Optical Interference Alignment for an Indoor Visible Light Communication X-Channel

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Introduction

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Visible light communication (VLC) has emerged as an important complement to conventional radio frequency communication. To achieve high data rate in a VLC network, one popular choice is to adopt arrays of many light-emitting diodes (LEDs). In such networks, it is common that a photo-detector receiver within the coverage of LEDs receives not only the desired stream, but also crosstalk streams with nontrivial power.

Challenges

The desired signal is subject to strong interference in VLC networks.

Introduction

The conventional solutions include

- *Treat interference as noise*: invalid when the interference is too strong;
- *Interference alignment technique:* separate the desired signals from interference leveraging the structure of interference (based on time-varying channel coefficients, multiple receiving antennas and/or frequency selective channels).

Introduction

However, these methods may be inapplicable for VLC since

-i- A single PD is usually employed. (limited signal subspace dimension)

-ii- Visible light channel is typically time-invariant, besides being positive and real.

-iii- Crucial lighting constraints need to be taken into account.

Introduction

Recently, a real interference alignment (RIA) [1] is proposed to explore the potential of single antenna radio frequency systems. Different from regular approaches, RIA imposes no constraints on the channel variation and no more than one receiving antenna is required.

Notice

However, considering the special lighting constraints and characteristics of optical signals, it is non-trivial to apply RIA to optical interference alignment in a VLC network with strong real optical interferences.

[1] Motahari, Abolfazl S., et al. "Real interference alignment: Exploiting the potential of single antenna systems." Information Theory, IEEE Transactions on 60.8 (2014): 4799-4810.

Introduction

Inspired by RIA, we propose an optical interference alignment (OIA) algorithm under lighting constraints. We consider a simple two-user X-channel case for illustrative purpose. The effectiveness of this algorithm is verified with guaranteed decoding error probability.

Optical Interference Alignment

System Model

Consider a two-user optical X-channel model as follows

$$Y_1(t) = h_{11}X_1(t) + h_{12}X_2(t) + N_1(t),$$

$$Y_2(t) = h_{22}X_2(t) + h_{21}X_1(t) + N_2(t),$$

where $X_i(t) \geq 0, i \in \{1, 2\}$ are transmitted intensity (real) signals at transmitter i (TX_i), $Y_i(t), i \in \{1, 2\}$ are received signals at receiver i (RX_i), and noise terms $N_1(t), N_2(t)$ are independently and identically distributed additive white Gaussian noise (AWGN).

Coding Approach

In consideration of interference alignment, the input signals $X_1(t)$,$X_2(t)$ are thus coded

$$X_1(t) = h_{22}\,U_1(t) + h_{12}\,V_1(t),$$

$$X_2(t) = h_{21}\,U_2(t) + h_{11}\,V_2(t),$$

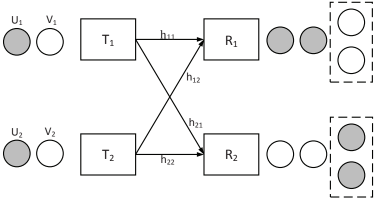

Figure: The system diagram. Transmitter 1 broadcasts independent messages $U_1(t)$, $V_1(t)$, and transmitter 2 broadcasts $U_2(t)$, $V_2(t)$ to the receivers, where $U_1(t)$, $U_2(t)$ are the desired signals for RX1 and $V_1(t)$, $V_2(t)$ are the desired signals for RX2.

Coding Approach

The received signals are further expressed as

$$Y_1 = (h_{11}h_{22})\,U_1 + (h_{21}h_{12})\,U_2 + (h_{11}h_{12})(\,V_1 + \,V_2) + N_1(t),$$

$$Y_2 = (h_{21}h_{12})\,V_1 + (h_{11}h_{22})\,V_2 + (h_{21}h_{22})(U_1 + U_2) + N_2(t),$$

Unlike the typical radio frequency channels, the interference among channels can be stronger especially when the light sources are placed close together to each other, which is a common case. **Treating interference as noise scheme may fail in VLC.**

Coding Approach

Corrupted by very strong interference, the same capacity region is achievable for a multi-user system as with the interference-free case, realized by lattice coding [2]. With OIA, constellation is also restrained on a lattice, while the ambient discrete space is further constrained due to the **nonnegative** and **real** intensity requirement with VLC.

The constellation points take values from

$$\{A_i \cdot \Lambda_{Q_i}\} \triangleq \{0, A_i, \ldots, (Q_i - 1)A_i, Q_i A_i\}, \qquad Q_i \in \mathbb{Z} \quad Q_i, A_i > 0,$$

where Q_i determines the modulation order and A scales the distance between constellation points.

[2] Sridharan, Sriram, et al. "Capacity of symmetric K-user Gaussian very strong interference channels." Global Telecommunications Conference, 2008. IEEE.

Coding Approach

Each message symbol is picked from aforementioned finite discrete set, i.e.

$$U_1 \in \mathbb{U}_1,\ U_2 \in \mathbb{U}_2,\ V_1 \in \mathbb{V}_1,\ V_2 \in \mathbb{V}_2,$$

The combined constellation $\mathbb{T}$ is four-dimensional and denote

$$\mathbb{T} = \mathbb{U}_1 \times \mathbb{U}_2 \times \mathbb{V}_1 \times \mathbb{V}_2, \tag{1}$$

where $\times$ denotes the Cartesian product.

At RX1, for example, interference V_1 and V_2 are aligned and are not decoded. Thus, the associated dimension of its constellation $\mathbb{D}$ is two, i.e.

$$\mathbb{D} = \mathbb{U}_1 \times \mathbb{U}_2, \tag{2}$$

where $\mathbb{D}$ is a collection of $|\mathbb{U}_1 \times \mathbb{U}_2|$ sets $\mathbb{T}$[3], where each set is consisted of $|\mathbb{V}_1 \times \mathbb{V}_2|$ points in $\mathbb{T}$.

[3] $|\cdot|$ denotes cardinality.

Minimum Inter-set Distance

Minimum Inter-set Distance

We denote the desired constellation for RX1 as $\mathbb{D}'$, and $\mathbb{T}'$ is similarly defined. Assume Φ_1 and Φ_2 are two arbitrary distinct sets in $\mathbb{D}'$. The minimum inter-set distance (MID) is defined as

$$d_{min} = \min_{\forall \phi_1 \in \Phi_1, \forall \phi_2 \in \Phi_2} |\phi_1 - \phi_2|. \tag{3}$$

where ϕ_1, ϕ_2 are denoted as constellation points in Φ_1, Φ_2, respectively. The decoding error rate probability is governed by the MID in the medium to high signal-to-noise ratio region.

We refers to the *Khintchine-Groshev* Theorem to demonstrate that the MID in received signal constellation has a lower bound depending on the number of integers (discussed in our paper in detail). The decoding error probability is reducible through real interference alignment.

Communication Algorithm with OIA

OIA Communication Algorithm

The transmitted signals are chosen from the following sets

$$u_1, u_2 = A_1 \cdot \Lambda_{Q_1},$$

$$v_1, v_2 = A_2 \cdot \Lambda_{Q_2}.$$

With VLC, limits on the average emitted optical intensities at both transmitters are imposed as follows

$$P_1 = h_{22} A_1 Q_1 + h_{12} A_2 Q_2,$$

$$P_2 = h_{21} A_1 Q_1 + h_{11} A_2 Q_2.$$

For simplicity, assume the following symmetric channel case

$$h_{22} = h_{11} = h_0,\ h_{12} = h_{21} = h_1, \quad h_0, h_1 \in \mathbb{R}^+$$

$$P_1 = P_2 = P > 0,\ Q_1 = Q_2 = Q \in \mathbb{Z},$$

Crucial lighting constraints are taken into account, as well as decoding error probability requirement. The proposed communication algorithm with OIA is summarized in the following slide.

The parameter negotiation algorithm is briefly listed in right column. Appropriate control factors A_1, A_2 can thus be decided.

We adopt traditional lattice decoding strategy to decode. At the first stage, the received signal is mapped to the most likely point in $\mathbb{T}$. Next, the affine transformation from $\mathbb{T}$ to $\mathbb{D}$ is performed to get the decoding message.

Input: Power constraints: P_1, P_2;
Channel information: $h_{11}, h_{22}, h_{12}, h_{21}$;
Decoding error requirement: E_{t_1}, E_{t_2};
Modulation order: Q_1, Q_2
Output: Control factor: A_1, A_2;
Actual error rate: E_r;
begin
  Initialize A_1, A_2;
  Estimate $d_{t\_i} (i = 1, 2)$ according to E_{t_i} ;
  forall the *receiver i(=1,2)* **do**
    Calculate the set minimum distance d_{min_i};
  end
  if $d_{min\_i} \geq d_{t\_i} (i = 1, 2)$ **then**
    return A_1, A_2;
  else
    if *only one* $d_{min\_i} < d_{t\_i}$ **then**
      Increase A_i by $A_i^{new} = A_i^{old} \cdot \frac{d_{t\_i}}{d_{min\_i}}$;
      The other A_i is adjusted;
      Return to **forall**
    else
      Appropriate A_1, A_2 values do not exist;
      Return;
    end
  end
end

Numerical Results and Conclusions

Numerical Results

We test the performance of the proposed algorithm for a two-user interference channel.

Parameters Setting

Assume that the optical power $P = 20\,W$ is fixed and channel coefficients are produced randomly in the range

$h_0 = \{19 \sim 21\} \times 10^{-5}$,

$h_1 = \{3 \sim 5\} \times 10^{-5}$.

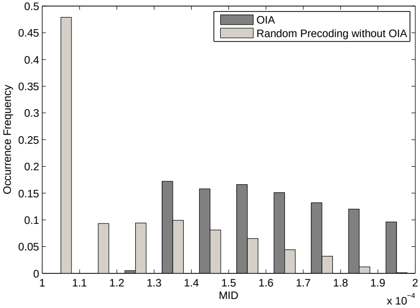

Figure: MID for pairwise channel parameters. As we test 10^3 pairwise channel parameters, the resulting MID distribution reveals that **the MID is significantly increased with OIA**.

Numerical Results

While the power constraints and the channel parameters remain fixed, three cases are compared in our test:

- -i- *OIA:* We calculate the mean bit error rate for a range of receiver SNRs.
- -ii- *Random Precoding Parameters:* The precoding parameters are produced randomly. Thus lattice coding is applied without OIA.
- -iii- *Treating Interference as Noise:* Treat the interference as noise.

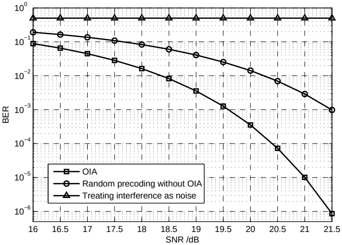

Figure: BER simulation results for different interference management schemes.

Conclusions

Obviously, the decoding-as-noise approach is completely inapplicable for high interference scenario. Further, the OIA algorithm achieves significantly lower BERs than random precoding because of enlarged MID.

Conclusions

We have shown that the optical interference alignment approach provides a communication solution for high interference scenario in VLC where decoding as noise scheme does not work.

We propose a concrete algorithm under lighting constraints and decoding error probability requirements.

Numerical results demonstrate that with OIA the decoding error performance is significantly improved. Our future work includes adapting this algorithm to large scale/massive LED arrays.

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Thank You

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