that multiple replicas of the same signal are transmitted via the fading channel aiming that every replica fades independently and differently from one another. Several diversity techniques have been developed to combat the effect of fading on communication systems. For instance, in RF systems, it is possible to obtain diversity in terms of frequency, time, polarization, and spatially. Particularly, spatial diversity stands for

Figure 4 - MIMO system special cases



Source: Author

the transmission of the same signal using different physical paths between transmitter and receiver and can be achieved by employing multiple antennas at the receiver (TSE; VISWANATH, 2005).

2.2.1.2 Spatial Multiplexing

For spatial multiplexing, the transmitter must employ multiple antennas. In this technique, the signal is divided into several streams, and each stream is transmitted through a different antenna simultaneously. Those slightly different propagation paths cause the spatial streams to separate into almost parallel channels. Therefore, the received signal consists of a sum of the transmitted data. Then, to reconstruct the original message, the receiver must estimate the CSI of the transmitter. Moreover, in general, the number of spatial streams is less than or equal to the number of transmitting antennas (SUN et al., 2014).

2.2.2 Multiuser Communication

Multiuser networks can also benefit from spatial diversity and multiplexing. However, although multiuser MIMO networks inherently increase the diversity gain, these networks suffer from a significant amount of interference (TSE; VISWANATH, 2005). To handle the interference, the main method considered is denominated precoding, which is described next.

2.2.2.1 Precoding

Precoding is a preprocessing technique where the transmitter is capable to achieve diversity by weighting the information streams. To accomplish it, the transmitter must first send a coded message to the user, for example, a pilot signal, and retrieve the CSI of each user in the network to design the precoder matrix. This technique can result in notable gains in terms of capacity and throughput and is especially efficient in multiuser scenarios, where users can benefit from the interference mitigation that precoding designs can achieve (GESBERT et al., 2007). Accordingly, precoders can be classified mainly into two categories: non-linear precoding and linear-precoding.

The best known non-linear precoding methods are the maximum-likelihood (ML) and the dirty-paper coding (DPC) (GESBERT et al., 2003). Although these methods present better precoder accuracy than the linear-precoding design, they are almost impracticable due to the high complexity and sophisticated signal processing (ALBREEM et al., 2021). Therefore, most works in the literature employ linear-precoding schemes, which are described next.

2.2.2.2 Linear Precoding

Given a MIMO multiuser scenario, where a source with M transmit antennas serves K -single antenna receiving terminals, the received signal vector can be written as (TSE; VISWANATH, 2005)

$$\mathbf{y} = \mathbf{H}^T \mathbf{x} + \mathbf{n}, \quad (18)$$

where $\mathbf{H} \in \mathbb{C}^{M \times K}$ is the channel coefficient matrix, $\mathbf{x} \in \mathbb{C}^{M \times 1}$ is the transmitted signal, and $\mathbf{n} \in \mathbb{C}^{1 \times K}$ is the noise vector. When employing linear precoding, $\mathbf{x}$ is derived from the vector containing the message intended to each user, $\mathbf{u} \in \mathbb{C}^{K \times 1}$, via a deterministic linear transformation, that is, $\mathbf{x} = \mathbf{W}\mathbf{u}$, with $\mathbf{W} \in \mathbb{C}^{M \times K}$ being the precoding matrix.

Accordingly, two of the most widely adopted linear precoding techniques are based on ZF and Minimum Mean Square Error (MMSE). Specifically, with ZF, the design of the precoder intends to mitigate the interference caused by other users by pointing the signal beam in the direction of the intended user, which in counterpart nulls the direction of other users. For this, the precoding matrix is set as the pseudo-inverse of the coefficient channel matrix, that is (WIESEL; ELDAR; SHAMAI, 2008)

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

This method has easy implementation and is effective for scenarios where the number of users is smaller than the number of transmit antennas. However, when the number of users is

equal to the number of transmit antennas, (19) may not describe the channel inversion correctly. It occurs because, in this case, the eigenvalues of the inverse matrix do not follow the same distribution. Therefore, the precoding matrix must be regularized as (PEEL; HOCHWALD; SWINDLEHURST, 2005)

$$\mathbf{W} = \mathbf{H}^H (\mathbf{H}\mathbf{H}^H + \nu \mathbf{I}_K)^{-1}, \quad (20)$$

where ν is the regularization parameter and K is the number of users in the network.

On the other hand, in the MMSE method, the idea is to minimize the reception error by comparing between the transmitted symbols and the received message. It exploits the benefits of ZF and maximal-ratio transmission by balancing the multiuser interference mitigation with noise enhancement and minimizing the total error. In this case, the precoding matrix is set as (ALBREEM et al., 2021)

$$\mathbf{W} = (\mathbf{H}\mathbf{H}^H + \chi \mathbf{I}_K)^{-1} \mathbf{H}^H, \quad (21)$$

where $\chi = \sigma_n^2 K / P_T$, with σ_n^2 being the variance of the noise component and P_T being the total transmit power.

2.3 GAME THEORY

Game theory is defined according to (DICTIONARY, 2022) as “the analysis of a situation involving conflicting interests (as in business or military strategy) in terms of gains and losses among opposing players”, which implies that the game is used to evaluate iteration and rational decision-making situations. Game theory can be seen as a branch of applied sciences, which has been greatly used to understand economic behaviors, but due to its abstract mathematics, can be applied to various scenarios, ranging from political sciences (GATES; HUMES, 1997) or philosophy to computer science (SHOHAM, 2008).

In wireless communications, the rapid advance in technology has led to a need of modern analytical frameworks, which should incorporate decision-making rules and techniques to meet the users' requirements for communication. On this matter, game theory appears as an important tool to design such frameworks for wireless communications. For instance, known examples of game theory in wireless communications include the problem of power control in cellular networks, and admission control (HAN et al., 2011). Under these circumstances, the fundamentals of game theory are explained next, followed by the description of different categories of games.

2.3.1 Game Fundamentals

As described in (RAPOPORT, 2012), game theory models comprehend a set of decision-makers, also called players, which must select a strategy to use during the game to obtain the best outcome possible. The outcome of each player's decision during the game can be numerically quantified by a mathematical function, which is named *payoff* or *utility function*.

The fundamentals of game theory are based on the assumption that the players are rational, that is, they are capable to assign some kind of numerical value to different outcomes of the games and act rationally to maximize it. Most games can be classified according to the following criteria:

- **Number of players:** The games are played by at least two players and must have a finite number of players. Thus, this classification distinguishes the game as a 2-person game or an N-person game ($N > 2$).
- **Zero-sum or non-zero-sum games:** Zero-sum games, also called constant-sum games, are games where the sum of all players' payoff equals zero, whereas non-zero-sum games indicate that players share some interests. For instance, if a 2-person game has zero-sum, it denominates problems where the interest of players are necessarily opposite since one player will have a higher payoff than the other one. However, for N-person games, it is possible that, even in zero-sum games, the interest of some of the players coincide.
- **Cooperation:** The main classification of games is if the game is cooperative or non-cooperative. Specifically, in cooperative games, agreements are enforceable to maximize the payoff of all players, that is, the players' decisions are made in group, and all players within the group must follow the same decision, which can be defined collectively or directly to the users. Four main points must be followed by all users within a cooperative game: i) common interest, ii) mandatory information exchange, iii) mutual benefit, and iv) compulsory agreement. Moreover, cooperative games are mainly divided in two categories: bargaining theory and coalitional games (HAN et al., 2011).

1. *Bargaining theory* was first studied by John Nash in 1950 and evaluates situations where players can mutually benefit from reaching a certain agreement but have conflicting interests on the terms of the agreement. Hence, no agreement can be imposed on the players, without their approvals (NASH, 1950).

A vast number of wireless network applications employs the bargaining theory. Particularly, scenarios with the problem of resource and/or rate allocation can highly benefit from Nash's bargaining solution (LARSSON; JORSWIECK, 2008).

2. *Coalitional Game* is defined by the pair $(\mathcal{N}, v)$, where $\mathcal{N}$ is the set of the players, and v is a mapping that determines the payoffs that these players receive in the game.

Specifically, the set of players aim to form cooperative groups, that is, coalitions, to strengthen their positions in a given situation (HAN et al., 2011).

Examples of coalition games in wireless networks include mainly heterogeneous networks with multiple users where to optimize the network resources, users must be associated to only one of the available sources (CHEN et al., 2021; XU et al., 2021).

In non-cooperative games, on the other hand, agreements cannot be forced, and each player needs to take its decision independently of the other players, given the possible choices of the other players and their effect on the player's objectives or utilities. Cooperation might still occur in non-cooperative games, however it must happen without communication or coordination among players (HAN et al., 2011). The most known example of a non-cooperative game is called Prisoner's dilemma (POUNDSTONE, 1992). This example considers that two criminals committed a crime and have been detained by the police. The police can convict them for a smaller or bigger crime conditioned on a possible confession of one or both of them. The police offer them the following option: the person who confesses is not convicted while the other receives a longer sentence. However, this offer entails the scenario where both of them confess and receive a longer sentence or neither of them confess and receive a smaller sentence. Accordingly, the game is designed as

- *players*: two criminals;
- *Strategies*: Confess/ not confess;
- *Outcomes*: not convicted; convicted with smaller sentence; convicted with longer sentence.

Different from the cooperative game, there is no information exchange between the two players, and each player chooses the strategy based only on their interest, which for this scenario results in both criminals confessing and receiving the longer sentence. Thus, rarely the non-cooperative game results in a beneficial outcome for all players involved.

2.4 SUMMARY OF THE CHAPTER

In this chapter, we presented an overview of the main concepts to be applied in this work, including visible light communications, MIMO systems and game theory. This overview is important for the understanding of the system model described in Chapter 3 and also for the optimization problems proposed to maximize the sum secrecy rate in Chapter 4.

3 SYSTEM AND CHANNEL MODEL

In this chapter, we describe the considered system model, followed by the description of the VLC and RF channel models, which are used to obtain the signal-to-interference-and-noise ratio (SINR) and secrecy capacity of each AP.

3.1 SYSTEM MODEL

Fig. 5 illustrates an indoor multiuser hybrid RF/VLC broadcast network in the presence of an eavesdropper (E). The eavesdropper is considered to be a passive attacker, overhearing the legitimate transmissions, while performing sporadic transmissions, so that the source have completely knowledge of the eavesdropper's CSI. This network consists of one VLC AP equipped with N LEDs and one RF AP equipped with M antennas, which transmit information to K users ($K \leq M + N$). Each user, as well as the eavesdropper, is equipped with a single PD and a single RF antenna.

3.2 CHANNELS AND SIGNAL MODELS

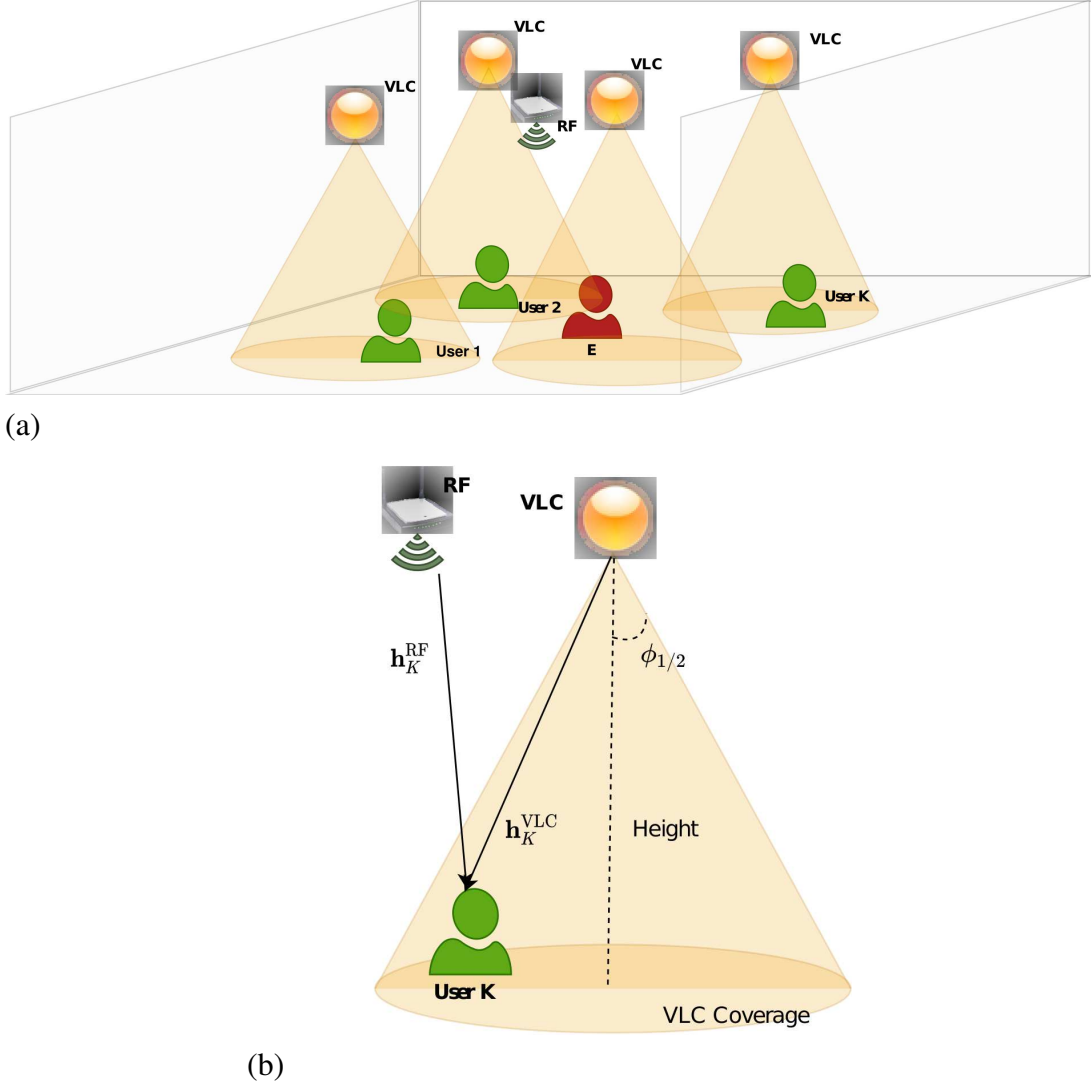
3.2.1 VLC Channel Model

VLC links are described in terms of LoS and non-LoS components. However, in typical indoor scenarios, the majority of the collected energy at the receivers' PD comes from the LoS component (Komine; Nakagawa, 2004). Therefore, therein we assume that the VLC channel is flat with a dominant LoS component, and the channel gain does not vary during data transmission as long as the receivers remain stationary. As previously presented in (5), considering a Lambertian emission pattern for the LEDs, the channel gain between the n th LED and the k th user, as well as between the n th LED and E is given by (Wang; Haas, 2015)

$$h_{n,i}^{\text{VLC}} = \begin{cases} \frac{(m+1) \cos^m(\theta) r^2 A D(\psi_{n,i}) \cos(\psi_{n,i}) R}{2\pi d_{n,i}^2 \sin^2(\psi_{FOV_i})}, & |\psi_{n,i}| \geq \psi_{FOV_i} \\ 0, & |\psi_{n,i}| < \psi_{FOV_i}, \end{cases}$$

where $i \in \{k, E\}$, as shown in Figure 6, $d_{n,i}$ represents the distance between the n th transmitting unit and the i th user, θ and $\psi_{n,i}$ are the angle of irradiance and angle of incidence with respect to the normal axis of the receiver plane, respectively, ψ_{FOV_i} is the FOV angle of the PD, A denotes the PD area, R is the responsivity of the PD, $D(\psi_{n,i})$ is the gain of the optical filter, r is

Figure 5 - System Model and Channel Configuration

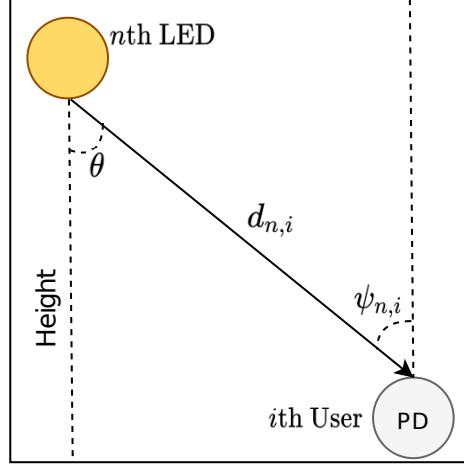


Source: Author

the refractive index, and $m = -1 / \log_2(\cos(\phi_{1/2}))$ represents the order of Lambertian emission, with $\phi_{1/2}$ being the LED half intensity view angle. Moreover, the noise component in VLC, $n_i^{\text{VLC}}, i \in \{k, E\}$, is modelled as signal-independent, zero-mean, AWGN with variance $\sigma_n^{\text{VLC}^2}$.

In addition, we consider that at the VLC link is employed an IM/DD scheme. Thus, the transmitting LEDs produce light intensity proportional to the input electric signal, and the received signal is then converted back to an electric signal by the receivers. Given the required level of illumination and the intensity modulation assumption, the input electric signal of the n th transmitter, s_n , must be non-negative and real-valued, and it must also have expectation equal to the nominal optical intensity of the n th LED, i.e., $\mathbb{E}[s_n] = p_n^{\text{VLC}}, \forall n$ (WANG et al., 2013). Furthermore, to guarantee a minimum dimming level and to ensure that the LED works in its linear dynamic range, s_n must be restricted within a certain range, i.e., $p_{\min} \leq s_n \leq p_{\max}$ (PHAM; LE-MINH; PHAM, 2017).

Figure 6 - Angles involved in VLC.



Source: Author, adapted from (ARFAOUI; GHRAYEB; ASSI, 2018)

Setting the total number of users connected to VLC AP as K^{VLC} , $\mathbf{x}^{\text{VLC}} = [x_1^{\text{VLC}}, \dots, x_k^{\text{VLC}}]^T \in \mathbb{R}^{K^{\text{VLC}} \times 1}$ is defined as the data symbol vector intended to the users, and $\mathbf{W} = [\mathbf{w}_1, \mathbf{w}_2, \dots, \mathbf{w}_k] \in \mathbb{R}^{N \times K^{\text{VLC}}}$ as the corresponding precoding matrix, with $\mathbf{w}_k \in \mathbb{R}^{N \times 1}$ being the VLC precoding vector of the k th user. Hence, the transmitted signal from the n th LED unit can be expressed as (ARFAOUI; GHRAYEB; ASSI, 2018)

$$\bar{s}_n = \sum_{k=1}^{K^{\text{VLC}}} w_{n,k} x_k^{\text{VLC}}. \quad (22)$$

Given the expectation constraint imposed on s_n , p_n^{VLC} is set as a DC-offset and added to the transmitted signal as

$$s_n = \bar{s}_n + p_n^{\text{VLC}}. \quad (23)$$

For simplicity, we assume that each symbol is independent and uniformly distributed over $[-1, 1]$ (DUONG et al., 2021; PHAM; PHAM, 2021), thus

$$-\sum_{k=1}^{K^{\text{VLC}}} |w_{n,k}| + p_n^{\text{VLC}} \leq s_n \leq \sum_{k=1}^{K^{\text{VLC}}} |w_{n,k}| + p_n^{\text{VLC}}. \quad (24)$$

Besides, by considering $p_{\min} \leq s_n \leq p_{\max}$, we have that

$$-\sum_{k=1}^{K^{\text{VLC}}} |w_{n,k}| + p_n^{\text{VLC}} \geq p_{\min}, \quad (25)$$

$$\sum_{k=1}^{K^{\text{VLC}}} |w_{n,k}| + p_n^{\text{VLC}} \leq p_{\max}, \quad (26)$$

which can be rewritten as

$$\sum_{k=1}^{K^{\text{VLC}}} |w_{n,k}| \leq \Delta_n, \forall n, \quad (27)$$

with $\Delta_n = \min(p_n^{\text{VLC}} - p_{\min}, p_{\max} - p_n^{\text{VLC}})$. Let $\mathbf{H}^{\text{VLC}} = [\mathbf{h}_1^{\text{VLC}}, \mathbf{h}_2^{\text{VLC}}, \dots, \mathbf{h}_K^{\text{VLC}}] \in \mathbb{R}^{N \times K^{\text{VLC}}}$ and $\mathbf{h}_E^{\text{VLC}} \in \mathbb{R}^{N \times 1}$ be the channel matrix for the legitimate VLC links and the eavesdropping link, respectively. Therefore, the received signal at the k th user and at E after the optical to electrical conversion can be respectively expressed as (PHAM; HAYASHI; PHAM, 2019)

$$y_k^{\text{VLC}} = \mathbf{h}_k^{\text{VLC}T} \bar{\mathbf{s}} + n_k = \mathbf{h}_k^{\text{VLC}T} \left(\mathbf{w}_k x_k^{\text{VLC}} + \sum_{\substack{l=1 \\ l \neq k}}^{K^{\text{VLC}}} \mathbf{w}_l x_l^{\text{VLC}} + \mathbf{p} \right) + n_k^{\text{VLC}}, \quad (28)$$

$$y_E^{\text{VLC}} = \mathbf{h}_E^{\text{VLC}T} \left(\sum_{l=1}^{K^{\text{VLC}}} \mathbf{w}_l x_l^{\text{VLC}} + \mathbf{p} \right) + n_E^{\text{VLC}}, \quad (29)$$

where $\mathbf{p} = [p_1^{\text{VLC}}, p_2^{\text{VLC}}, \dots, p_N^{\text{VLC}}]$. Also, in (28) the term $\mathbf{h}_k^{\text{VLC}T} \mathbf{w}_k x_k^{\text{VLC}}$ is the desired signal, $\mathbf{h}_k^{\text{VLC}T} \sum_{\substack{i=1 \\ i \neq k}}^{K^{\text{VLC}}} \mathbf{w}_i x_i^{\text{VLC}}$ is the MUI, and $\mathbf{h}_k^{\text{VLC}T} \mathbf{p}$ is the offset, which carries no data and can be removed by the receiver with alternating current (AC) coupling. Therefore, the instantaneous received SINR from the VLC link at the k th user and at E for the wiretapped data symbol targeted to the k th user are given, respectively, by

$$\text{SINR}_k^{\text{VLC}} = \frac{|\mathbf{h}_k^{\text{VLC}T} \mathbf{w}_k|^2 \sigma_x^{\text{VLC}^2}}{\sum_{\substack{i=1 \\ i \neq k}}^{K^{\text{VLC}}} |\mathbf{h}_k^{\text{VLC}T} \mathbf{w}_i|^2 \sigma_x^{\text{VLC}^2} + \sigma_n^{\text{VLC}^2}}, \quad (30)$$

$$\text{SINR}_E^{\text{VLC}} = \frac{|\mathbf{h}_E^{\text{VLC}T} \mathbf{w}_k|^2 \sigma_x^{\text{VLC}^2}}{\sum_{\substack{i=1 \\ i \neq k}}^{K^{\text{VLC}}} |\mathbf{h}_E^{\text{VLC}T} \mathbf{w}_i|^2 \sigma_x^{\text{VLC}^2} + \sigma_n^{\text{VLC}^2}}, \quad (31)$$

where $\sigma_x^{\text{VLC}^2}$ is the variance of the data symbol.

3.2.2 RF Channel Model

The RF AP is assumed to cover the entire room area, and due to the likely strong LoS component of the indoor scenario, we assume that RF links undergo independent Rician block fading. Thus, $\mathbf{H}^{\text{RF}} = [\mathbf{h}_1^{\text{RF}}, \mathbf{h}_2^{\text{RF}}, \dots, \mathbf{h}_K^{\text{RF}}] \in \mathbb{C}^{M \times K^{\text{RF}}}$ and $\mathbf{h}_E^{\text{RF}} \in \mathbb{C}^{M \times 1}$ denotes the channel matrix between the RF AP and the legitimate users, and the channel vector between the RF AP and E, respectively. For the Rician distribution, we consider the K-factor $\mathcal{K}_k$ and $\mathcal{K}_E$ and a scale parameter equal to the average channel gain of the corresponding link, $\Omega_i = \mathbb{E}\{|h_i^{\text{RF}}|^2\}$, with $i \in \{k, E\}$. Furthermore, we assume that the RF AP employs a conventional secure-block level precoding

technique, thus $\mathbf{x}^{\text{RF}} = [x_1^{\text{RF}}, \dots, x_k^{\text{RF}}]^T \in \mathbb{C}^{K^{\text{RF}} \times 1}$ is precoded by $\mathbf{V} = [\mathbf{v}_1, \mathbf{v}_2, \dots, \mathbf{v}_k] \in \mathbb{C}^{M \times K^{\text{RF}}}$, with $\mathbf{v}_k \in \mathbb{C}^{N \times 1}$ being the RF precoding vector of the k th user.. Accordingly, the transmitted signal is written as

$$\mathbf{s}^{\text{RF}} = \mathbf{V}\mathbf{x}^{\text{RF}} = \sum_{k=1}^{K^{\text{RF}}} \mathbf{v}_k x_k^{\text{RF}}. \quad (32)$$

So, the received signals from the RF AP at the k th user and at E are given, respectively, by

$$y_k^{\text{RF}} = \mathbf{h}_k^{\text{RFH}} \mathbf{s}^{\text{RF}} + n_k^{\text{RF}} = \mathbf{h}_k^{\text{RFH}} \mathbf{v}_k x_k^{\text{RF}} + \mathbf{h}_k^{\text{RFH}} \sum_{\substack{i=1 \\ i \neq k}}^{K^{\text{RF}}} \mathbf{v}_i x_i^{\text{RF}} + n_k^{\text{RF}}, \quad (33)$$

$$y_E^{\text{RF}} = \mathbf{h}_E^{\text{RFH}} \sum_{i=1}^{K^{\text{RF}}} \mathbf{v}_i x_i^{\text{RF}} + n_E^{\text{RF}}, \quad (34)$$

where $n_i^{\text{RF}}, i \in \{k, E\} \sim \mathcal{CN}(0, \sigma_n^{\text{RF}^2})$ is the AWGN noise component of the RF AP. Accordingly, the instantaneous received SINR at the k th user and at E, when it eavesdrops the signal to the k th user, are expressed respectively as

$$\text{SINR}_k^{\text{RF}} = \frac{|\mathbf{h}_k^{\text{RFH}} \mathbf{v}_k|^2 \sigma_x^{\text{RF}^2}}{\sum_{\substack{i=1 \\ i \neq k}}^{K^{\text{RF}}} |\mathbf{h}_k^{\text{RFH}} \mathbf{v}_i|^2 \sigma_x^{\text{RF}^2} + \sigma_n^{\text{RF}^2}}, \quad (35)$$

$$\text{SINR}_E^{\text{RF}} = \frac{|\mathbf{h}_E^{\text{RFH}} \mathbf{v}_k|^2 \sigma_x^{\text{RF}^2}}{\sum_{\substack{i=1 \\ i \neq k}}^{K^{\text{RF}}} |\mathbf{h}_E^{\text{RFH}} \mathbf{v}_i|^2 \sigma_x^{\text{RF}^2} + \sigma_n^{\text{RF}^2}}. \quad (36)$$

where $\sigma_x^{\text{RF}^2}$ is the variance of the RF data symbol, which is assumed to be unitary.

3.3 SECRECY CAPACITY

3.3.1 RF Channel

Definition 1. The secrecy capacity is defined as the difference between the channel capacities of the legitimate and wiretap channels. Therefore, given (35) and (36), the secrecy capacity for the k th user when connected to the RF link is expressed as (Leung-Yan-Cheong; Hellman, 1978)

$$\begin{aligned} C_s^{\text{RF}} &= \max\{C_k^{\text{RF}} - C_E^{\text{RF}}, 0\} \\ &= \left[\log_2 \left(1 + \frac{|\mathbf{h}_k^{\text{RFH}} \mathbf{v}_k|^2 \sigma_x^{\text{RF}^2}}{\sum_{\substack{l=1 \\ l \neq k}}^{K^{\text{RF}}} |\mathbf{h}_k^{\text{RFH}} \mathbf{v}_l|^2 \sigma_x^{\text{RF}^2} + \sigma_n^{\text{RF}^2}} \right) - \log_2 \left(1 + \frac{|\mathbf{h}_E^{\text{RFH}} \mathbf{v}_k|^2 \sigma_x^{\text{RF}^2}}{\sum_{\substack{i=1 \\ i \neq k}}^{K^{\text{RF}}} |\mathbf{h}_E^{\text{RFH}} \mathbf{v}_i|^2 \sigma_x^{\text{RF}^2} + \sigma_n^{\text{RF}^2}} \right) \right]^+, \end{aligned}$$

$$= \left[\log_2 \left(\frac{1 + (1/\sigma_n^{\text{RF}^2}) \sum_{l=1}^{K^{\text{RF}}} |\mathbf{h}_k^{\text{RF}^H} \mathbf{v}_l|^2}{1 + (1/\sigma_n^{\text{RF}^2}) \sum_{l=1, l \neq k}^{K^{\text{RF}}} |\mathbf{h}_k^{\text{RF}^H} \mathbf{v}_l|^2} \right) - \log_2 \left(\frac{1 + (1/\sigma_n^{\text{RF}^2}) \sum_{l=1}^{K^{\text{RF}}} |\mathbf{h}_E^{\text{RF}^H} \mathbf{v}_l|^2}{1 + (1/\sigma_n^{\text{RF}^2}) \sum_{l=1, l \neq k}^{K^{\text{RF}}} |\mathbf{h}_E^{\text{RF}^H} \mathbf{v}_l|^2} \right) \right]^+ . \quad (37)$$

3.3.2 VLC Channel

Since the VLC channel is amplitude-constrained, the exact channel capacity can be achieved only numerically (SMITH, 1971). Thus, based on (ARFAOUI; GHAYEB; ASSI, 2018) and (DUONG et al., 2021), we consider a closed-form lower-bound for the secrecy capacity of the VLC link, given in the following theorem.

Theorem 1. *A lower-bound on the secrecy capacity of the k th user connected to the VLC AP is given by*

$$C_{S_k}^{\text{VLC}} \approx \left[\frac{1}{2} \log_2 \left(\frac{1 + \alpha \sum_{l=1}^{K^{\text{VLC}}} (\mathbf{h}_k^{\text{VLC}^T} \mathbf{w}_l)^2}{1 + \beta \sum_{l=1, l \neq k}^{K^{\text{VLC}}} (\mathbf{h}_k^{\text{VLC}^T} \mathbf{w}_l)^2} \right) - \frac{1}{2} \log_2 \left(\frac{1 + \alpha \sum_{l=1}^{K^{\text{VLC}}} (\mathbf{h}_E^{\text{VLC}^T} \mathbf{w}_l)^2}{1 + \beta \sum_{l=1, l \neq k}^{K^{\text{VLC}}} (\mathbf{h}_E^{\text{VLC}^T} \mathbf{w}_l)^2} \right) \right]^+ , \quad (38)$$

where $\alpha = 2^{2h_{x^{\text{VLC}}} / 2\pi e \sigma_n^{\text{VLC}^2}}$ and $\beta = \sigma_x^{\text{VLC}^2} / \sigma_n^{\text{VLC}^2}$, with $h_{x^{\text{VLC}}}$ being the differential entropy of the random variable x^{VLC} .

Proof. The proof is provided in appendix A. □

3.4 SUMMARY OF THE CHAPTER

In this chapter, we described the system model and signal model for the considered hybrid RF/VLC system and obtained the SINR and secrecy capacity for the RF and VLC AP, which are employed on the optimization problems studied to maximize the sum secrecy rate of the system in Chapter 4.

4 MAXIMIZATION OF THE SUM SECRECY RATE

In this chapter, we propose a joint precoding design and user association framework to maximize the sum secrecy rate of the network. Accordingly, we start by designing the VLC and RF precoders, which are employed next by the proposed user association algorithm.

4.1 PRECODING DESIGN

The maximal achievable secrecy rate for the k th user connected to the RF or VLC AP is given by the secrecy capacity, in bits per second, as

$$R_k = \begin{cases} R_k^{\text{VLC}} = C_s^{\text{VLC}}, & k \in \mathcal{T}^{\text{VLC}} \\ R_k^{\text{RF}} = C_s^{\text{RF}}, & k \in \mathcal{T}^{\text{RF}}, \end{cases} \quad (39)$$

where $\mathcal{T}^{\text{VLC}}$ is the set of VLC transmitters and $\mathcal{T}^{\text{RF}}$ denotes the set of transmit antennas at the RF AP. Then, the following optimization problems are formulated to maximize the sum secrecy rate of the VLC and RF AP, subject to a QoS constraint, as well as to transmit power constraints.

$$\mathcal{P}1. : \max_W \left\{ \sum_{k=1}^{K^{\text{VLC}}} b_k^i R_k^{\text{VLC}} \right\}, i \in \{\text{RF}, \text{VLC}\} \quad (40a)$$

$$\text{s. t. } C_k^{\text{VLC}} > \mathcal{R}_k, \quad (40b)$$

$$b_k^{\text{RF}} = 0, b_k^{\text{VLC}} = 1, \quad (40c)$$

$$\|\mathbf{W}\|_{\infty} \leq \Delta, \quad (40d)$$

$$\mathcal{P}2. : \max_V \left\{ \sum_{k=1}^{K^{\text{RF}}} b_k^i R_k^{\text{RF}} \right\}, i \in \{\text{RF}, \text{VLC}\}, \quad (41a)$$

$$\text{s. t. } C_k^{\text{RF}} > \mathcal{R}_k, \quad (41b)$$

$$b_k^{\text{RF}} = 1, b_k^{\text{VLC}} = 0, \quad (41c)$$

$$\sum_{k=1}^{K^{\text{RF}}} \|\mathbf{v}_k\|^2 < P_s^{\text{RF}}, \quad (41d)$$

where $b_k^i, i \in \{\text{RF}, \text{VLC}\}$ is a binary connection variable, which indicates that a user can only be connected to one of the APs, C_k^{VLC} and C_k^{RF} are the capacity of the legitimate channel between the VLC AP or the RF AP and the k th user, as given in (38) and (37), respectively. $\mathcal{R}_k$ is the target rate, and $P_s^{\text{RF}} > 0$ is the transmit power limit for the RF AP. Also, $\Delta = \max\{\Delta_n\}, \forall n$, and Δ_n is given as in (27). Note that neither (40a) nor (41a) are convex optimization problems, due to the non-concave objective functions and non-convex constraints in (40b) and (41b). Accordingly, in the following section, we employ CCCP to develop an algorithm capable to effectively solve the optimization problems $\mathcal{P}1$ and $\mathcal{P}2$. In the CCCP, the objective and constraint functions are expressed as a sum of a concave and a convex part. Therefore, it can be applied to most of optimization problems and it is proven to converge to a local optimal (YUILLE; RANGARAJAN, 2003a).

4.1.1 Application of the CCCP to Solve $\mathcal{P}1$ and $\mathcal{P}2$

4.1.1.1 CCCP for $\mathcal{P}1$

By following a similar approach of (DUONG et al., 2021), to turn $\mathcal{P}1$ into a concave problem, we begin introducing the following slack variables

$$r_{1,i}^{\text{VLC}} = \frac{1}{2} \log_2 \left(1 + \alpha \sum_{l=1}^{K^{\text{VLC}}} (\mathbf{h}_i^{\text{VLC}^T} \mathbf{w}_l)^2 \right), \quad (42)$$

$$r_{2,i}^{\text{VLC}} = \frac{1}{2} \log_2 \left(1 + \beta \sum_{\substack{l=1 \\ l \neq k}}^{K^{\text{VLC}}} (\mathbf{h}_i^{\text{VLC}^T} \mathbf{w}_l)^2 \right), \quad (43)$$

$$\rho_{1,i}^{\text{VLC}} = \alpha \sum_{l=1}^{K^{\text{VLC}}} (\mathbf{h}_i^{\text{VLC}^T} \mathbf{w}_l)^2, \quad (44)$$

$$\rho_{2,i}^{\text{VLC}} = \beta \sum_{\substack{l=1 \\ l \neq k}}^{K^{\text{VLC}}} (\mathbf{h}_i^{\text{VLC}^T} \mathbf{w}_l)^2, \quad (45)$$

where $i \in \{k, E\}$. Thus, $\mathcal{P}1$ can be rewritten as

$$\mathcal{P}1' : \max_{\substack{\mathbf{w}, r_{1,k}^{\text{VLC}}, r_{2,k}^{\text{VLC}}, \\ \rho_{1,k}^{\text{VLC}}, \rho_{2,k}^{\text{VLC}}, r_{1,E}^{\text{VLC}}, \\ r_{2,E}^{\text{VLC}}, \rho_{1,E}^{\text{VLC}}, \rho_{2,E}^{\text{VLC}}}} \sum_{k=1}^{K^{\text{VLC}}} (r_{1,k}^{\text{VLC}} - r_{2,k}^{\text{VLC}} - (r_{1,E}^{\text{VLC}} - r_{2,E}^{\text{VLC}})) \quad (46a)$$

$$\text{s. t. } r_{1,k}^{\text{VLC}} \leq \frac{1}{2} \log_2(1 + \rho_{1,k}^{\text{VLC}}), \quad (46b)$$

$$\rho_{1,k}^{\text{VLC}} \leq \alpha \sum_{l=1}^{K^{\text{VLC}}} (\mathbf{h}_k^{\text{VLC}^T} \mathbf{w}_l)^2, \quad (46c)$$

$$r_{2,k}^{\text{VLC}} \geq \frac{1}{2} \log_2(1 + \rho_{2,k}^{\text{VLC}}), \quad (46d)$$

$$\rho_{2,k}^{\text{VLC}} \geq \beta \sum_{\substack{l=1 \\ l \neq k}}^{K^{\text{VLC}}} (\mathbf{h}_k^{\text{VLC}^T} \mathbf{w}_l)^2, \quad (46e)$$

$$r_{1,E}^{\text{VLC}} \geq \frac{1}{2} \log_2(1 + \rho_{1,E}^{\text{VLC}}), \quad (46f)$$

$$\rho_{1,E}^{\text{VLC}} \geq \alpha \sum_{l=1}^{K^{\text{VLC}}} (\mathbf{h}_E^{\text{VLC}^T} \mathbf{w}_l)^2, \quad (46g)$$

$$r_{2,E}^{\text{VLC}} \leq \frac{1}{2} \log_2(1 + \rho_{2,E}^{\text{VLC}}), \quad (46h)$$

$$\rho_{2,E}^{\text{VLC}} \leq \beta \sum_{\substack{l=1 \\ l \neq k}}^{K^{\text{VLC}}} (\mathbf{h}_E^{\text{VLC}^T} \mathbf{w}_l)^2, \quad (46i)$$

$$r_{1,k}^{\text{VLC}} - r_{2,k}^{\text{VLC}} \geq \mathcal{R}_k, \quad (46j)$$

$$(40c), (40d),$$

Note from (42) and (43) that the new objective function in (46a) is a concave function with respect to $\mathbf{W}$, $r_{1,k}$, $r_{2,k}$, $r_{1,E}$, and $r_{2,E}$. Also, it can be seen that constraints (46b), (46e), (46g), (46h), and (46j) are convex, while (46c), (46d), (46f), and (46i) are not. To handle this latter issue, we consider the first-order Taylor approximation to linearize the non-convex constraints and employ the CCCP to iteratively solve the approximated convex problem until a convergence criterion is attained (YUILLE; RANGARAJAN, 2003b). More specifically, at the i th iteration, the following optimization problem is solved

$$\begin{aligned} \mathcal{P}1'' : \quad & \max_{\substack{\mathbf{W}, r_{1,k}^{\text{VLC}}, r_{2,k}^{\text{VLC}}, \\ \rho_{1,k}^{\text{VLC}}, \rho_{2,k}^{\text{VLC}}, r_{1,E}^{\text{VLC}}, \\ r_{2,E}^{\text{VLC}}, \rho_{1,E}^{\text{VLC}}, \rho_{2,E}^{\text{VLC}}}} \sum_{k=1}^{K^{\text{VLC}}} (r_{1,k}^{\text{VLC}} - r_{2,k}^{\text{VLC}} - (r_{1,E}^{\text{VLC}} - r_{2,E}^{\text{VLC}})) \\ & \text{s. t.} \end{aligned} \quad (47a)$$

$$\rho_{1,k}^{\text{VLC}} \leq \sum_{l=1}^{K^{\text{VLC}}} \alpha \left((\mathbf{h}_k^{\text{VLC}^T} \mathbf{w}_l^{(i-1)})^2 + 2 [\mathbf{w}_l^{(i-1)}]^T \mathbf{h}_k^{\text{VLC}} \mathbf{h}_k^{\text{VLC}^T} (\mathbf{w}_l - \mathbf{w}_l^{(i-1)}) \right), \quad (47b)$$

$$r_{2,k}^{\text{VLC}} \geq \frac{1}{2} \log_2(1 + \rho_{2,k}^{(i-1)}) + \frac{(\rho_{2,k} - \rho_{2,k}^{(i-1)})}{2 \ln(2) (1 + \rho_{2,k}^{(i-1)})}, \quad (47c)$$

$$r_{1,E}^{\text{VLC}} \geq \frac{1}{2} \log_2(1 + \rho_{1,E}^{(i-1)}) + \frac{(\rho_{1,E} - \rho_{1,E}^{(i-1)})}{2 \ln(2) (1 + \rho_{1,E}^{(i-1)})}, \quad (47d)$$

$$\rho_{2,E}^{\text{VLC}} \leq \sum_{\substack{l=1 \\ l \neq k}}^{K^{\text{VLC}}} \beta \left((\mathbf{h}_E^{\text{VLC}^T} \mathbf{w}_l^{(i-1)})^2 + 2 [\mathbf{w}_l^{(i-1)}]^T \mathbf{h}_E^{\text{VLC}} \mathbf{h}_E^{\text{VLC}^T} (\mathbf{w}_l - \mathbf{w}_l^{(i-1)}) \right), \quad (47e)$$

(46b), (46e), (46g), (46h), (46j), (40c), (40d).

Accordingly, $\mathcal{P}1''$ have been transformed into a concave problem and can be efficiently solved by the convex programming toolbox CVX (GRANT; BOYD, 2014). The entire algorithm is summarized in Algorithm 1, where ε is the error tolerance for convergence and $i_{\max}$ is the maximum number of iterations.

Algorithm 1 CCCP Iterative Algorithm

```

1: Choose error tolerance  $\varepsilon$ , maximum number of iterations  $i_{\max}$ , and feasible initial points  $\mathbf{W}^{(0)}$ ,  $\rho_{2,k}^{(0)}$ , and  $\rho_{1,E}^{(0)}$ .
2:  $i \leftarrow 0$ 
3: repeat
4:   Solve (47a) to obtain  $\mathbf{W}^{(i)}$ ,  $\rho_{2,k}^{(i)}$  and  $\rho_{1,E}^{(i)}$  using  $\mathbf{W}^{(i-1)}$ ,  $\rho_{2,k}^{(i-1)}$  and  $\rho_{1,E}^{(i-1)}$  from the previous iteration.
5:    $i++$ 
6: until  $\frac{\|\mathbf{W}^i - \mathbf{W}^{i-1}\|}{\|\mathbf{W}^i\|} \leq \varepsilon$  or  $i \geq i_{\max}$ 
7: return  $\mathbf{W}^*$ 

```

4.1.1.2 CCCP for $\mathcal{P}2$

- Feasibility of $\mathcal{P}2$

Note that, differently from restriction (40d) considered in $\mathcal{P}1$ for the VLC AP, given the random nature of the RF channel, it is reasonable to consider that the power constraint for the RF AP is set by the transmit power to each user, as in (41d). Under these considerations, we must first evaluate the feasibility of $\mathcal{P}2$.

Similar to (NIU et al., 2019), we consider the power minimization problem to verify the feasibility of $\mathcal{P}2$, as follows

$$\mathcal{P}3. : \min_{\mathbf{V}} \sum_{k=1}^{K^{\text{RF}}} \|\mathbf{v}_k\|^2, \quad (48a)$$

$$\text{s. t. } \text{SINR}_k^{\text{RF}} \geq \gamma_k, \quad (48b)$$

where (48a) is feasible, if and only if, γ_k satisfy the following condition (NIU et al., 2019),:

$$\sum_{k=1}^{K^{\text{RF}}} \frac{\gamma_k}{1 + \gamma_k} \leq \text{rank}(\mathbf{H}^{\text{RF}}). \quad (49)$$

Considering that the above condition is satisfied, we begin to solve the problem in (48a)

by first rearranging (48b), considering (33)

$$\begin{aligned} \frac{|\mathbf{h}_k^{\text{RFH}} \mathbf{v}_k|^2 \sigma_x^{\text{RF}^2}}{\sum_{\substack{l=1 \\ l \neq k}}^{K^{\text{RF}}} |\mathbf{h}_k^{\text{RFH}} \mathbf{v}_l|^2 \sigma_x^{\text{RF}^2} + \sigma_n^{\text{RF}^2}} &\geq \gamma_k, \\ \gamma_k \left(\sum_{\substack{l=1 \\ l \neq k}}^{K^{\text{RF}}} |\mathbf{h}_k^{\text{RFH}} \mathbf{v}_l|^2 + \frac{\sigma_n^{\text{RF}^2}}{\sigma_x^{\text{RF}^2}} \right) &\leq |\mathbf{h}_k^{\text{RFH}} \mathbf{v}_k|^2, \\ \sum_{l=1}^{K^{\text{RF}}} |\mathbf{h}_k^{\text{RFH}} \mathbf{v}_l|^2 + \frac{\sigma_n^{\text{RF}^2}}{\sigma_x^{\text{RF}^2}} &\leq \left(1 + \frac{1}{\gamma_k}\right) |\mathbf{h}_k^{\text{RFH}} \mathbf{v}_k|^2. \end{aligned} \quad (50)$$

Then, we can express the respective Lagrangian function of (48a) as

$$\begin{aligned} \mathcal{L}(\lambda, \mathbf{v}) &= \sum_{k=1}^{K^{\text{RF}}} \mathbf{v}_k^H \mathbf{v}_k - \sum_{k=1}^{K^{\text{RF}}} \lambda_k \left(\left(1 + \frac{1}{\gamma_k}\right) |\mathbf{h}_k^H \mathbf{v}_k|^2 - \sum_{l=1}^{K^{\text{RF}}} |\mathbf{h}_k^H \mathbf{v}_l|^2 - \frac{\sigma_n^{\text{RF}^2}}{\sigma_x^{\text{RF}^2}} \right), \\ &= \sum_{k=1}^{K^{\text{RF}}} \lambda_k \frac{\sigma_n^{\text{RF}^2}}{\sigma_x^{\text{RF}^2}} + \sum_{k=1}^{K^{\text{RF}}} \mathbf{v}_k^H \left(\mathbf{I} + \sum_{l=1}^{K^{\text{RF}}} \lambda_l \mathbf{h}_l \mathbf{h}_l^H - \left(1 + \frac{1}{\gamma_k}\right) \lambda_k \mathbf{h}_k \mathbf{h}_k^H \right) \mathbf{v}_k. \end{aligned} \quad (51)$$

Thus, the dual function of (48a) is written as

$$g(\lambda) = \begin{cases} \sum_{k=1}^{K^{\text{RF}}} \lambda_k \frac{\sigma_n^{\text{RF}^2}}{\sigma_x^{\text{RF}^2}}, & \text{if } \mathbf{I} + \sum_{l=1}^{K^{\text{RF}}} \lambda_l \mathbf{h}_l \mathbf{h}_l^H - \left(1 + \frac{1}{\gamma_k}\right) \lambda_k \mathbf{h}_k \mathbf{h}_k^H \succcurlyeq 0 \\ -\infty, & \text{otherwise} \end{cases} \quad (52)$$

Finally, based on (52), we attain the dual problem of (48a) as

$$\mathcal{P}3' : \max_{\lambda} \sum_{k=1}^{K^{\text{RF}}} \lambda_k \frac{\sigma_n^{\text{RF}^2}}{\sigma_x^{\text{RF}^2}}, \quad (53a)$$

$$\text{s. t. } \mathbf{I} + \sum_{\substack{l=1 \\ l \neq k}}^{K^{\text{RF}}} \lambda_l \mathbf{h}_l \mathbf{h}_l^H - \left(1 + \frac{1}{\gamma_k}\right) \lambda_k \mathbf{h}_k \mathbf{h}_k^H \succcurlyeq 0, \forall k \quad (53b)$$

$$\lambda_k \geq 0. \quad (53c)$$

Note that (53a) is a convex problem and can also be solved with the aid of the CVX tool. Note also that, at the optimal solution, we have that (BENGTTSSON; OTTERSTEN, 2018)

$$\sum_{k=1}^{K^{\text{RF}}} \lambda_k \frac{\sigma_n^{\text{RF}^2}}{\sigma_x^{\text{RF}^2}} = \sum_{k=1}^{K^{\text{RF}}} \|\mathbf{v}_k\|^2. \quad (54)$$

Accordingly, setting the optimal solution of (53a) as P_s^* , we have that if P_s^* is greater than P_s^{RF} , there is no possible solution for $\mathcal{P}2$. Meanwhile, if $P_s^* < P_s^{\text{RF}}$, $\mathcal{P}2$ is feasible.

Assuming $\mathcal{P}2$ is feasible, it can be modified into a concave problem by applying a similar

approach used for solving $\mathcal{P}1$. For that purpose, we introduce slack variables to rewrite $\mathcal{P}2$ as

$$\mathcal{P}2' : \max_{\mathbf{V}, r_{1,k}^{\text{RF}}, r_{2,k}^{\text{RF}}, \rho_{1,k}^{\text{RF}}, \rho_{2,k}^{\text{RF}}, r_{1,E}^{\text{RF}}, r_{2,E}^{\text{RF}}, \rho_{1,E}^{\text{RF}}, \rho_{2,E}^{\text{RF}}} \sum_{k=1}^{K^{\text{RF}}} (r_{1,k}^{\text{RF}} - r_{2,k}^{\text{RF}} - (r_{1,E}^{\text{RF}} - r_{2,E}^{\text{RF}})) \quad (55a)$$

$$\text{s. t. } r_{1,k}^{\text{RF}} \leq \log_2(1 + \rho_{1,k}^{\text{RF}}), \quad (55b)$$

$$\rho_{1,k}^{\text{RF}} \leq (1/\sigma_n^{\text{RF}^2}) \sum_{l=1}^{K^{\text{RF}}} (\mathbf{h}_k^{\text{RF}H} \mathbf{v}_l)^2, \quad (55c)$$

$$r_{2,k}^{\text{RF}} \geq \log_2(1 + \rho_{2,k}^{\text{RF}}), \quad (55d)$$

$$\rho_{2,k}^{\text{RF}} \geq (1/\sigma_n^{\text{RF}^2}) \sum_{\substack{l=1 \\ l \neq k}}^{K^{\text{RF}}} (\mathbf{h}_k^{\text{RF}H} \mathbf{v}_l)^2, \quad (55e)$$

$$r_{1,E}^{\text{RF}} \geq \log_2(1 + \rho_{1,E}^{\text{RF}}), \quad (55f)$$

$$\rho_{1,E}^{\text{RF}} \geq (1/\sigma_n^{\text{RF}^2}) \sum_{l=1}^{K^{\text{RF}}} (\mathbf{h}_E^{\text{RF}H} \mathbf{v}_l)^2, \quad (55g)$$

$$r_{2,E}^{\text{RF}} \leq \log_2(1 + \rho_{2,E}^{\text{RF}}), \quad (55h)$$

$$\rho_{2,E}^{\text{RF}} \leq (1/\sigma_n^{\text{RF}^2}) \sum_{\substack{l=1 \\ l \neq k}}^{K^{\text{RF}}} (\mathbf{h}_E^{\text{RF}H} \mathbf{v}_l)^2, \quad (55i)$$

$$r_{1,k}^{\text{RF}} - r_{2,k}^{\text{RF}} \geq \mathcal{R}_k, \quad (55j)$$

$$(41c), (41d).$$

Next, the first-order Taylor approximation is applied on the non-convex constraints (55c), (55e), (55f) and (55i), and the CCCP is employed. Thus, at the i th iteration, we have that

$$\mathcal{P}2'' : \max_{\mathbf{V}, r_{1,k}^{\text{RF}}, r_{2,k}^{\text{RF}}, \rho_{1,k}^{\text{RF}}, \rho_{2,k}^{\text{RF}}, r_{1,E}^{\text{RF}}, r_{2,E}^{\text{RF}}, \rho_{1,E}^{\text{RF}}, \rho_{2,E}^{\text{RF}}} \sum_{k=1}^{K^{\text{RF}}} (r_{1,k}^{\text{RF}} - r_{2,k}^{\text{RF}} - (r_{1,E}^{\text{RF}} - r_{2,E}^{\text{RF}})) \quad (56a)$$

s. t.

$$\rho_{1,k}^{\text{RF}} \leq \sum_{l=1}^{K^{\text{RF}}} (1/\sigma_n^{\text{RF}^2}) \left(\left(\mathbf{h}_k^{\text{RF}H} \mathbf{v}_l^{(i-1)} \right)^2 + 2 \left[\mathbf{v}_l^{(i-1)} \right]^H \mathbf{h}_k^{\text{RF}} \mathbf{h}_k^{\text{RF}H} \left(\mathbf{v}_l - \mathbf{v}_l^{(i-1)} \right) \right), \quad (56b)$$

$$r_{2,k}^{\text{RF}} \geq \log_2 \left(1 + \rho_{2,k}^{(i-1)} \right) + \frac{(\rho_{2,k} - \rho_{2,k}^{(i-1)})}{\ln 2 \left(1 + \rho_{2,k}^{(i-1)} \right)}, \quad (56c)$$

$$r_{1,E}^{\text{RF}} \geq \log_2 \left(1 + \rho_{1,E}^{(i-1)} \right) + \frac{(\rho_{1,E} - \rho_{1,E}^{(i-1)})}{\ln 2 \left(1 + \rho_{1,E}^{(i-1)} \right)}, \quad (56d)$$

$$\rho_{2,E}^{\text{RF}} \leq \sum_{\substack{l=1 \\ l \neq k}}^{K^{\text{RF}}} (1/\sigma_n^{\text{RF}^2}) \left(\left(\mathbf{h}_E^{\text{RFH}} \mathbf{v}_l^{(i-1)} \right)^2 + 2 \left[\mathbf{v}_l^{(i-1)} \right]^H \mathbf{h}_E^{\text{RF}} \mathbf{h}_E^{\text{RFH}} \left(\mathbf{v}_l - \mathbf{v}_l^{(i-1)} \right) \right), \quad (56e)$$

(55b), (55e), (55g), (55h), (55j), (41c), (41d).

Finally, replacing the optimization variables in (47a) by (56a), Algorithm 1 can be employed to solve $\mathcal{P}2''$.

4.1.2 Complexity of the Algorithm

In this section, we evaluate the complexity of the proposed algorithm. For that purpose, by considering (DUONG et al., 2021) and (PHAM; PHAM, 2021), and since (47a) and (56a) are convex, both problems can be solved via the Interior Point Algorithm (IPA) (YE, 2011). Therefore, the total number of Newton steps, N_s^{Total} , can be assumed as a complexity measure. Starting the Algorithm from a given initial value, N_s^{Total} indicates the number of recursive iterations necessary to achieve convergence that can be estimated as

$$N_s^{\text{Total}} = N_i + N_s, \quad (57)$$

where N_i is the number of iterations necessary for the algorithm's convergence, and N_s measures the number of Newton steps needed to solve (47a) or (56a). In this sense, N_i is properly investigated on Chapter 5. Regarding N_s and based on (NESTEROV; NEMIROVSKII, 1994), we have that the worst-case N_s required to reach a local solution is estimated as

$$N_s \sim \sqrt{\text{problem size}}, \quad (58)$$

where problem size is the number of optimization scalar variables. For $\mathcal{P}1''$ and $\mathcal{P}2''$ there are $(N+4)K^{\text{VLC}}+4$ and $(M+4)K^{\text{RF}}+4$ scalar variables, respectively. From (47a) and (56a), it can be noted that one optimization variable has size NK^{VLC} for VLC and MK^{RF} for RF. On the other hand, the other optimization variables were previously added as slack variables to turn $\mathcal{P}1$ and $\mathcal{P}2$ into concave problems, with four variables related to the intended users and other four variable related to the eavesdropper.

4.1.3 Zero-Forcing Precoding

As a baseline scheme, the regularized ZF method is considered. As described in Chapter 2, this method aims to mitigate the interference caused by other users in the network by pointing the signal beam in the direction of the intended user and nulling the direction of other users. Accordingly, with this consideration, the precoding matrix for the VLC and RF APs are written,

respectively, as (NGUYEN; EVANS, 2008)

$$\mathbf{W} = \chi^{\text{VLC}} \mathbf{H}^{\text{VLC}^T} (\mathbf{H}^{\text{VLC}} \mathbf{H}^{\text{VLC}^T} + v^{\text{VLC}} \mathbf{I})^{-1}, \quad (59)$$

$$\mathbf{V} = \chi^{\text{RF}} \mathbf{H}^{\text{RF}^H} (\mathbf{H}^{\text{RF}} \mathbf{H}^{\text{RF}^H} + v^{\text{RF}} \mathbf{I})^{-1}, \quad (60)$$

where $\chi^i, i \in (\text{VLC}, \text{RF})$ is a normalizing constant, and $v^i, i \in (\text{VLC}, \text{RF})$ is the regularization parameter, given, respectively, by

$$\chi = \sqrt{\frac{P_t}{\text{Tr}((\mathbf{H}\mathbf{H}^H + v\mathbf{I})^{-1}\mathbf{H}\mathbf{H}^H(\mathbf{H}\mathbf{H}^H + v\mathbf{I})^{-1})}}, \quad (61)$$

with P_t being the total transmit power and

$$v = \begin{cases} 0, & K < N \\ K/P_t, & K = N. \end{cases} \quad (62)$$

4.2 USER ASSOCIATION STRATEGY

Given that each user can be allocated to only one AP, along with the optimization of precoders, we must identify the best way to associate each user with one of the APs in order to attain the maximum sum secrecy rate. Thus, the user association problem can be written as

$$\mathcal{P}4. : \max \sum_{k=1}^K b_k^i R_k^i, i \in \{\text{RF}, \text{VLC}\} \quad (63a)$$

$$\text{s. t. } b_k^i \in \{0, 1\}, \forall k, \forall i \in \{\text{RF}, \text{VLC}\} \quad (63b)$$

$$b_k^{\text{RF}} + b_k^{\text{VLC}} = 1, \quad (63c)$$

$$\sum_{k=1}^{K^{\text{RF}}} b_k^{\text{RF}} \leq M, \quad (63d)$$

$$\sum_{k=1}^{K^{\text{VLC}}} b_k^{\text{VLC}} \leq N, \quad (63e)$$

Constraints (63d) and (63e) ensure that the number of users connected to the RF and VLC AP is inferior to the number of antennas and LEDs, respectively. Accordingly, the user association problem can be viewed as a way of partitioning the user set between the VLC and RF APs, where the intersection set between both subsets is empty and the union between the subsets results on the set of all users. Verifying all the possible combinations is an arduous task and demands high computational cost, specially as the number of users connected on the network increases. Thus, one efficient way to solve the user association problem is resorting to tools from game theory. Particularly, for this specific problem, we model the user association as

a coalitional formation game, whose structure and the non-transferable utility are defined as follows.

Definition 2. A coalitional structure is defined as the set $S = \{S^{\text{RF}}, S^{\text{VLC}}\}$ of mutually disjoint coalitions that partitions the set of players, $\mathbb{K} = \{1, \dots, K\}$, which is also named the grand coalition (APT; WITZEL, 2009).

Definition 3. A coalitional game with non-transferable utility is defined in terms of $\mathbb{K}$ and $\mathbb{U}$, where $\mathbb{U}(S) \in \mathbb{R}^S$ maps the payoff that players in S can achieve. That is, for a certain user k with utility function u_k , $\mathbb{U}(S)$ is given by

$$\mathbb{U}(S) = \{\mathbf{x}(S) \in \mathbb{R}^S | x_k(S) = u_k(S), \forall k \in S\}. \quad (64)$$

Thus, we can define the proposed game as a hedonic coalitional formation game, that is, the payoff of the players depends solely on the coalition in which the player is inserted (PANIKOLAOU; DIAMANTOULAKIS; KARAGIANNIDIS, 2019).

4.2.1 User Preference Relation

From (63a), we define the utility function of a user k connected to one of the APs as the achievable secrecy rate, given by (37) and (38). Furthermore, from *Definition 2*, it is observed that, for the considered network, the coalitional structure have two coalitions, i.e. $S = \{S^{\text{RF}}, S^{\text{VLC}}\}$, and the utility function of those coalitions is given by (ELIODOROU et al., 2019)

$$U(S^i) = \left\{ \sum_{k=1}^{K^i} u_k | \forall k \in S^i, i \in \{\text{RF}, \text{VLC}\} \right\}. \quad (65)$$

Next, we present three definitions related to the user preference and operation of reallocation of APs (ELIODOROU et al., 2019).

Definition 4. The preference of any user $k \in \mathbb{K}$ between a new coalition, S^{i*} , and the previous coalition, S^i , with $i \in \{\text{RF}, \text{VLC}\}$, depends on whether or not the utility of the coalitions $U(S)$ increases. We employ the symbol $\succ_k$ to denote this preference, so that

$$S^{i*} \succ_k S^i \Leftrightarrow U(S^i \setminus \{k\}) + U(S^{i*} \cup \{k\}) > U(S^i) + U(S^{i*}). \quad (66)$$

Definition 5. If the number of users connected to coalition S^{i*} is less than the number of transmitting units i.e., M or N , a user k connected to coalition S^i may decide to move to coalition S^{i*} if and only if (66) is satisfied. This operation is defined as split and merge and can be written

as

$$\{S^i, S^{i*}\} \rightarrow \{S^i \setminus \{k\}, S^{i*} \cup \{k\}\}. \quad (67)$$

Definition 6. *If the number of users connected to coalition S^{i*} is equal to the respective constraint on the number of transmitters, (63d) or (63e), a user k connected to coalition S^i may decide to swap position with a user k^* , connected to coalition S^{i*} if and only if (66) is satisfied for both coalitions. The swap operation is defined as*

$$\{S^i, S^{i*}\} \rightarrow \{S^i \setminus \{k\} \cup \{k^*\}, S^{i*} \setminus \{k^*\} \cup \{k\}\}. \quad (68)$$

4.2.2 Coalitional Game Algorithm

Given the previous definitions, the proposed algorithm can be described into three phases:

- **Phase 1.** All K users are randomly assigned to the APs, and Algorithm 1 is solved to encounter the optimal precoder values, $\mathbf{V}^*$ and $\mathbf{W}^*$, for this first association, according to problems $\mathcal{P}1''$ and $\mathcal{P}2''$ in (47a) and (56a), respectively. Next, the initial sum secrecy rate is calculated.
- **Phase 2.** In this phase, the coalitional game is initiated to identify the association that maximizes the sum secrecy rate. For each iteration, $\mathcal{P}1''$ and $\mathcal{P}2''$ are found with Algorithm 1, and it is verified if a user should stay in the previously assigned coalition or if it moves to the other one in case (66) is satisfied.
- **Phase 3.** Finally, the association that provides the maximum sum secrecy rate is set.

Accordingly, the coalitional game algorithm is presented in Algorithm 2.

4.2.2.1 Convergence and Complexity Analysis of the User Association Algorithm

In this subsection, important properties of the proposed algorithm such as, convergence, stability and complexity are evaluated. First, Theorem 2 and Proposition 1 are revisited from (ELIODOROU et al., 2019) to state the convergence and stability of Algorithm 2.

Theorem 2. *For any initial allocation, the proposed coalitional game algorithm is always bound to converge to a final user association partition, S_f .*

Proof. Users perform either split and merge or swap operations to join a different coalition. A new partition occurs if and only if (66) is satisfied, which entails an increase in the utility of the game, so each new partition is guaranteed to enhance the sum secrecy rate. However, given that

Algorithm 2 Coalitional Game Algorithm

```

1: Initialize
2:    $S_{init}$ : Random allocation of users to APs.
3:   Execute Algorithm 1 and obtain  $\mathbf{V}^*$  and  $\mathbf{W}^*$  for  $S_{init}$ .
4:    $S_c \leftarrow S_{init}$ .
5:   while convergence = 0 do
6:      $S_{alloc} \leftarrow S_c$ 
7:     for  $k \leftarrow 1$  to  $K$  do
8:       if  $K^{i*} = M$  then
9:         select user  $k^*$  of coalition  $S^{i*} \in S_c$  with highest  $u_{k^*}$ .
10:         $S_{aux} \leftarrow$  swap  $k$  with  $k^*$ .
11:        Execute Algorithm 1 and obtain  $\mathbf{V}^*$  and  $\mathbf{W}^*$  for  $S_{aux}$ .
12:        if  $S_{aux} \succ_k S_c$  then
13:           $S_c \leftarrow \{S_c \setminus \{S^i, S^{i*}\}\} \cup \{S^i \setminus \{k\} \cup \{k^*\}, S^{i*} \setminus \{k^*\} \cup \{k\}\}$ 
14:        end if
15:      else
16:         $S_{aux} \leftarrow k$  moves to  $S^{i*}$ .
17:        Execute Algorithm 1 and obtain  $\mathbf{V}^*$  and  $\mathbf{W}^*$  for  $S_{aux}$ .
18:        if  $S_{aux} \succ_k S_c$  then
19:           $S_c \leftarrow \{S_c \setminus \{S^i, S^{i*}\}\} \cup \{S^i \setminus \{k\}, S^{i*} \cup \{k\}\}$ 
20:        end if
21:      end if
22:    end for
23:    if  $S_c = S_{alloc}$  then
24:      convergence = 1
25:    end if
26:  end while

```

the number of users is finite, the number of partition sets is also limited and related to the Bell number (ELIODOROU et al., 2019). The Bell number counts the number of ways a set of n elements can be partitioned into nonempty subsets (ROTA, 1964). $\square$

Proposition 1. Any S_f for the considered coalitional game algorithm is Nash-stable.

Proof. A partition is considered Nash-stable if

$$S^i \succ_k S^{i*}, S^i \in \{S^{\text{RF}}, S^{\text{VLC}}\}, S^{i*} \in \{S^{\text{RF}}, S^{\text{VLC}}\}, \forall k \in \{K^{\text{RF}}, K^{\text{VLC}}\}. \quad (69)$$

Therefore, a partition is stable if the users have no incentive to join another partition. If S_f is assumed not Nash-stable, then exists a user that prefers to leave its current partition, which results in $S_{aux} \succ_k S_f$, and indicates that S_f is not the final partition. Also, Theorem 2 proved that $S_{aux} \succ_k S_f$ is not possible since the number of users and partition sets is finite. Hence, S_f is Nash-stable. $\square$

Furthermore, as previously stated, evaluating all possible combinations to perform the user association has a high computational cost, which is strictly related to the complexity of an exhaustive method search. Assuming $\Theta^i \in \{\text{RF}, \text{VLC}\}$ as the complexity of Algorithm 1, previously presented in Section 4.1.2, we achieve $O(2^K(\Theta^{\text{RF}} + \Theta^{\text{VLC}}))$ as the complexity for the exhaustive method search. For the proposed algorithm, the complexity is associated with

the number of iterations necessary until convergence, which is explained in the next proposition (ELIODOROU et al., 2019):

Proposition 2. *For a given number of iterations, $\mathcal{I}$, the complexity of Algorithm 2 is given by $O((\mathcal{I}K + 1)(\Theta^{\text{RF}} + \Theta^{\text{VLC}}))$.*

Proof. At the initialization of Algorithm 2, a random association is made and Algorithm 1 is executed to obtain the optimal precoders for RF and VLC APs. In sequence, for each iteration $\mathcal{I}$ of Algorithm 2, $K(\Theta^{\text{RF}} + \Theta^{\text{VLC}})$ computational operations are implemented. $\square$

4.3 SUMMARY OF THE CHAPTER

In this chapter, a joint precoding and user association framework was proposed in order to maximize the sum secrecy rate of the considered hybrid RF/VLC system. Specifically, in Section 4.1 the precoding design for the VLC and RF APs is described, and employed in Section 4.2 on the proposed user association strategy. Accordingly, the performance of the proposed framework is evaluated next on Chapter 5.

5 NUMERICAL RESULTS AND DISCUSSIONS

In this chapter, numerical results are provided to verify the performance of the proposed framework. For this purpose, considering the Cartesian coordinate system, the center of the room is defined as the origin, and the users are uniformly distributed within this space. In addition, the average channel gains of the RF links are assumed to be determined by the path loss, i.e., $\Omega_i = d_i^{-\alpha}$, $i \in \{k, E\}$, the K-factor of legitimate user k , $\mathcal{K}_k$, and that of the eavesdropper E , $\mathcal{K}_E$ are assumed equal to $\mathcal{K}$, and the target rate is equal to $\mathcal{R} = 1$ bps/Hz. In Algorithm 1, the error tolerance is set to $\varepsilon = 0.1$, and $i_{\max} = 10$ was proved to render a sufficient number of iterations. Beyond that, for the VLC AP, $p_{\min} = 0$ and $p_{\max} \gg p_n^{\text{VLC}}$, thus $\Delta = p_n^{\text{VLC}}$. Also, the initial point for the precoding design, $\mathbf{W}^{(0)}$, is chosen randomly; whereas for the RF AP, $\mathbf{V}^{(0)}$ is the one obtained after performing the power optimization in (53a). Moreover, 40 channel realizations for the VLC and RF AP proved to be sufficient to adequately represent the average performance of the system. Furthermore, unless otherwise specified, Table 1 summarizes the considered values for the system parameters.

Figure 7 illustrates the normalized average sum secrecy rate versus the total number of users in the network, K , for the proposed JPUA framework. For comparison purposes, it is also illustrated the performance attained with, i) ZF precoding plus user association as described in Section 4.2 (ZFUA), ii) precoding design as described in Section 4.1 plus random association, iii) VLC Standalone precoding design exhibited in Section 4.1.1.1 plus user association as described in Section 4.2, and iv) RF Standalone precoding design exhibited in Section 4.1.1.2 plus user association as described in Section 4.2. For the VLC and RF standalone schemes, the user association problem must still comply with constraints (63e) and (63d), that is, the system can assure connection only to $K = N$ users for the VLC standalone scheme, and $K = M$ users for the RF standalone scheme.

Accordingly, note that the proposed JPUA strategy achieves the best performance independently of the number of users in the network. Precisely, the behavior of the proposed design is similar to the VLC standalone case until a number of users $K = 3$, which is expected for a small number of users, since the VLC AP can provide higher secrecy rates. However, for $K = 4$, even though the VLC standalone case still performs well, its performance is worse than the one achieved with the JPUA strategy, since the resources available at the VLC AP are limited by the number of LEDs. Hence, for $K \geq 4$, the advantage of the JPUA strategy is more pronounced. In addition, note that as the number of users increases, employing the proposed user association method entails spatial diversity for the VLC standalone case. Although the number of users connected to the AP is limited to N , an enhancement on the sum secrecy rate is observed.

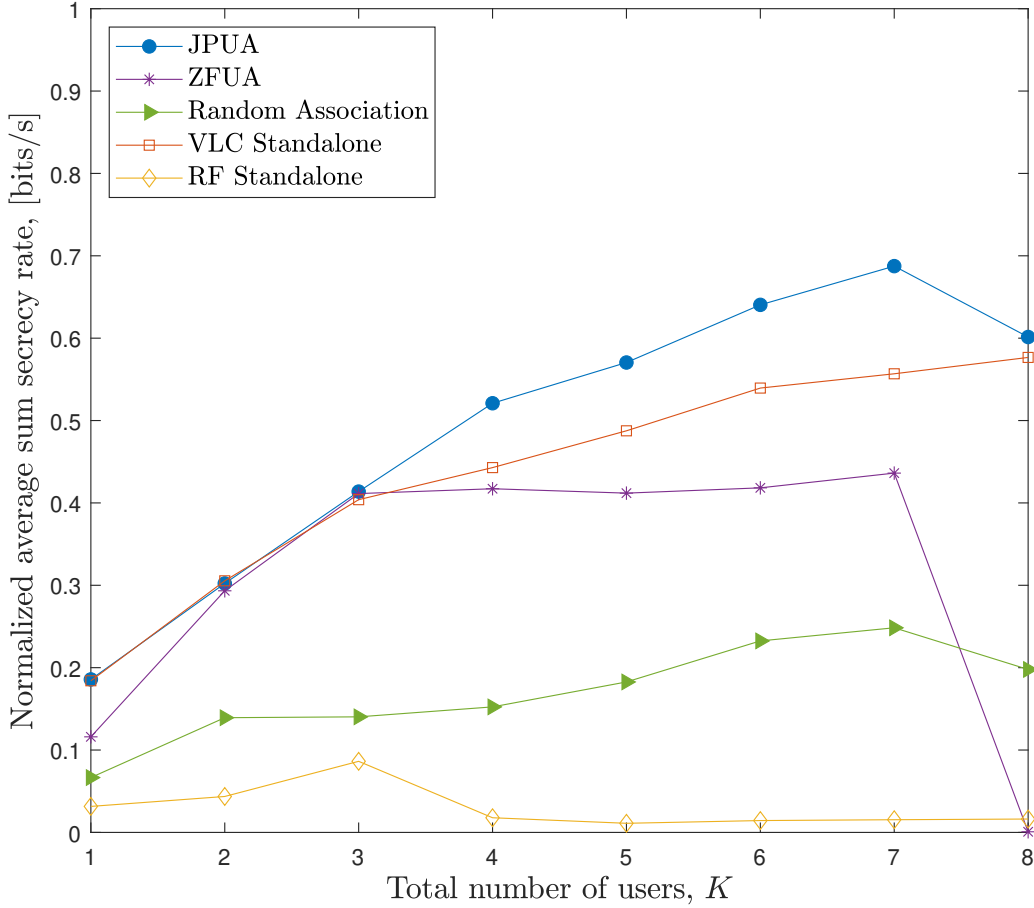
Table 1 - Simulation parameters

RF AP	
Number of transmitting antennas, M	4
Transmit power limitation, P_S^{RF}	20 dBm
Noise power, $\sigma_n^{\text{RF}^2}$	-100 dBm
K-factor, $\mathcal{K}$	10 dB
Path loss exponent, ϕ	1.8
VLC AP	
Number of emitting LEDs, N	4
Nominal optical intensity, p_n^{VLC}	40 dBm
Noise power spectral density, $\sigma_n^{\text{VLC}^2}$	10^{-21} A ² /Hz
Field of view (FOV) at PD, ψ_C	60°
Physical area of PD, A	1 cm ²
Responsivity of PD, R	0.54 A/W
Refractive index, r	1.5
Optical filter gain, $D(\psi)$	1
Angle of irradiance, ψ	120°
Angle of incidence, θ	120°
LED half intensity view angle, $\phi_{1/2}$	60°
Room Specifications	
Length $\times$ Width $\times$ Height	5 m $\times$ 5 m $\times$ 2.5 m
Position of the RF AP	(0, 0, 2.5)
Position of LED 1	($\sqrt{2}$, $\sqrt{2}$, 2.5)
Position of LED 2	($-\sqrt{2}$, $\sqrt{2}$, 2.5)
Position of LED 3	($\sqrt{2}$, $-\sqrt{2}$, 2.5)
Position of LED 4	($-\sqrt{2}$, $-\sqrt{2}$, 2.5)

On the other hand, for the case, $K=1$, the achievable sum secrecy rate for ZFUA is limited and perceivable smaller than that attained by the JPUA since the objective of ZF is to cancel possible interferers on the desired user's signal. Besides, the ZF precoder is almost inefficient when the transmit power is small (RUSEK et al., 2013), which is the case for the RF AP. Also, observe that the sum secrecy rate for the ZFUA strategy is close to zero when $K=8$. It occurs because, as previously pointed out in Chapter 2, with $K=M+N$, the usual ZF design may not correctly implement the channel inversion in (59) and (60), and even though the regularization parameter is considered, the performance of the ZFUA strategy is severely compromised in that point (PEEL; HOCHWALD; SWINDLEHURST, 2005). For those reasons, note that, although ZFUA obtains a similar sum secrecy rate as the JPUA strategy with $K=2$ and $K=3$, its performance is limited to the value attained by the ZF precoder for the VLC link when $K=3$ users are connected to the VLC AP.

To complement the results observed in Figure 7, Figure 8 shows the average number of

Figure 7 - Normalized average sum secrecy rate versus total number of users, K for the proposed JPUA method compared to different combinations of precoding design and user association.

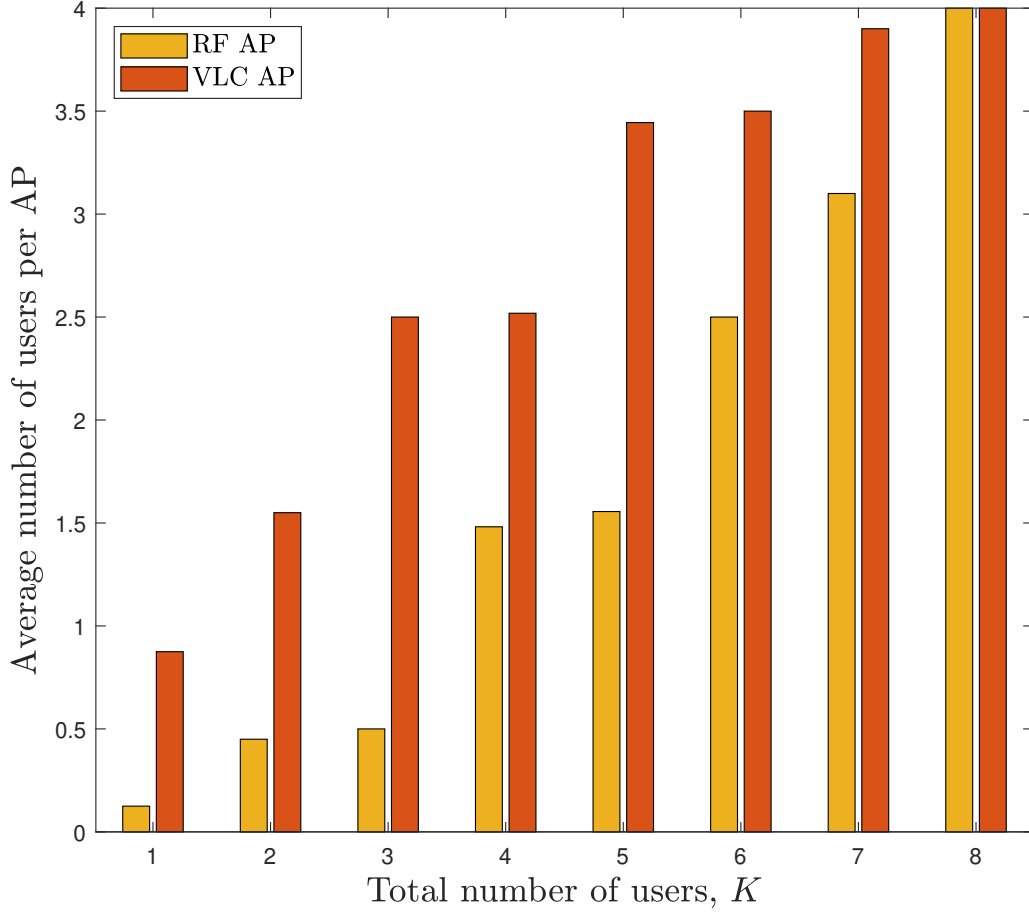


Source: Author

users connected per AP versus the total number of users, K , for the JPUA strategy. Note that more users are associated with the VLC AP, as expected, except for the case $K=8$. This is in agreement with the observations from Figure 7. For $K=1, 2$ and 3 , the sum secrecy rate attained with the VLC standalone network is almost identical to the JPUA strategy. However, VLC may not be capable to provide a positive secrecy rate to one or more users within the coverage of the AP when E is closer to a certain LED unit. In those scenarios, the RF AP can still attend to the requirements of secrecy and target a data rate $\mathcal{R}$, thus guaranteeing that all users remain connected to the network. In addition, note that, on average, two or three users are associated with the VLC AP when the total number of users in the network is $K=4$, validating the observations from Figure 7.

Figure 9 illustrates the normalized average sum secrecy rate versus the number of iterations of the proposed user association method for the JPUA and ZFUA strategies, with a total number

Figure 8 - Average number of users connected per AP versus total number of users, K for the JPUA design.

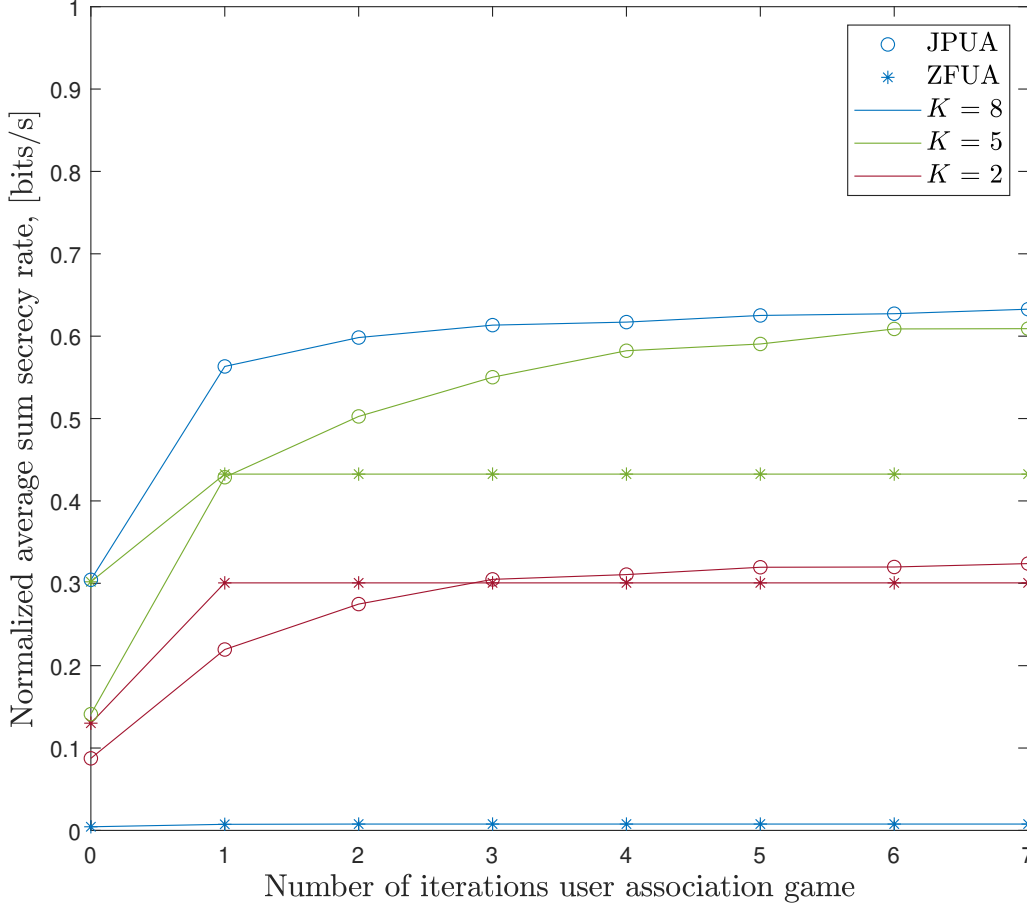


Source: Author

of users equal to $K=2, 5, 8$. Note that, since the users initiate with a random association, the sum secrecy rate of both JPUA and ZFUA strategies at iteration 0 is low and starts to increase as the user association game is performed. Note also that, for the ZFUA strategy, one iteration is sufficient to achieve convergence, while a large number of iterations is necessary for the JPUA strategy. However, it is observed that the proposed JPUA scheme outperforms the ZFUA method after three iterations with $K=2$, and only two iterations are sufficient when $K=5$, indicating the advantage of the proposed method, and that a particular association is not necessary for the initial association.

As previously mentioned in Figure 7, the ZFUA strategy does not work properly with $K=8$, thus resulting in a very low sum secrecy rate. On the other hand, the JPUA strategy is capable to attain a notable enhancement in performance for that same number of users after performing user association. Also, observe that differently from the cases with $K=2$ and $K=5$, there is no notable performance increase after several iterations when $K=8$. Also from Figure 7, it is

Figure 9 - Normalized average sum secrecy rate versus number of iterations of the user association game for the JPUA and ZFUA methods, with the total number of users equal to $K=2, 5, 8$.



Source: Author

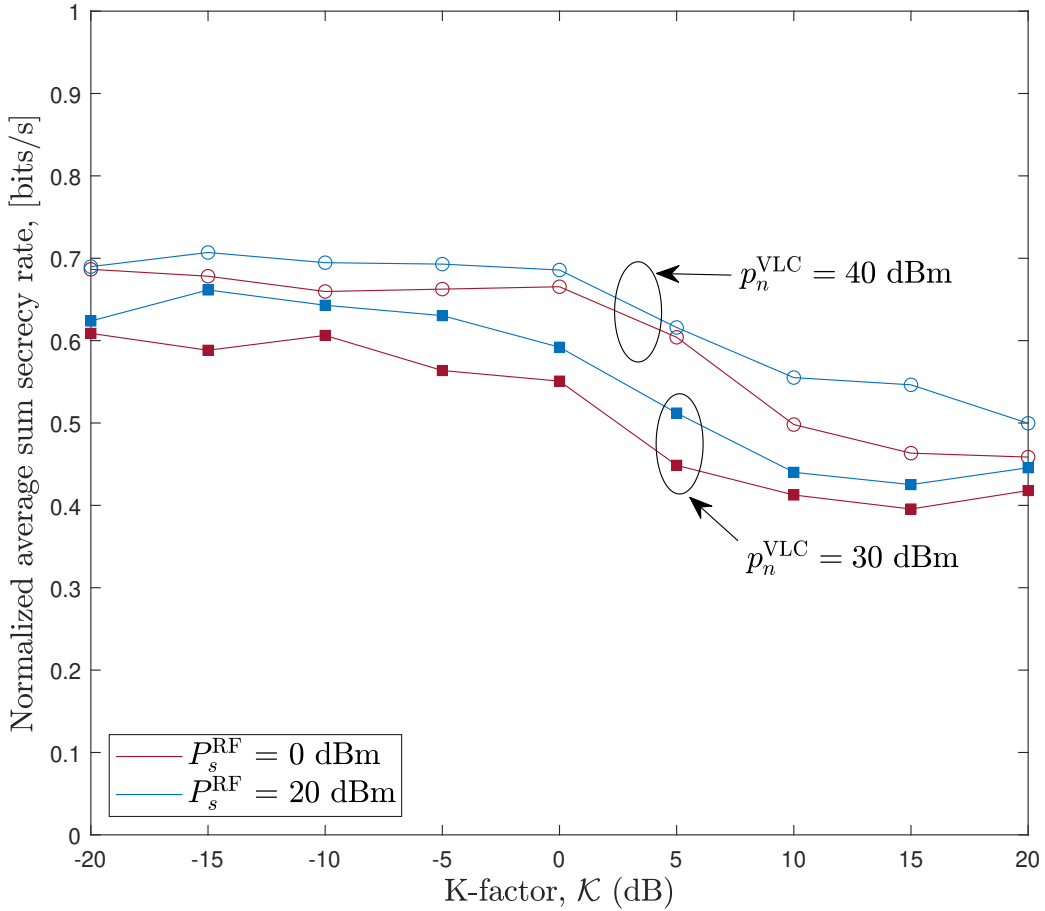
observed in the RF standalone case that when four users connect to the RF AP, i.e. $K^{\text{RF}}=M$, the secrecy performance of the RF link is drastically affected. Hence, although there is a higher spatial diversity in the network, the sum secrecy rate improvement after several iterations of the user association is minimum when $K=8$.

Finally, from Figure 9 is possible to conclude that the proposed user association method successfully provides a nearly-optimal solution after a small number of iterations while ensuring a smaller complexity compared to the exhaustive method, exhibited in Section 4.2.2.1.

Aiming to evaluate the effect of key parameters of the RF and VLC APs on the proposed JPUA strategy, Figures 10 and 11 illustrates the Normalized average sum secrecy rate vs the K-factor, $\mathcal{K}$, of the RF links and the LED half intensity view angle, $\phi_{1/2}$, respectively. For this purpose, it is considered that the RF transmit power is set to $P_s^{\text{RF}}=0$ and 20 dBm and the nominal optical intensity is set to $p_n^{\text{VLC}}=30$ and 40 dBm, with $K=5$. Specifically in Figure 10,

the best secrecy performance is obtained when $P_s^{\text{RF}}=20$ dBm and $p_n^{\text{VLC}}=40$ dBm, as expected. Also, since the users connected to the VLC AP achieve higher secrecy rates, lower values of the nominal optical intensity present a bigger impact on the sum secrecy rate than reducing the transmit power constraint for the RF AP.

Figure 10 - Normalized average sum secrecy rate versus K-factor, $\mathcal{K}$, for RF transmit power constraint $P_s^{\text{RF}}=0, 20$ dBm and nominal optical intensity $p_n^{\text{VLC}}=30, 40$ dBm, with $K=5$.

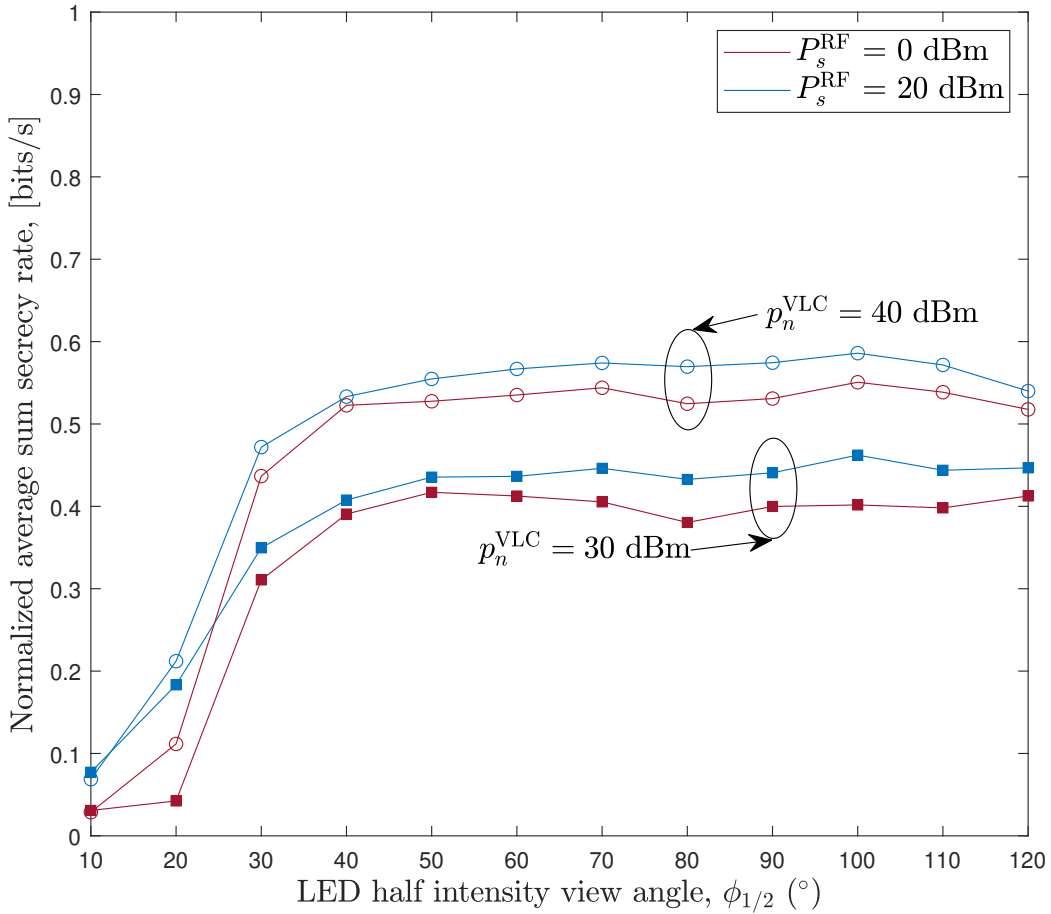


Source: Author

On the other hand, note that smaller values of $\mathcal{K}$ results in a performance improvement. Since the K-factor is defined as a ratio between the LoS and diffuse components of the transmitted signal, it is known that a weaker LoS component indicates a worse channel condition. Accordingly, notice from (37) that, the secrecy capacity of a certain k user connected to the RF AP is given in terms of the channel coefficient of k , the $K^{\text{RF}} - 1$ interferers, and E. Hence, the secrecy capacity is more influenced by the channel condition of the interferers and E. Therefore, lower $\mathcal{K}$ -factors for these channels result in an increased secrecy performance. In addition, since the precoding design of the RF link is also affected by the secrecy capacity of users con-

nected to the RF AP, in spite of the fact that the channel condition of the intended user has deteriorated, constraints (55d), (55e), (55f), and (55g) become looser, thus the secrecy rate achieved with the precoder is increased. However, as expected, this performance enhancement is limited by the capability of Algorithm 1 to solve $\mathcal{P}2$ with strict restrictions on the precoder design of the intended user. In summary, given that smaller values of $\mathcal{K}$ achieve better performance, this result indicates that might not be necessary to place the RF AP inside the indoor environment since an external RF AP could guarantee similar levels of received power.

Figure 11 - Normalized average sum secrecy rate vs LED half intensity view angle, $\phi_{1/2}$ for RF transmit power constraint $P_s^{\text{RF}}=0, 20$ dBm and nominal optical intensity $p_n^{\text{VLC}}=30, 40$ dBm, with $K=5$.



Source: Author

In Figure 11, the LED half intensity view angle, $\phi_{1/2}$, is varied from a narrow beam angle, 10° (JKL, 2009), up to an extra-wide beam angle, 120° (OSRAM, 2022). Given the height of the room and the geometry presented in Figure 6, it is simple to infer that, for the narrow beam angle, the coverage of each VLC AP has a diameter of 88 cm, while for the extra-wide beam angle, the diameter has 8.66 m. Accordingly, given the strikingly small coverage of the VLC

APs when $\phi_{1/2}=10^\circ$, the sum secrecy rate achieved is given by the users that could associate with the RF AP, resulting in the same performance for the curves with $P_s^{\text{RF}}=0$ dBm, and those with $P_s^{\text{RF}}=20$ dBm. On the other hand, as $\phi_{1/2}$ increases, notice that the system's behaviour in terms of P_s^{RF} and p_n^{VLC} matches with the results attained in Figure 10, that is, the best secrecy performance is obtained when $P_s^{\text{RF}}=20$ dBm and $p_n^{\text{VLC}}=40$ dBm, and varying p_n^{VLC} presents a higher influence on the secrecy performance than P_s^{RF} , as expected. In addition, even though increasing the LED view angle guarantees that all users may connect to the VLC APs, it also implies a possibly higher MUI. Despite that issue, the proposed JPUA method is capable to maintain the maximum sum secrecy rate achieved for the network.

6 CONCLUSIONS

In this work, the problem of maximizing the sum secrecy rate of a hybrid RF/VLC network with multiple users in the presence of an eavesdropper is addressed. To tackle this problem, a joint precoding and user association strategy was adopted. The optimization of the RF and VLC precoding was carried out by resorting to CCCP, and the association of users to the APs was solved by modeling according to a coalitional game. The performance of the proposed framework was contrasted to baseline schemes, such as the ZFUA and VLC and RF standalone, and proposed precoding with random association. From the obtained results, it was possible to verify that the proposed framework presents low complexity and is efficient, converging to a nearly optimal solution with a small number of iterations. In addition, the proposed strategy could provide communication to the maximum number of users with notable improvement in the secrecy performance compared to the baseline schemes while also complying with the QoS and power restrictions. Moreover, it was observed that the JPUA strategy is robust in terms of the VLC coverage, being able to maintain a higher secrecy rate for users connected to the VLC AP, despite the higher MUI. Finally, it was shown that the proposed strategy can reach even higher secrecy rates if the channel condition of the interferers and eavesdropper, when both are connected to the RF AP is deteriorated, even though it implies tighter constraints imposed on the precoding design of each legitimate user.

6.1 FUTURE WORKS

To evaluate the sum secrecy rate of the considered hybrid RF/VLC system, it is assumed that both VLC and RF APs have completely knowledge of the eavesdropper's CSI. Therefore, for future works, it could be considered that the APs have an imperfect knowledge of the eavesdropper's CSI. In addition, another possible future work may include the evaluation of the hybrid RF/VLC system in the presence of multiple eavesdroppers.

APPENDIX A - PROOF OF THEOREM I.

Given the received signal at the k th user via the VLC link in (28), and based on (MA et al., 2019), the capacity of a MISO VLC system is defined as the maximum mutual information between the input and output of the channel over all possible input distributions, that is

$$\begin{aligned}
 C_k^{\text{VLC}} &= \max_{f(x_k)} \mathbb{I}(x_k^{\text{VLC}}, y_k^{\text{VLC}}), \\
 &= \max_{f(x_k^{\text{VLC}})} h(y_k^{\text{VLC}}) - h(y_k^{\text{VLC}} | x_k^{\text{VLC}}), \\
 &= \max_{f(x_k^{\text{VLC}})} h \left(\underbrace{\sum_{l=1}^K (\mathbf{h}_k^{\text{VLC}^T} \mathbf{w}_l)^2 x_l^{\text{VLC}} + n_k^{\text{VLC}}}_{\zeta_1} \right) - h \left(\underbrace{\sum_{\substack{l=1 \\ l \neq k}}^K (\mathbf{h}_k^{\text{VLC}^T} \mathbf{w}_l)^2 x_l^{\text{VLC}} + n_k^{\text{VLC}}}_{\zeta_2} \right), \quad (70)
 \end{aligned}$$

where $f(x_k^{\text{VLC}})$ denotes the distribution of x_k^{VLC} . According to (DUONG et al., 2021), by using the entropy power inequality (EPI), $h(\zeta_1)$ is lower-bounded by

$$\begin{aligned}
 h(\zeta_1) &\geq \frac{1}{2} \log_2 \left(\sum_{l=1}^K 2^{2h(\mathbf{h}_k^{\text{VLC}^T} \mathbf{w}_l x_l^{\text{VLC}})} + 2^{2h(n_k^{\text{VLC}})} \right), \\
 &= \frac{1}{2} \log_2 \left(\sum_{l=1}^K (\mathbf{h}_k^{\text{VLC}^T} \mathbf{w}_l)^2 \frac{2^{2h_x^{\text{VLC}}}}{2\pi e \sigma_n^{\text{VLC}^2}} + 1 \right) + \frac{1}{2} \log_2 (2\pi e \sigma_n^{\text{VLC}^2}), \quad (71)
 \end{aligned}$$

and $h(\zeta_2)$ is upper-bounded as

$$\begin{aligned}
 h(\zeta_2) &\leq \frac{1}{2} \log_2 \left(2\pi e \left(\sum_{\substack{l=1 \\ l \neq k}}^K (\mathbf{h}_k^{\text{VLC}^T} \mathbf{w}_l)^2 \sigma_x^{\text{VLC}^2} + \sigma_n^{\text{VLC}^2} \right) \right), \\
 &= \frac{1}{2} \log_2 \left(\sum_{\substack{l=1 \\ l \neq k}}^K (\mathbf{h}_k^{\text{VLC}^T} \mathbf{w}_l)^2 \frac{2\pi e \sigma_x^{\text{VLC}^2}}{2\pi e \sigma_n^{\text{VLC}^2}} + 1 \right) + \frac{1}{2} \log_2 (2\pi e \sigma_n^{\text{VLC}^2}). \quad (72)
 \end{aligned}$$

Next, considering that the eavesdropper wiretaps the data symbol intended to the k th user, (29) is rewritten as

$$y_E^{\text{VLC}} = \mathbf{h}_E^{\text{VLC}^T} \left(\mathbf{w}_k x_k^{\text{VLC}} + \sum_{\substack{l=1 \\ l \neq k}}^K \mathbf{w}_l x_l^{\text{VLC}} + \mathbf{p} \right) + n_k^{\text{VLC}}. \quad (73)$$

Accordingly, the deduction of C_E^{VLC} is analog to C_k^{VLC} . Thus, by combining (71), (72) and after applying the correct substitutions for C_E^{VLC} , (38) is obtained.

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