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: 17 (+ 2 Adjunct Faculty + 2 Visiting Faculty)
- Postdoc Fellows & Research Scientists: 30
- PhD Students: 75 - MS/PhD: 30 - MS: 15
- Fall 2015: 55 students out of 933 applicants, 18 countries
- ee.kaust.edu.sa
Agenda

- **Spectrum Scarcity**
  - Radio Frequency (RF) spectrum
  - Mobile traffic growth and spectrum scarcity
  - Potential solutions

- **Free Space Optical (FSO) Communications**
  - Capacity of FSO systems
  - Impact of turbulence and pointing errors
  - Application to 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)
Growth of Mobile Phone Subscribers

Global Mobile Data Traffic

Mobile internet traffic is pushing the capacity limits of wireless networks!
RF Spectrum “Crunch”

• Smartphone usage tripled in 2011.

• Between 2011 and 2016, global wireless data traffic is expected to increase 18 times more.

• Rapid increase in the use of wireless services has lead the problems of RF spectrum exhaustion and eventually RF spectrum 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

• 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.
Developed a fast simulator to calculate accurately the UWOC channel path loss.

Demonstrated 1 Gb/s transmission rates over 10 m.

References:
1- H. Oubei, K. H. Park, C. Li, T. K. Ng, J. Yao, M. -S. Alouini, and B. Ooi, “2.3 Gbit/s underwater wireless optical communications using directly modulated 520 nm laser diode”, Optics Express, August 2015.
Free Space Optical (FSO) Communications

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

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

**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
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 ...
Free Space Optical (FSO) 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
Hybrid RF/FSO Systems

Offers FSO high-speed without giving up RF availability

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

## Commercial Deployment

<table>
<thead>
<tr>
<th>Vendor</th>
<th>Wavelength</th>
<th>Data Rate</th>
<th>Range (@ 10 dB/km)</th>
<th>MIMO</th>
<th>Hybrid RF/FSO</th>
<th>Price Range (USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>fSONA (Canada)</td>
<td>1550nm</td>
<td>Full Duplex with 2.5 Gbps</td>
<td>1 km</td>
<td>No</td>
<td>Yes</td>
<td>8-12K</td>
</tr>
<tr>
<td>LightPointe (USA)</td>
<td>850nm</td>
<td>Full Duplex with 1.25 Gbps</td>
<td>1.6 kms</td>
<td>Yes (2 X 2)</td>
<td>Yes</td>
<td>11-19K</td>
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<tr>
<td></td>
<td>1550nm</td>
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<tr>
<td>RedLine (South-Africa)</td>
<td>850nm</td>
<td>Full Duplex with 1.25 Gbps</td>
<td>0.9 kms</td>
<td>Yes (4 X 4)</td>
<td>Yes</td>
<td>15-24K</td>
</tr>
</tbody>
</table>
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
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Facebook Aquila Project
On-Going Research Directions

• Capacity of FSO 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

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

**FSO IM/DD Channel Capacity**

- IM/DD channel model

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

Channel Capacity

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

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

Reliable: Error-probability $P_e = \mathbb{P}(W \neq \hat{W}) \to 0$ as code-length $n \to \infty$
On-Going Research Directions: Capacity of FSO IM/DD Channels

Sphere Packing Perspective: Classical Case

Upper bound: \( M \leq \frac{V(B_y^n)}{V(B_z^n)} = \frac{(n(P+\sigma^2))^{\frac{n}{2}}}{(n\sigma^2)^{\frac{n}{2}}} = (1 + SNR)^{\frac{n}{2}} \Rightarrow \)

\( C = \frac{\log(M)}{n} \leq \frac{1}{2} \log(1 + SNR) \) achievable by random coding [Shannon 48]
On-Going Research Directions: Capacity of FSO IM/DD Channels

Sphere Packing Perspective: IM/DD Case

\[ E[X] \leq \mathcal{E} \Rightarrow \sum_{i=1}^{n} X_i \leq n\mathcal{E} \text{ for large } n \Rightarrow (X_1, \cdots, X_n) \text{ in a } \text{Simplex}. \]

\[ E[Z^2] = \sigma^2 \Rightarrow \sum_{i=1}^{n} Z_i^2 = n\sigma^2 \text{ for large } n \Rightarrow (Z_1, \cdots, Z_n) \text{ on a } \text{Ball}. \]
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On-Going Research Directions: Capacity of FSO 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.
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On-Going Research Directions: Capacity of FSO 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.

Analytical Results

Lapidtoh et al.\textsuperscript{1}: \( C_\varepsilon \leq \inf_{\beta, \delta > 0} B_L(\beta, \delta) \),

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

Farid & Hranilovic\textsuperscript{2}: \( C_\varepsilon \leq \sup_{\alpha \in [0, 1]} B_1(\alpha) \),

\[
B_1(\alpha) = \alpha \log \left( \frac{e\varepsilon}{2\sqrt{\pi} \sigma} \right) - \log \left( \alpha^{\frac{3}{2}} (1 - \alpha)^{\frac{1}{2}} (1 - \frac{\alpha}{2})^{1 - \frac{\alpha}{2}} \right).
\]

Recursive approach: \( C_\varepsilon \leq \sup_{\alpha \in [0, 1]} B_2(\alpha) \),

\[
B_2(\alpha) = B_1(\alpha) + \frac{1}{2} \log \left( \left( \frac{2}{e} \right)^\alpha \left( 1 - \frac{\alpha}{2} \right)^{2-\alpha} (1 - \alpha)^{\alpha-1} \right) < 0 \ \forall \alpha \in (0, 1)
\]


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

Numerical Results

- Simpler and tighter than Lapidoth et al. bound
- Tighter than Farid & Hranilovic bound \((B_2(\alpha) \leq B_1(\alpha) \quad \forall \alpha \in (0, 1])\).
- Characterizes high SNR capacity, \(C = \frac{1}{2} \log \left( \frac{e}{2\pi} \frac{\xi^2}{\sigma^2} \right)\)

![Graph showing numerical results for different bounds and approximations.](image-url)
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On-Going Research Directions: Capacity of FSO 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: $\Psi(\gamma) = \frac{1}{2} \log \left( 1 + c_1 \gamma^2 + \frac{(c_2-c_1)\Theta_1(\gamma)}{\Theta_2(\gamma)} \gamma^2 \right)$, \quad $\gamma = \frac{\epsilon}{\sigma}$

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

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

- $d_1, d_2$: depend on the desired SNR range,
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**On-Going Research Directions:** Capacity of FSO IM/DD Channels

**FSO Capacity HD vs. IM/DD**

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 \( \frac{\sigma^2}{2} \), \( \text{SNR gap} \ 10 \log_{10} \left( \frac{4\pi}{e} \right) = 3.32 \) dB,
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On-Going Research Directions: Asymptotic Analysis of Ergodic Capacity

**Unified SNR Statistics**

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

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

- **Unified**
  \[
  \gamma_r = \eta_e^r \frac{I^r}{N_0}
  \]
  \[
  \mu_r = \eta_e^r \mathbb{E}_I^r [I] / N_0
  \]
  with irradiance \( I = I_a I_p \)
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]

$$\overline{C} \approx \left. \frac{\partial}{\partial n} \mathbb{E}[\gamma^n] \right|_{n=0} = \left. \frac{\partial}{\partial n} \mathbb{E}[I_a^{rn}] \right|_{n=0} - \frac{2}{w_{zeq}} \mathcal{M}_{r2}'(0)$$

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

On-Going Research Directions: Asymptotic Analysis of Ergodic Capacity

**Exact Closed-Form Moments**

- \( I = I_a I_p = I_R I_L I_p \) where \( I_R, I_L, \) and \( I_p \) are independent random processes

- Unified Rician Moments

\[
\mathbb{E} [I_R^rn] = \left[ \Omega / (k^2 + 1) \right]^{rn} \Gamma (rn + 1) \frac{1}{r} \sum_{n=0}^{\infty} \frac{(-rn)!}{(1-k^2)^n} \frac{1}{(n+1)!} \mu_r^n
\]

\[
\mathbb{E} [\gamma_r^n] = \eta_e^n \mathbb{E} [I_R^rn]/N_0^n = \mu_r^n \mathbb{E} [(I_R I_L I_P)^rn]/\mathbb{E}^rn[I_R I_L I_P]
\]

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

\[
= \frac{\xi^{2(1-rn)}}{(\xi^2 + rn) (\xi^2 + 1)^{-rn}}
\]

\[
\times \exp \left\{ \frac{rn \sigma^2}{2} (rn - 1) \right\} \frac{1}{r} \sum_{n=0}^{\infty} \frac{(-rn)!}{(1-k^2)^n} \frac{1}{(n+1)!} \mu_r^n
\]
Free Space Optical (FSO) Communications: Towards the Speeds of Wireline Networks

On-Going Research Directions: Asymptotic Analysis of Ergodic Capacity

Asymptotic Results

- **High SNR**

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

- **Low SNR**

  \[
  \overline{C} \approx \frac{\xi^{2(1-r)}}{\mu_r} \frac{\xi^2 + r}{\xi^2 + 1}^{-r} \exp \left\{ \frac{r \sigma^2}{2} (r - 1) \right\} \\
  \times \left( 1 + k^2 \right)^{-r} \Gamma \left( r + 1 \right) \text{1}_1F_1 \left[ -r; 1; -k^2 \right] \ c \mu_r
  \]
On-Going Research Directions: Asymptotic Analysis of Ergodic Capacity

**Asymptotic Results**

Comparison between Analytical and Simulation Results at High SNR for IM/DD ($r = 2$)

- **Actual Asymptote**
- **Simulation**
- LN with pointing errors only

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

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

\[ I_p \approx A_0 \exp \left( \frac{2r^2}{w_{Zeq}^2} \right) \] where \( r = [x \ y]^t, \ r = \sqrt{x^2 + y^2} \)
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**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

**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]

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

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

The random variable \( r \) follows a **Beckman** distribution.
On-Going Research Directions: Ergodic Capacity Calculations under the Impact of Pointing Errors

Moments of the Irradiance

\[
E[I^n] = E \left[ A^n_0 \exp \left( -\frac{2nr^2}{w_{zeq}^2} \right) \right] = A^n_0 \mathcal{M}_{r^2} \left( -\frac{2n}{w_{zeq}^2} \right)
\]

\[
E[I^n] = \frac{A^n_0 \xi_x \xi_y}{\sqrt{(n + \xi_x^2)(n + \xi_y^2)}} \exp \left( -\frac{2n}{w_{zeq}^2} \left[ \frac{\mu_x^2}{1 + \frac{n}{\xi_x^2}} + \frac{\mu_y^2}{1 + \frac{n}{\xi_y^2}} \right] \right),
\]

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.

\[
E[I^n] = E[I^n_a]E[I^n_p] = A^n_0 E[I^n_a] \mathcal{M}_{r^2} \left( -\frac{2n}{w_{zeq}^2} \right).
\]

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

- The asymptotic ergodic capacity can be obtained as

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

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

\[
\overline{C}_{|_{ΓΓ}} \approx \log \left( \frac{\sqrt{(r + \xi_x^2)(r + \xi_y^2)} \Gamma(\alpha) \Gamma(\beta)}{\xi_x \xi_y \Gamma(r + \alpha) \Gamma(r + \beta)} \right) \\
+ \frac{2r}{w_{zeq}^2} \left( \frac{\mu_x^2 \xi_x^2}{r + \xi_x^2} + \frac{\mu_y^2 \xi_y^2}{r + \xi_y^2} \right) - \frac{r}{2} \left( \frac{4(\mu_x^2 + \mu_y^2)}{w_{zeq}^2} + \frac{1}{\xi_x^2} + \frac{1}{\xi_y^2} \right) + r\psi(\alpha) + r\psi(\beta)
\]
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 $\xi_y = 0.9$

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 MPSK and MDPSK**

- Symbol error rate performance of MPSK and MDPSK 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

\[\eta = (M - 1)/M \text{ and } \kappa = \sin^2(\pi/M)\]
Free Space Optical (FSO) Communications: Towards the Speeds of Wireline Networks

On-Going Research Directions: Average Probability of Error Computations

Asymptotic SER Performance Comparison of MPSK and MDPSK

• 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

\[
g(t) = \int_0^{\eta \pi} \left(1 + \cos \frac{\pi}{M} \cos \theta\right)^{t+1} d\theta, \quad h(t) = \int_0^{\eta \pi} (\sin^2 \theta)^{t+1} d\theta
\]

and \( \eta = \left( M - 1 \right)/M \)

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

\[
\text{SNR}_{\text{MDPSK-MPSK}} = 10 \log \left( 1 + \cos \frac{\pi}{M} \right) \text{ dB}
\]
Free Space Optical (FSO) Communications: Towards the Speeds of Wireline Networks

On-Going Research Directions: Average Probability of Error Computations

Comparison of SER for MPSK and MDPSK in Lognormal Fading

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

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

**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.
Backhaul Design Problem Formulation

\[
\min \frac{1}{2} \sum_{i=1}^{M} \sum_{j=1}^{M} X_{ij} \pi^{(O)}(d(b_i, b_j)) + Y_{ij} \pi^{(h)}(d(b_i, b_j))
\]

s.t. \( X_{ij} = X_{ji} \)

\( Y_{ij} = Y_{ji} \)

\( X_{ij}Y_{ij} = 0 \)

\[
\sum_{j=1}^{M} X_{ij} R^{(O)}(d(b_i, b_j)) + Y_{ij} R^{(h)}(d(b_i, b_j)) \geq 1
\]

\( \lambda_2 > 0 \)

\( X_{ij}, Y_{ij} \in \{0, 1\}, \ 1 \leq i, j \leq M, \)
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

\( \pi^{(h)} = 40,000 \)
\( \pi^{(h)} = 20,000 \)
\( \pi^{(h)} = 10,000 \)
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

Graph showing the total cost vs. cost of a hybrid RF/FSO link for different planning scenarios.
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Percentage of OF Usage vs. Cost of Hybrid RF/FSO

![Percentage of OF Usage vs. Cost of Hybrid RF/FSO](chart)

- **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
• Analytical and fast simulation results can be used to perform initial system level trade-offs
• On-going deployment and testing the capabilities of FSO systems in hot & humid desert climate conditions.
Thank You
Questions?