Spectrum Scarcity and Optical Wireless Communications

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King Abdullah University of Science & Technology (KAUST)
Where is KAUST?

Built on 36 million square meters on the Red Sea in Thuwal 80 Km north of the city of Jeddah.
What is KAUST?

- Graduate Level research university governed by an independent Board of Trustees
- Merit based, open to all from around the world
- Research Centers as primary organizational units
- Research funding and collaborative educational programs
- Collaborative research projects, linking industry R&D and economic development
- Environmentally responsible campus
Electrical Engineering @ KAUST

Electro-Physics

- Faculty members: 18 (+ 2 Adjunct Faculty + 2 Visiting Faculty)
- Postdoc Fellows & Research Scientists: 30
- PhD Students: 75 - MS/PhD: 30 - MS: 15
- Fall 2015: 55 students/933 applicants, 18 countries
- ee.kaust.edu.sa

Systems

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Agenda

• Spectrum Scarcity
  – Radio Frequency (RF) spectrum
  – Mobile traffic growth and spectrum scarcity
  – Potential solutions
• Optical Wireless Communications (OWC)
  – Capacity of OWC systems
  – Secrecy rate of OWC systems with friendly jammers
  – Impact of turbulence and pointing errors
  – Application to cost-effective wireless backhaul
• Concluding Remarks
Spectrum Scarcity

Challenges and Solutions
RF Spectrum

- RF spectrum typically refers to the full frequency range from 3 KHz to 300 GHz.
- RF spectrum is a national resource that is typically considered as an exclusive property of the state.
- RF spectrum usage is regulated and optimized.
- RF spectrum is allocated into different bands and is typically used for:
  - Radio and TV broadcasting
  - Government (defense and public safety) and industry
  - Commercial services to the public (voice and data)
Mobile internet traffic is pushing the capacity limits of wireless networks! => Spectrum exhaustion/deficit
Potential Solution

• More efficient usage of the available spectrum:
  – Multiple antenna systems
  – Adaptive modulation and coding systems
Other Potential Solutions

• More aggressive temporal and spatial reuse of the available spectrum:
  – Cognitive radio systems
  – Femto cells & offloading solutions

• Use of unregulated bandwidth in the upper portion of the spectrum:
  – Microwave and millimeter-wave such as 60 GHz & 90 GHz
  – THz carriers
  – Optical spectrum
Optical Wireless Communications

Towards the Speeds of Wireline Networks
Optical Wireless Communications

- Point-to-point free space optical communications (FSO) using lasers in the near IR band (750 nm -> 1600 nm)
- Visible light communications (know also as Li-Fi for Light-Fidelity) using LEDs in the 390 nm -> 750 nm band.
- NLOS UV communication in the 200 nm to 280 nm band.
FSO Basic Principle

- Connects using narrow beams two optical wireless transceivers in line-of-sight.
- Light is transmitted from an optical source (laser or LED) through the atmosphere and received by a lens.
- Provides full-duplex (bi-directional) capability.
- 3 “optical windows”: 850 nm, 1300 nm, & 1550 nm.
- WDM can be used => 10 Gb/s (4x2.5 Gb/s) over 1 Km & 1.28 Tb/s (32x40 Gb/s) over 210 m.
Why FSO?

- License-free
- Cost-effective
- Behind windows
- Fast turn-around time
- Suitable for brown-field
- Very high bandwidth (similar to fiber)
- Narrow beam-widths (point-to-point)
  - Energy efficient
  - Immune to interference
  - High level of security
FSO Applications

- Initially used for secure military as well as space applications
- Commercial use: Last mile solution, optical fiber back-up, high data rate temporary links, cellular communication backhaul, etc ...

Optical Wireless Communications: Towards the Speeds of Wireline Networks
FSO Challenges & Solutions

- Additive noise (photo-detector) and background radiation (direct, scattered, and reflected sun light) => sensitive detectors + filters + heterodyne detection
- Free space path loss => limited range
- Atmospheric losses depends on relative size of air particles and transmission wavelength (rain, snow, fog, aerosol gases, smoke, low cloud, sand storms, etc ...) => power control + mesh architecture + hybrid RF/FSO
- Atmospheric turbulences => space diversity
- Buildings swaying, motion, and vibrations => tracking systems
Deployment Example: FSO for High-Speed Traders (CNN)

Lasers for high-speed traders

Laser-based communications can facilitate trades at even faster speeds than fiber-optic networks.
Future Applications: Facebook and Google Projects
Optical Wireless Communications: Towards the Speeds of Wireline Networks

Facebook Aquila Project
Underwater Optical Wireless Communications (UOWC)

- Developed a fast simulator to calculate accurately the UWOC channel path loss.
- Demonstrated 1 Gb/s transmission rates over 10 m.

References:
Optical Wireless Communications: Towards the Speeds of Wireline Networks

On-Going Research Directions

• Capacity of OWC channels
  – Bounds and exact results (IM/DD vs. heterodyne detection)
  – Accurate approximations
  – High SNR and low SNR bounds and approximations for the ergodic capacity of FSO turbulent channels subject to pointing error

• Physical layer security for OWC systems
  – Achievable secrecy rate of visible light communication
  – Effect of channel state information on the secrecy rate

• Average probability of error computations over FSO turbulent channels
  – Differentially coherent vs. coherent system performance
  – Asymptotic results (coding and diversity gains)

• Cost effective backhaul design using hybrid RF/FSO technology
Capacity of OWC Channels

IM/DD Case
On-Going Research Directions: Capacity of OWC IM/DD Channels

OWC IM/DD Channel Capacity

- IM/DD channel model

\[ W \xrightarrow{Enc.} X \oplus Y \xrightarrow{Dec.} \hat{W} \]

- Channel input \( X \) (optical intensity).
- Constraints: \( X \in [0, A], \mathbb{E}[X] \leq \varepsilon \).
- Output \( Y = X + Z \).
- \( Z \) Gaussian, zero mean, variance \( \sigma^2 \).
On-Going Research Directions: Capacity of OWC IM/DD Channels

Channel Capacity

For $M$ codewords of length $n$ symbols:

Rate: $\frac{\log_2(M)}{n}$ bits/transmission

Reliable: Error-probability $P_e = P(W \neq \hat{W}) \to 0$ as code-length $n \to \infty$

$$P_e \to 0 \text{ as } n \to \infty$$

Information-theory

Geometry

Densest sphere-packing

$$C = \max_{p(x)} I(X; Y)$$
On-Going Research Directions: Capacity of OWC IM/DD Channels

Sphere Packing Perspective: Classical Case

Upper bound: \[ M \leq \frac{V(B^n_y)}{V(B^n_z)} = \frac{(n(P+\sigma^2))^\frac{n}{2}}{(n\sigma^2)^\frac{n}{2}} = (1 + \text{SNR})^\frac{n}{2} \Rightarrow \]

\[ C = \frac{\log(M)}{n} \leq \frac{1}{2} \log(1 + \text{SNR}) \text{ achievable by random coding [Shannon 48]} \]
Optical Wireless Communications: Towards the Speeds of Wireline Networks

On-Going Research Directions: Capacity of OWC IM/DD Channels

**Sphere Packing Perspective: IM/DD Case**

- \( \mathbb{E}[X] \leq \mathcal{E} \Rightarrow \sum_{i=1}^{n} X_i \leq n\mathcal{E} \) for large \( n \Rightarrow (X_1, \cdots, X_n) \) in a **Simplex**.
- \( \mathbb{E}[Z^2] = \sigma^2 \Rightarrow \sum_{i=1}^{n} Z_i^2 = n\sigma^2 \) for large \( n \Rightarrow (Z_1, \cdots, Z_n) \) on a **Ball**.
On-Going Research Directions: Capacity of OWC IM/DD Channels

Bounds on Capacity


\[
\#\text{codewords} \leq \frac{\text{Vol(Simplex + Ball)}}{\text{Vol(Ball)}}
\]

- Obtained bounds are geometry-independent: Replacing the ball by any other object with the same volume yields the same bound.
On-Going Research Directions: Capacity of OWC IM/DD Channels

Alternative Bounds on Capacity

• Use a geometry-dependent recursive approach.

- Divide the $n$-balls in two groups:
  - $M_n$ balls and portions of balls inside the $n$-simplex: $M_n \leq \frac{\text{Vol(Simplex)}}{\text{Vol(Ball)}}$.
  - $L_n$ portions outside the simplex,

- $L_n \leq M_{n-1}$ the number of $n$-balls that fit on the faces of the simplex.

- Faces are $n-1$-simplexes, intersection of $n$-ball with face is $n-1$-ball.

- Packing problem in $n-1$ dimensions, repeat.

On-Going Research Directions: Capacity of OWC IM/DD Channels

Analytical Results

\[ C_\varepsilon \leq \inf_{\beta, \delta > 0} B_L(\beta, \delta), \]
\[ B_L(\beta, \delta) = \log \left( \beta e^{-\frac{\delta^2}{2\sigma^2}} + \sqrt{2\pi} \sigma Q \left( \frac{\delta}{\sigma} \right) \right) + \frac{1}{2} \frac{\delta}{\sigma} \left( \frac{\delta}{\sigma} \right) e^{-\frac{\delta^2}{2\sigma^2}} \]
\[ + \frac{\delta^2}{2\sigma^2} \left( 1 - Q \left( \frac{\delta + \varepsilon}{\sigma} \right) \right) + \frac{1}{\beta} \left( \delta + \varepsilon + \frac{\sigma}{\sqrt{2\pi}} e^{-\frac{\delta^2}{2\sigma^2}} \right) - \frac{1}{2} \log(2\pi e\sigma^2) \]

Farid & Hranilovic\(^2\): \[ C_\varepsilon \leq \sup_{\alpha \in [0,1]} B_1(\alpha), \]
\[ B_1(\alpha) = \alpha \log \left( \frac{e\varepsilon}{2\sqrt{\pi}\sigma} \right) - \log \left( \alpha \frac{3\alpha}{2} (1 - \alpha)^{\frac{1-\alpha}{2}} \left( 1 - \frac{\alpha}{2} \right)^{1-\frac{\alpha}{2}} \right). \]

Recursive approach: \[ C_\varepsilon \leq \sup_{\alpha \in [0,1]} B_2(\alpha), \]
\[ B_2(\alpha) = B_1(\alpha) + \frac{1}{2} \log \left( \left( \frac{2}{e} \right) \alpha \left( 1 - \frac{\alpha}{2} \right)^{2-\alpha} (1 - \alpha)^{\alpha - 1} \right) \]
<0 \forall \alpha \in (0,1]

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\(^2\) A. Farid and S. Hranilovic, “Capacity bounds for wireless optical intensity channels with Gaussian noise”, Trans. IT, vol. 56, no. 12, Dec. 10
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On-Going Research Directions: Capacity of OWC IM/DD Channels

Numerical Results

- Simpler and tighter than Lapidoth et al. bound
- Tighter than Farid & Hranilovic bound \( B_2(\alpha) \leq B_1(\alpha) \) \( \forall \alpha \in (0, 1] \).
- Characterizes high SNR capacity,
  \[ C = \frac{1}{2} \log \left( \frac{e}{2\pi} \frac{\xi^2}{\sigma^2} \right) \]
On-Going Research Directions: Capacity of OWC IM/DD Channels

FSO Capacity Fitting

Best known rate [Farid & Hranilovic 10]:

- No closed form
- Closed form expression: Important for studying ergodic/outage performance
- Solution: fitting

Global fitting: \( \Psi(\gamma) = \frac{1}{2} \log \left( 1 + c_1 \gamma^2 + \frac{(c_2-c_1)}{\Theta_2(\gamma)} \gamma^2 \right), \quad \gamma = \frac{\xi}{\sigma} \)

- \( c_1, c_2 \): Fixed constants,
- \( \Theta_1(\gamma), \Theta_2(\gamma) \): Polynomials of degrees \( m_1 \) and \( m_2 \), with \( m_1 < m_2 \),

Local fitting: \( \widehat{\Psi}(\gamma) = \frac{d_1}{2} \log(1 + d_2 \gamma^2), \)

- \( d_1, d_2 \): depend on the desired SNR range,
FSO with heterodyne detection (HD)

- Higher rate than IM-DD since it enables complex signaling
- Higher complexity and cost

**HD vs. IM-DD:**

- Amplitude and phase modulation supported (2 dimensions),
- \( \text{SNR gap} = 10 \log_{10} \left( \sqrt{\frac{2\pi}{e}} \gamma \right) \) dB,

**HD-PAM vs. IM-DD:**

- Only amplitude modulation supported (1 dimension),
- Real-valued noise with variance \( \frac{\sigma^2}{2} \), SNR gap \( 10 \log_{10} \left( \frac{4\pi}{e} \right) = 3.32 \) dB,
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On-Going Research Directions: Extensions

• Capacity region of the IM/DD optical broadcast channel
• Capacity bounds for parallel IM/DD optical wireless channels
• Capacity bounds for the Gaussian IM/DD optical multiple-access channel
• Asymptotic ergodic capacity of IM/DD optical over turbulent channels

References:
Ergodic Capacity of OWC Channels

Asymptotic Results
Optical Wireless Communications: Towards the Speeds of Wireline Networks

On-Going Research Directions: Asymptotic Analysis of Ergodic Capacity

Unified SNR Statistics

- Heterodyne Detection
  \[ \gamma = \eta_e l / N_0 \]
  \[ \mu_{\text{heterodyne}} = \mathbb{E}_{\gamma_{\text{heterodyne}}} [\gamma] = \bar{\gamma}_{\text{heterodyne}} = \eta_e \mathbb{E}_I [l] / N_0 \]

- IM/DD
  \[ \gamma = \eta_e^2 l^2 / N_0 \]
  \[ \mu_{\text{IM/DD}} = \mathbb{E}_{\gamma_{\text{IM/DD}}} [\gamma] \mathbb{E}_I^2 [l] / \mathbb{E}_I [l^2] \]
  \[ = \bar{\gamma}_{\text{IM/DD}} \mathbb{E}_I^2 [l] / \mathbb{E}_I [l^2] = \eta_e^2 \mathbb{E}_I^2 [l] / N_0 \]

- Unified
  \[ \gamma_r = \eta_e^r l^r / N_0 \]
  \[ \mu_r = \eta_e^r \mathbb{E}_I^r [l] / N_0 \]

with irradiance \( I = I_a l_p \)
On-Going Research Directions: Asymptotic Analysis of Ergodic Capacity

Asymptotic Ergodic Capacity

- Recall that the irradiance $I = I_a I_p$ and SNR $\gamma$ is proportional to $I^r$
- The asymptotic ergodic capacity can be obtained as [Yilmaz and Alouini, SPAWC’2012]

$$\overline{C} \approx \frac{\partial}{\partial n} \mathbb{E}[\gamma^n] \bigg|_{n=0} = \frac{\partial}{\partial n} \mathbb{E}[I_{a}^{rn}] \bigg|_{n=0} - \frac{2}{\omega_{eq}} \mathcal{M}^{r2}(0)$$

- We need to find the moments of $I_a$ then compute derivatives.

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On-Going Research Directions: Asymptotic Analysis of Ergodic Capacity

Exact Closed-Form Moments

- $I_a I_p = I_R I_L I_p$ where $I_R$, $I_L$, and $I_p$ are independent random processes

- Unified Rician Moments

$$\mathbb{E}[I_R^r] = \left[ \Omega / (k^2 + 1) \right]^r \Gamma (r n + 1) \, _1F_1 \left[ -r n; 1; -k^2 \right]$$

$$\mathbb{E}[\gamma_r^n] = \frac{\eta_e^n \, \mathbb{E}[I_R^r]}{N_0^n} = \mu_r^n \, \mathbb{E} \left[ (I_R I_L I_P)^r \right] / \mathbb{E}^r[I_R I_L I_P]$$

$$= \mu_r^n \mathbb{E}[I_R^r] \mathbb{E}[I_L^r] \mathbb{E}[I_P^r] / (\mathbb{E}^r[I_R] \mathbb{E}^r[I_L] \mathbb{E}^r[I_P])$$

$$= \xi^{2(1-r n)} / \left[ (\xi^2 + r n) (\xi^2 + 1)^{-r n} \right]$$

$$\times \exp \left\{ \frac{r n \sigma^2}{2} (r n - 1) \right\} \frac{1}{(1 + k^2)^r \Gamma (r n + 1)} \mu_r^n \left[ -r n; 1; -k^2 \right]^{-1}$$
Asymptotic Results

- **High SNR**

\[
\overline{C} \approx \ln \{ c \mu_r \} - r \left[ \frac{1}{\xi^2} + \frac{\sigma^2}{2} + \ln \left\{ \frac{\xi^2}{(\xi^2 + 1)} \right\} \right] \\
- \ln \left\{ \frac{k^2}{(1 + k^2)} \right\} - E_1(k^2)
\]

- **Low SNR**

\[
\overline{C} \approx \frac{\xi^{2(1-r)}}{(\xi^2 + r)(\xi^2 + 1) - r} \exp \left\{ \frac{r \sigma^2}{2} (r - 1) \right\} \\
\times (1 + k^2)^{-r} \Gamma(r + 1) \ _1 F_1 \left[ -r; 1; -k^2 \right] c \mu_r
\]
On-Going Research Directions: Asymptotic Analysis of Ergodic Capacity

Asymptotic Results

Figure: Ergodic capacity results for IM/DD technique and varying $k$ at high SNR regime for RLN turbulence
Impact of the Pointing Errors

The Beckman Distribution
Impact of Pointing Errors

• **Effect on Communication:** These pointing errors may lead to an additional performance degradation and are a serious issue in urban areas, where the FSO equipments are placed on high-rise buildings.

• **Model:** The pointing error model developed and parameterized by $\xi$ which is the ratio between the equivalent beam radius and the pointing error jitter can be:
  
  - With pointing error: $\xi$ is between 0 and 7
  - Without pointing error: $\xi \rightarrow \infty$
Original Pointing Error Model

\[ I = |a|_s \]

- The fraction of collected power at the receiver can be approximated by [Farid and Hranilovic, IEEE/OSA JLT 2007]

\[ I_p \approx A_0 \exp \left( \frac{2r^2}{W_{eq}^2} \right) \text{ where } r = [x y]^t, \ r = \sqrt{x^2 + y^2} \]
Free Space Optical (FSO) Communications: Towards the Speeds of Wireline Networks

On-Going Research Directions: Ergodic Capacity Calculations under the Impact of Pointing Errors

Other Pointing Errors Models

- The general model reduces to special cases as follows:

  - No misalignment

  - Figure: $\mu_x = \mu_y = 0$ and $\sigma_x^2 = \sigma_y^2$ (Rayleigh)

  - Figure: $\mu_x = \mu_y$ and $\sigma_y^2 = 0$ (Gaussian)

  - Figure: $\mu_x = \mu_y = 0$ and $\sigma_x^2 \neq \sigma_y^2$ (Hoyt)

  - Figure: $\mu_x \neq \mu_y$ and $\sigma_x^2 = \sigma_y^2$ (Rician)
On-Going Research Directions: Ergodic Capacity Calculations under the Impact of Pointing Errors

Generalized Pointing Error Model

- The fraction of collected power at the receiver can be approximated by [Farid and Hranilovic, IEEE/OSA JLT, 2007]

\[ I_p \approx A_0 \exp \left( \frac{2r^2}{w_{\text{eq}}^2} \right), \text{ where } r = \sqrt{x^2 + y^2} \text{ and } x \sim \mathcal{N}(\mu_x, \sigma_x^2), \quad y \sim \mathcal{N}(\mu_y, \sigma_y^2) \]

\[ f_r(r) = \frac{r}{2\pi\sigma_x\sigma_y} \int_0^{2\pi} \exp \left( - \frac{(r \cos \theta - \mu_x)^2}{2\sigma_x^2} - \frac{(r \sin \theta - \mu_y)^2}{2\sigma_y^2} \right) d\theta. \]

The random variable \( r \) follows a **Beckman** distribution.
Moments of the Irradiance

\[ \mathbb{E}[l^n] = \mathbb{E} \left[ A_0^n \exp \left( -\frac{2nr^2}{w_{zeq}^2} \right) \right] = A_0^n \mathcal{M}_{r^2} \left( -\frac{2n}{w_{zeq}^2} \right) \]

\[ \mathbb{E}[l^n] = \frac{A_0^n \xi_x \xi_y}{\sqrt{(n + \xi_x^2)(n + \xi_y^2)}} \exp \left( -\frac{2n}{w_{zeq}^2} \left[ \frac{\mu_x^2}{1 + \frac{n}{\xi_x^2}} + \frac{\mu_y^2}{1 + \frac{n}{\xi_y^2}} \right] \right), \]

where \( \xi_x = \frac{w_{zeq}}{2\sigma_x} \) and \( \xi_y = \frac{w_{zeq}}{2\sigma_y} \), are the ratio between the equivalent beam width and jitter variance for each direction.

\[ \mathbb{E}[l^n] = \mathbb{E}[l^n] \mathbb{E}[l^n] = A_0^n \mathbb{E}[l^n] \mathcal{M}_{r^2} \left( -\frac{2n}{w_{zeq}^2} \right). \]

\( \mathcal{M}_{r^2}(.) \) is the moment-generating function of the random variable \( r^2 \).
Asymptotic Ergodic Capacity

- The asymptotic ergodic capacity can be obtained as

\[
\frac{C}{\gamma} \approx \frac{\partial}{\partial n} \mathbb{E}[\gamma^n] \bigg|_{n=0} = \frac{\partial}{\partial n} \mathbb{E}[I_a^{\text{rn}}] \bigg|_{n=0} - \frac{2}{w_{zeq}} \mathcal{M}_r'(0)
\]

- The moments of $I_a$ are known for both lognormal (LN) and Gamma-Gamma (ΓΓ). Then, the asymptotic capacity can be written as

\[
\frac{C}{\Gamma\Gamma} \approx \log \left( \frac{\sqrt{(r + \xi_x^2)(r + \xi_y^2)} \Gamma(\alpha) \Gamma(\beta)}{\xi_x \xi_y \Gamma(r + \alpha) \Gamma(r + \beta)} \right) \\
+ \frac{2r}{w_{zeq}^2} \left( \frac{\mu_x^2}{r + \xi_x^2} + \frac{\mu_y^2}{r + \xi_y^2} \right) - \frac{r}{2} \left( \frac{4(\mu_x^2 + \mu_y^2)}{w_{zeq}^2} + \frac{1}{\xi_x^2} + \frac{1}{\xi_y^2} \right) + r\psi(\alpha) + r\psi(\beta)
\]
Free Space Optical (FSO) Communications: Towards the Speeds of Wireline Networks

**On-Going Research Directions:** Ergodic Capacity Calculations under the impact of pointing errors

**Asymptotic Ergodic Capacity**

**Figure:** The ergodic capacity for:

(a) $\xi_x = 6.7$ and $\xi_y = 5.1$
(b) $\xi_x = 6.7$ and $\xi_y = 0.9$
(c) $\xi_x = 0.8$ and $\xi_y = 0.9$

Outage Capacity

• FSO channels are typically viewed as slowly varying channels => Coherence time is greater than the latency requirement

• Outage capacity is considered to be a more realistic metric of channel capacity for FSO systems

• Closed-form expressions are not possible => Importance sampling-based Monte Carlo simulations
Importance Sampling (IS)

\[ P = P(\gamma < \gamma_{th}) = P(I = I_a I_p < I_{th}) = P(y_a + y_p < \varepsilon) \]

where \( y_a = \log(I_a) \), \( y_p = \log(I_p) \), and \( \varepsilon = \log(I_{th}) \)

• IS estimator:

\[ I^* = \frac{1}{N^*} \sum_{n=1}^{N^*} 1(y_{a,n}^*+y_{p,n}^*<\varepsilon)w_{y_a}(y_{a,n}^*)w_{y_p}(y_{p,n}^*) \]

where \( y_{k}^*(.) \sim f_{y_k}^*(.) = \frac{f_{y_k}(.)}{w_{y_k}(.)}, \quad k = a, p \)
IS Exponential Twisting

- Weighting Choice: \( w_{y_k}(x) = e^{-\theta x} M_{y_k}(\theta) \)
  where \( M_{y_k}(\cdot) \) is the MGF of \( y_k \)
- IS Estimator:
  \[
  I^* = \frac{1}{N^*} \sum_{n=1}^{N^*} 1_{(y_{\hat{a},n}+y_{\hat{p},n}<\varepsilon)} e^{-\theta(y_{\hat{a},n}+y_{\hat{p},n})} M_{y_a}(\theta) M_{y_p}(\theta)
  \]
  - \( M_{y_a}(\theta) = E[h_{\theta a}^\theta] = \exp\left(\frac{1}{2} \theta (\theta - 1) \sigma^2_R\right) \) (LN fading)
  - \( M_{y_a}(\theta) = E[h_{\theta a}^\theta] = \frac{(\alpha\beta)^{-\theta} \Gamma(\alpha+\theta)\Gamma(\beta+\theta)}{\Gamma(\alpha)\Gamma(\beta)} \) (G-G fading)
  - \( M_{y_p}(\theta) = E[h_{\theta p}^\theta] = \xi_x \xi_y A_0^\theta \exp\left(-\frac{2\theta}{w_{2eq}^2} \left[ \frac{\mu_x^2 \xi_x^2}{\xi_x^2+\theta} + \frac{\mu_y^2 \xi_y^2}{\xi_y^2+\theta} \right] \right) \sqrt{(\xi_x^2+\theta)(\xi_y^2+\theta)} \)
Optimal $\theta$

• Minimization problem:

$$\min_{\theta} E \left[ 1(y_a + y_p < \epsilon) w_{y_a}^2(y_a, \theta) w_{y_p}^2(y_a, \theta) \right]$$

→ Stochastic optimization problem: Not feasible analytically except for a few simple cases.

→ Alternative: Find a sub-optimal $\theta$:

  – Cumulant generating function:

$$\mu(\theta) = \log \left( E \left[ e^{\theta(y_a + y_p)} \right] \right) = \log(M_a(\theta)) + \log(M_p(\theta))$$

  – Sub-optimal $\theta$:

$$\mu'(\theta) = \epsilon$$
Sub-Optimal $\theta$

- Weak turbulence:

$$\log(A_0) + \frac{\sigma_R^2}{2} (2\theta - 1) - \frac{\xi_x^2 + \xi_y^2 + 2\theta}{2(\xi_x^2 + \theta)(\xi_y^2 + \theta)} - \frac{2\theta}{w_{z_{eq}}^2} \left[ \frac{\mu_x^2 \xi_x^4}{(\xi_x^2 + \theta)^2} + \frac{\mu_y^2 \xi_y^4}{(\xi_y^2 + \theta)^2} \right] = \epsilon$$

- Strong turbulence:

$$\log \left( \frac{A_0}{\alpha\beta} \right) - \frac{\xi_x^2 + \xi_y^2 + 2\theta}{2(\xi_x^2 + \theta)(\xi_y^2 + \theta)} - \frac{2\theta}{w_{z_{eq}}^2} \left[ \frac{\mu_x^2 \xi_x^4}{(\xi_x^2 + \theta)^2} + \frac{\mu_y^2 \xi_y^4}{(\xi_y^2 + \theta)^2} \right] + \psi(\alpha + \theta) + \psi(\beta + \theta) = \epsilon$$

where $\psi(x) = \frac{\Gamma'(x)}{\Gamma(x)}$
Outage Probability

**Outage Probability over LN fading (N=10^8, N_c=10^4)**

- **MC**
- **IS**

**Outage Probability over G-G fading (N=10^8, N_c=10^4)**

- **MC**
- **IS**
Efficiency Indicator

Efficiency indicator over LN fading

Efficiency indicator over G-G fading
Impact of Jitter Unbalance on Outage Probability

Outage Probability over LN fading

Outage Probability over G-G fading
Secrecy Rate of VLC Systems

Friendly Jammers
On-Going Research Directions:

**Improved Achievable Secrecy Rate of Visible Light Communication with Cooperative Jammers**

- Physical layer security (PLS) is a paradigm that aims at securing communications leveraging randomness in fading channels.
- PLS achieves its goal via a sophisticated combination of both coding and signaling techniques.
- PLS has been recognized as a complementary technique to existing cryptographic systems.
- There exists a large body of work on PLS over RF communications.
- Recently, there has been several attempts to extend the previous studies to VLC e.g., [Mostafa & Lampe, JSAC’2015 and Zaid & al., GlobalSIP’2015].

Reference

Consider a VLC network with a transmitter (Alice), a legitimate receiver (Bob), an eavesdropper (Eve) and a (friendly) jammer equipped with Nj light fixtures.

- Alice transmits her data via a single fixture.
- The jammer has no access to data transmitted by Alice.
- Bob and Eve are equipped each with a single photodetector.
On-Going Research Directions:

**System Model (Continued)**

Signals observed by Bob and Eve are given by:

\[
\begin{align*}
  y &= h_{AB} x + h_{JB}^T s + w_B \\
  z &= h_{AE} x + h_{JE}^T s + w_E,
\end{align*}
\]

- $h_{AB}, h_{AE} \in \mathbb{R}_+$ are the channel gains from Alice to Bob and Eve, respectively.
- $h_{JB}, h_{JE} \in \mathbb{R}_{+}^{N_j}$ are the channel gain vectors from the jammer to Bob and Eve, respectively.
- $x \in \mathbb{R}$ is the data signal.
- $s \in \mathbb{R}^{N_j}$ is the jamming signal.
- Both the data and the jamming signals must satisfy an amplitude constraint:

\[
|b| \leq A,
\]

where $b \in \{x, s_1, \ldots, s_{N_j}\}$.

- $w_B$ and $w_E$ are AWGN samples with variance $\sigma^2$, each.
**On-Going Research Directions:**

**Friendly Jamming Scheme**

- Assume that the jammer has CSI of the $h_{JB}$ link.
- He can then design the jamming signal in the orthogonal subspace of $h_{JB}$, denoted by $h_{JB}^\perp$.
- Thus, he induces no interference to the legitimate receiver Bob.
- We only consider a potentially sub-optimal beamforming strategy at the jammer, i.e., $s = w_j$, where $w \in \mathbb{R}^{N_j}$, $w \in h_{JB}^\perp$, $|w_i| \leq 1$, $i = 1, \ldots, N_j$, and $j \in \mathbb{R}$ is a zero mean random jamming symbol, with $|j| \leq A$.
- Then, (1) simplifies to:

\[
\begin{cases}
  y = h_{AB} x + w_B \\
  z = h_{AE} x + (h_{JE}^T w) j + w_E.
\end{cases}
\]

- What is the highest secrecy rate, under constraint (2)?
On-Going Research Directions:

Achievable Secrecy Rate

Assume that $A_{CSI} = \{h_{AB}, h_{JB}, h_{AE}, h_{JE}\}$, $B_{CSI} = \{h_{AB}\}$, $E_{CSI} = \{h_{AB}, h_{JB}, h_{AE}, h_{JE}\}$ and $J_{CSI} = \{h_{JB}\}$. Then, an achievable secrecy rate for the wiretap channel described by (1) is equal to $\max (R_s, 0)$, where $R_s$ is given by:

$$R_s = \frac{1}{2} \log_2 \left( 1 + \frac{\sigma_1^2 h_{AB}^2 e^{2\eta}}{\sigma^2} \right) - \mathbb{h}(V_0)$$

$$+ \frac{1}{2} \log_2 (2 \pi e \sigma_1^2) + \log_2 \left( |h_{JE}^T w| \right) + \eta,$$

where $\mathbb{h}(V_0)$ is the entropy of the random variable (r.v.) $V_0 = h_{AE} X_t + (h_{JE}^T w) J_t$; $X_t$ and $J_t$ follow the truncated Gaussian distribution $\mathcal{N}_{\mathbb{A}}(0, \sigma_1^2)$; $\eta = \log (Z) + \frac{\alpha \phi(\alpha) - \beta \phi(\beta)}{2Z}$, $Z = \Phi(\beta) - \Phi(\alpha)$ with $\beta = \frac{A}{\sigma_1}$ and $\alpha = \frac{-A}{\sigma_1}$.
Visible Light Communications: Towards the Speeds of Wireline Networks

On-Going Research Directions:

Comparison
Visible Light Communications: Towards the Speeds of Wireline Networks

**On-Going Research Directions:**

Eve’s CSI Known Perfectly to the Jammer: Optimal Beamforming

- If $J_{CSI} = \{h_{JB}\}$, the result in Theorem 1 holds true.
- However, if $J_{CSI} = \{h_{JB}, h_{JE}\}$, it is possible to maximize the secrecy rate via an optimal design of $h_{JE}^T w$, for a given $\sigma_1^2$.
- The optimal beamformer $w^*$ is obtained by solving:

$$w^* = \arg \max_w R_s = \arg \max_w h_{JE}^T w$$

$$s.t. \begin{cases} h_{JB}^T w = 0 \\ |w_i| \leq 1, \quad i = 1, \ldots, N_j. \end{cases}$$

(5) is a linear program which can be solved easily.
On-Going Research Directions:

**Eve’s CSI Not Known Perfectly to the Jammer: Robust Beamforming**

- What if the jammer knows Eve’s CSI within a bounded uncertainty?
- Assume Eve exists within a certain bounded area $A_E$ known to the jammer.
- Assume two-dimensional location uncertainty and Eve’s height is fixed and is known.
- Let $H_{A_E}$ be the set of all admissible channel realizations for Eve within the area $A_E$.
- Find $w^*$ which maximizes the worst case secrecy rate:

$$\max_w \min_{h_E \in H_{A_E}} R_s \tag{6}$$

s.t. \[
\begin{align*}
&h_{JB}^Tw = 0 \\
&|w_i| \leq 1, \quad i = 1, \ldots, N_j,
\end{align*}
\]

where $h_E = \begin{bmatrix} h_{AE} \\ h_{JE} \end{bmatrix}$. 
Visible Light Communications: Towards the Speeds of Wireline Networks

On-Going Research Directions:

Eve’s CSI Known Perfectly

(a) $R_{SU}$ (bits/sec/Hz)

(b) $R_{ST}$ (bits/sec/Hz)
On-Going Research Directions:

Eve’s CSI Not Known Perfectly

(a) $R_sU$ (bits/sec/Hz)

(b) $R_sT$ (bits/sec/Hz)
Probability of Error Computation

Comparison M-PSK vs. M-DPSK
On-Going Research Directions:

Average Probability of Error Computations

- Generic Exact and Asymptotic Results over Gamma-Gamma Channels
- Average Performance of Differentially Coherent & Coherent MPSK
On-Going Research Directions: Average Probability of Error Computations

SER Performance of M-PSK and M-DPSK

• Symbol error rate performance of M-PSK and M-DPSK over AWGN are given by [Pawula, TCOM, Sept 1999]

\[
P_{e,\text{MPSK}}(\gamma) = \frac{1}{\pi} \int_0^{\eta\pi} \exp \left( -\frac{\kappa \gamma}{\sin^2 \theta} \right) d\theta
\]

and

\[
P_{e,\text{MDPSK}}(\gamma) = \frac{1}{\pi} \int_0^{\eta\pi} \exp \left( -\frac{\kappa \gamma}{1 + \cos \frac{\pi}{M} \cos \theta} \right) d\theta
\]

with

\[
\eta = (M - 1)/M \quad \text{and} \quad \kappa = \sin^2(\pi/M)
\]
On-Going Research Directions: Average Probability of Error Computations

Asymptotic SER Performance Comparison of M-PSK and M-DPSK

- Well known that MDPSK performs 3 dB worse than MPSK in the Rayleigh fading channels when the SNR is asymptotically large [Ekanayake, TCOM, October 1990]

- Asymptotic SER performance of MDPSK with respect to MPSK over a fading channel with diversity order $t+1$

  $$\text{SNR}_{\text{MDPSK-MPSK}} = \frac{10}{t + 1} \log \left( \frac{g(t)}{h(t)} \right) \text{ dB}.$$ 

  with 

  $$g(t) \triangleq \int_0^\eta \pi (1 + \cos \frac{\pi}{M} \cos \theta)^{t+1} d\theta, \quad h(t) \triangleq \int_0^\eta \pi (\sin^2 \theta)^{t+1} d\theta$$

  and 

  $$\eta = \frac{(M - 1)}{M}$$

- Asymptotic SER performance of MDPSK with respect to MPSK over lognormal turbulence channel

  $$\text{SNR}_{\text{MDPSK-MPSK}} = 10 \log \left( 1 + \cos \frac{\pi}{M} \right) \text{ dB}$$
On-Going Research Directions: Average Probability of Error Computations

Comparison of SER for M-PSK and M-DPSK in Lognormal Fading

**Figure:** Average SER of FSO using MPSK and MDPSK over weak turbulence Lognormal fading channels.

Cost Effective Backhaul Design

Combining Optical Fibers and RF/FSO Systems
On-Going Research Directions: Cost Effective Backhaul Design

Backhaul Design

• An enormous demand for mobile data services is expected in next generation mobile networks (5G).

• Need to significantly increase:
  • Data capacity,
  • Coverage performance,
  • Energy efficiency.

• Move from the traditional single base-station to heterogeneous networks (HetNets).

• Backhaul congestion should be addressed.
On-Going Research Directions: Cost Effective Backhaul Design

**Backhaul Technologies**

- Various technologies are available for the backhaul:
  - Copper links: Low capacity and thus not suitable for 5G.
  - Optical fiber (OF) links: High data rates over long distances however very expensive.
  - Radio-frequency (RF) links: Limited capacity but cost-effective and scalable solution.
  - Free-space optics (FSO) links: High data rates, free to use, and immune to electromagnetic interference but sensitive to weather conditions.

- In order to combine the advantages of RF links (reliability) and FSO links (capacity), the usage of hybrid RF/FSO technology has been proposed.
On-Going Research Directions: Cost Effective Backhaul Design

**Optimization Problem**

- Minimizing network deployment cost under the constraints:
  - Connections between nodes can be either OF or hybrid RF/FSO.
  - Each node has a data rate that exceeds the target data rate.
  - Each node can communicate with any other node through single or multiple hop links (i.e. the graph is connected).
On-Going Research Directions: Cost Effective Backhaul Design

System Parameters

- **d(.,.)**: Distance operator.
- **\(\pi^{(o)}(x)\) and \(\pi^{(h)}(x)\)**: Cost of an OF link and a hybrid RF/FSO over a distance \(x\).
- **\(R^{(o)}(x)\) and \(R^{(h)}(x)\)**: Normalized data rates of an OF and a hybrid RF/FSO links over a distance \(x\).
- **\(\lambda_2\)**: Second smallest eigenvalue of the Laplacian matrix known as the algebraic connectivity.
- **X and Y**: Existence of an OF or a hybrid RF/FSO link.
On-Going Research Directions: Cost Effective Backhaul Design

Backhaul Design Problem Formulation

$$\begin{align*}
\text{min} & \quad \frac{1}{2} \sum_{i=1}^{M} \sum_{j=1}^{M} X_{ij} \pi^{(O)}(d(b_i, b_j)) + Y_{ij} \pi^{(h)}(d(b_i, b_j)) \\
\text{s.t.} & \quad X_{ij} = X_{ji} \\
& \quad Y_{ij} = Y_{ji} \\
& \quad X_{ij} Y_{ij} = 0 \\
& \quad \sum_{j=1}^{M} X_{ij} R^{(O)}(d(b_i, b_j)) + Y_{ij} R^{(h)}(d(b_i, b_j)) \geq 1 \\
& \quad \lambda_2 > 0 \\
& \quad X_{ij}, Y_{ij} \in \{0, 1\}, \quad 1 \leq i, j \leq M,
\end{align*}$$
On-Going Research Directions: Cost Effective Backhaul Design

Close to Optimal Heuristic Solution

- Optimization problem is NP-hard.
- Difficult to solve because:
  - Simultaneous optimization over X and Y.
  - Connectivity condition $\lambda_2$.
- Adopted sub-optimal strategy:
  - Solve the optical fiber only problem.
  - Use the solution to replace the condition on $\lambda_2$.
  - Reformulate the problem as a maximum weight clique problem.

Free Space Optical (FSO) Communications: Towards the Speeds of Wireline Networks

On-Going Research Directions: Cost Effective Backhaul Design

**Total Cost vs. Number of Base Stations**

- **Optimal Planning**
- **OF Only Planning**
- **RF/FSO-OF Planning**

- $\pi^{(h)} = 40,000$
- $\pi^{(h)} = 20,000$
- $\pi^{(h)} = 10,000$
Free Space Optical (FSO) Communications: Towards the Speeds of Wireline Networks

On-Going Research Directions: Cost Effective Backhaul Design

Total Cost vs. Cost of Hybrid RF/FSO

- Optimal Planning
- OF Only Planning
- RF/FSO-OF Planning

Cost of an RF/FSO link vs. Total cost of the network
Free Space Optical (FSO) Communications: Towards the Speeds of Wireline Networks

On-Going Research Directions: Cost Effective Backhaul Design

Percentage of OF Usage vs. Cost of Hybrid RF/FSO

- **Optimal Planning**
- **OF Only Planning**
- **RF/FSO-OF Planning**
Concluding Remarks

Summary and Next Steps?
Conclusion and Current Work

• Spectrum scarcity is becoming a reality
• This scarcity can be relieved through:
  – Heterogeneous networks
  – Extreme bandwidth communication systems
• Need to develop new information theoretical results specific to OWC channels
• Analytical and fast simulation results can be used to perform initial system level trade-offs
• On-going deployment and testing the capabilities of OWC systems in hot & humid desert climate conditions.
Thank You
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