Paving the Way Towards 5G Wireless Communication Networks

Mohamed-Slim Alouini
Communication Theory Lab. @ KAUST
ctl.kaust.edu.sa
King Abdullah University of Science & Technology (KAUST)

www.kaust.edu.sa
Where is KAUST?

Built on 36 million square meters on the Red Sea shore 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
EE @ KAUST by the Numbers

- Faculty Members: 21 (+ 2 Adjunct)
- Postdocs/Research Scientists: 30
- Students:
  - PhD: 80
  - MS/PhD: 40
  - MS: 20
  - Fall 2016: 55 Students/1000 Applicants (18 Countries)
EE Tracks: Electro-Physics

Electro-Physics

Talal Al-Attar (PhD-Stanford)
Hakan Bagci (PhD-UIUC)
Hossein Fariborzi (PhD-MIT)
Andrea Fratalocchi (PhD-Roma Tre)
Jr-Hau He (PhD-NTCU)
Muhammad Hussain (PhD-UT Austin)

Jurgen Kosel (PhD-Vienna Univ)
Xiahong Li (PhD-Gatech)
Aurelien Manchon (PhD-Fourier University)
Boon Ooi (PhD-Glasgow)
Khaled Salama (PhD-Stanford)
Atif Shamim (PhD-Carleton)
EE Tracks: Systems

Systems

Tarek Al-Naffouri (PhD-Stanford)
Mohamed-Slim Alouini (PhD-Caltech)
Bernard Ghanem (PhD-Illinois)
Wolfgang Heidrich (PhD-Erlangen)

Meriem Laleg-Kirati (PhD-INRIA)
Jeff Shamma (PhD-MIT)
Basem Shihada (PhD-Waterloo)
Ahmed Sultan (PhD-Stanford)
Ganesh Sundaramoorthi (PhD-Georgia Tech)
Agenda

• 5G Vision
  – Mobile data growth & 5G prospects
  – Challenges and potential solutions

• Some Enabling Technologies:
  – Full duplex radio
  – Massive MIMO
  – Optical wireless communications

• Concluding Remarks
5G Vision

Challenges and Proposed Solutions
Growth of Mobile Phone Subscribers & Data Traffic

Mobile internet traffic growth is pushing the capacity limits of wireless networks!
5G Vision: Challenges and Solutions

From 3G (IMT-2000) to 5G (IMT-2020)

Overview of timeline for IMT development and deployment

- **1985**: SQ Adopted FPLMTS
- **2000**: IMT-2000 Vision
  - Rec. ITU-R M.1457 (1st release)
- **2003**: IMT-Advanced Vision
  - Rec. ITU-R M.1645
- **2012**: IMT-2020 Vision
  - Rec. ITU-R M.2012 (1st release)
- **2015**: IMT-2020 Vision
- **2020**: IMT-2020

(*) Deployment timing may vary across countries.

M.2083-01
Prospects in 5G

• 10-100x higher user data rate (Up to 20 Gbps)
• 10-100x higher number of connected devices (IoT with 50/500 Billions devices)
• 10-100x higher mobile data volume per area
• 10x reduced latency (to 1 ms)
• 10x longer battery life
• 10-100x network energy efficiency (i.e. lower Joules per transmitted bits)
5G Expectations

Enhancement of key capabilities from IMT-Advanced to IMT-2020

- Peak data rate (Gbit/s)
- User experienced data rate (Mbit/s)
- Area traffic capacity (Mbit/s/m²)
- Spectrum efficiency
- Network energy efficiency
- Mobility (km/h)
- Connection density (devices/km²)
- Latency (ms)

IMT-2020

IMT-advanced
5G Vision: Usage Scenarios
RF Spectrum

- RF spectrum typically refers to the full frequency range from 3 KHz to 30 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)
5G Vision: Challenges and Solutions

Increasing the Area Spectral Efficiency

\[
\frac{\text{bits/s}}{Km^2} = \frac{\text{bits/s}}{Hz \cdot \text{node}} \cdot \frac{\text{node}}{Km^2} \cdot Hz
\]

Spectral Efficiency Improvement

Network Densification

More Spectrum

Required Performance \(\sim 1,000 \times\) Current Performance
5G Vision: Challenges and Solutions

Potential Enabling Technologies

- Spectral Efficiency Improvement
  - Massive MIMO
  - Interference Management
  - Full-Duplex Radio
- Network Densification
  - Spectrum Sharing
  - Cloud-RAN
  - Small Cells
- More Spectrum
  - Carrier Aggregation
  - Mm-Wave (60 Ghz)
  - THz Com
  - Optical Wireless Com
Enabling Technologies: Massive MIMO

Massive MIMOs

Base stations are equipped with a very large number of antennas, thereby scaling up the conventional MIMO systems by many orders of magnitude.

**Potential:**
- Increase the capacity by 10 times or more.
- Improve the radiated energy-efficiency: more directed beams.
- Can be built with inexpensive, low-power components.
- Robustness to noise and man-made interference.

**Challenges:**
- Design of compact antenna arrays, while minimizing the fading correlation between antenna elements.
- Acquisition of high dimension CSI.
- Increase in pilot overhead.
- Classical precoding and receiving techniques are very computationally demanding in massive MIMO.
Enabling Technologies: Full-Duplex Radio

Full-Duplex Radio: Potentials and Challenges

**Recovering Spectral-Efficiency**

1. **Bidirectional FD:**
   - ![Bidirectional FD Diagram]

2. **FD BSs:**
   - ![FD BSs Diagram]

3. **FD Relaying:**
   - ![FD Relaying Diagram]

**Self-Interference**

- Received Signal (Attenuated)
- Transmitted Signal (Freshly Generated)
Small Cells & CRANs

- CRAN allows base-stations to connect to centralized cloud computing processors via high-speed links.
- CRANs enable large-scale interference management through coordinated and joint signal processing.
Device-to-Device (D2D) Communication

- **What is D2D?**
  - Users interested in communicating lie close by
  - By-pass BS and communicate directly

- **Benefits:**
  - Lower power consumption
  - Improved latency
  - Increased spatial frequency reuse

- **Challenges:**
  - Increased network interference
  - More complex network management – when should D2D be used?
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** (known also as Li-Fi) using LEDs in the 390 nm -> 750 nm band.

- **NLOS UV communication** in the 200 nm to 280 nm band.
Full Duplex Radio

Towards Simultaneous Tx & Rx
Full-Duplex Radio: Potentials and Challenges

1. Bidirectional FD:
   - Received Signal (Attenuated)
   - Transmitted Signal (Freshly Generated)

2. FD BSs:

3. FD Relaying:
Full Duplex Radio: Towards Simultaneous Tx & Rx

Full-Duplex Radio Examples

2x Capacity

Forward Link 1

\[ f_1 \]

B

Reverse Link 1

\[ f_1 \]

B

Forward Link 2

\[ f_2 \]

B

Reverse Link 2

\[ f_2 \]

2x Rate

Forward Link

\[ f_1 \]

2B

Reverse Link

\[ f_1 \]

2B
Full Duplex Radio: Towards Simultaneous Tx & Rx

Can Up-Link Transmission Survive in Full-Duplex Cellular Environments?
Full Duplex Radio: Towards Simultaneous Tx & Rx

Interference Maps & Implications

• Full duplex deployment in a cellular environment:
  • Almost doubles the down-link rate
  • Significantly degrade the up-link rate
Proposed Solution: $\alpha$-Duplexing + Pulse Shaping

- Allow only partial overlap between up-link and down-link channels
- Use pulse shaping to mitigate cross mode interference
Cross Mode Interference Reduction

• Interesting illustrative example with Sinc & Sinc^2 pulse shaping
System Model

- Actual BSs locations for different operators in downtown London
- 3GPP recommended propagation environment
  \[ PL(r) = 22 \log(d) + 28 + 20 \log(f_c) \]
- Raleigh fading environment
- Uniform user distribution
- Strongest signal power based association
- Single antenna BSs and users
- Truncated channel inversion power control in the uplink and fixed transmit power in the uplink

Reference:
Results and Discussion

- Full duplex communication almost doubles the downlink rate at the expense of more than 1000-fold degradation in the uplink rate.
- $\alpha$-duplexing balances the tradeoff between the uplink and downlink performance and there is an optimal $\alpha$ that balances this tradeoff.
- For the optimal $\alpha$, $\alpha$-duplexing harvests simultaneous improvement of 30% for each of the uplink and downlink rates.
DETECTION ALGORITHMS FOR MASSIVE MIMO ON A GPU PLATFORM: A PERFORMANCE-COMPLEXITY TRADEOFF

M. -A. Arfaoui, H. Ltaief, Z. Rezki, M. -S. Alouini, and D. Keyes, "Efficient sphere detector algorithm for massive MIMO using GPU hardware accelerator", in Proc. of International Conference on Computational Science (ICCS'2016), San Diego, California, June 2016.
Massive MIMO Technology

- deployment of antenna arrays with few hundreds of antennas.
- Extract all the benefits of conventional multiple-input multiple-output (MIMO), but on a large scale.
- A key to enable the development of next generation data networks.

New technology $\Rightarrow$ New challenges.

Challenges

- High complexity of channel estimation, synchronization, optimal decoding algorithms, etc.
- Achieving real-time signal processing.

Idea: Leverage the high performance computing of graphic processor units (GPUs).
An $M \times N$ MIMO system ($M$ transmit antennas and $N$ receive antennas) is modeled as

$$y = H \times s + n$$  \hspace{1cm} (1)$$

where

- $y = [y_1, y_2, ..., y_N]^T$ is the received signal.
- $H = (H_{ij})_{NM}$ is the $N \times M$ channel matrix whose elements are i.i.d. and distributed according to a complex circularly symmetric Gaussian $\mathcal{CN}(0, \sigma_H^2)$.
- $s = [s_1, s_2, ..., s_M]^T \in \mathcal{S}^M$ is the transmitted signal, where $\mathcal{S}$ is the set of constellation symbols which depends on the modulation scheme.
- $n = [n_1, n_2, ..., n_N]$ is the noise vector whose elements are i.i.d. and distributed according to a complex circularly symmetric Gaussian $\mathcal{CN}(0, \sigma^2)$.
Let $H_{\text{inv}}$ be an $M \times N$ linear detector matrix which depends on the channel $H$. To retrieve the transmitted vector $s$, the received signal $y$ is processed as follows

$$y_r = H_{\text{inv}}^H \times y$$  \hspace{1cm} (2)

The three conventional linear decoders are maximum ratio combining (MRC), zero forcing (ZF) and minimum mean square error (MMSE) where for

- **MRC**: $H_{\text{inv}} = H$
- **ZF**: $H_{\text{inv}} = H(H^H H)^{-1}$
- **MMSE**: $H_{\text{inv}} = H(H^H H + \frac{1}{SNR} I)^{-1}$, where $SNR$ is the transmit signal to noise ratio and $I$ is the identity matrix.

The structure of the linear decoders is based on the matrices product and the matrices inversion. Consequently, their complexity is equal to $O(M^3)$. 
Non-linear Decoders

Maximum Likelihood Decoder (MLD)
- Maximizing the probability of correctly estimating $s$ which is equivalent to

$$ s_d = \arg \min_{s \in S^M} \| y - Hs \|^2 $$  \hspace{1cm} (3)

- Good performance in terms of bit error rate (BER), but high algorithmic complexity, $O(|S|^M)$, especially when $M$ and/or $|S|$ go(es) large.

Sphere Decoder (SD)
- SD is a sub-optimal alternative to MLD and consists on solving (3) over a restricted set $\mathcal{L}_M \subseteq S^M$ given by

$$ \mathcal{L}_M = \{ s \in S^M, \| y - Hs \|^2 \leq r^2 \} $$  \hspace{1cm} (4)

- Algorithmic complexity: $O(|S|^\gamma M)$, where $\gamma \in [0, 1]$. 

36
The algorithmic complexity of DFS and BFS is the same. However, BFS can be implemented as a parallel algorithm which makes it more suitable for the GPU platform than DFS.

Figure: sphere decoder problem illustrated as a tree-search problem for $M = 3$ and BPSK modulation ($\mathcal{S} = \{-1, 1\}$)
Performances of SD and Linear Decoders for a $50 \times 25$ MIMO System and BPSK Modulation

(a) BER versus SNR

(b) Execution time versus SNR
Performances of SD for a $50 \times 25$ MIMO system and Different Modulations

(c) BER versus SNR

(d) Execution time versus SNR
Performances of SD for 4-QAM Modulation and $30 \times 10$, $40 \times 10$ and $50 \times 25$ MIMO Systems

(e) BER versus SNR

(f) Execution time versus SNR
Optical Wireless Communications

Towards the Speeds of Wireline Networks
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 (known 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.
• 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
Optical Wireless Communications: Towards the Speeds of Wireline Networks

**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...
FSO Challenges & Solutions

- Atmospheric losses depend on the 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
Optical Wireless Communications: Towards the Speeds of Wireline Networks

Deployment Example: FSO for High-Speed Stock Trading (CNN)

Mike Persico
CEO, ANOVA TECHNOLOGIES
Future Applications: Facebook and Google Projects

Facebook Will Build Drones and Satellites to Beam Internet Around the World

Image: Internet.org
Facebook Aquila Project
Underwater Optical Wireless Communications (UOWC)

- Developed a fast simulator to calculate accurately the UWOC channel path loss.
- Demonstrated 5 Gb/s transmission rates over 10 m.

References:
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, approximations, fast simulations for the ergodic/outage capacity of turbulence channels subject to pointing errors
  - Multi-user scenarios
  - Secrecy constraints

- Design of Optical MIMO systems
  - Limitations of optical MIMO systems
  - Improved mirror aided receivers

- Average probability of error computations over FSO turbulence 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 \( P_e = \mathbb{P}(W \neq \hat{W}) \rightarrow 0 \) as code-length \( n \rightarrow \infty \)
On-Going Research Directions: Capacity of OWC IM/DD Channels

Sphere Packing Perspective: Classical Case

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

\[
C = \frac{\log(M)}{n} \leq \frac{1}{2} \log(1 + SNR) \text{ achievable by random coding [Shannon 48]}
\]
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

• Bounds using the Steiner-Minkowski formula [Farid & Hranilovic, IEEE Trans. IT, Dec 2010]

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

• Obtained bounds are \textit{geometry-independent}: Replacing the ball by any other object with the same volume yields the same bound.
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: \( M_n \leq \frac{\text{Vol}(\text{Simplex})}{\text{Vol}(\text{Ball})} \).
  - \( L_n \) 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

Lapidtoh et al.\(^1\): \(C_E \leq \inf_{\beta, \delta > 0} B_L(\beta, \delta),\)

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

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

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

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

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

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


\(^2\) 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 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,
  $C = \frac{1}{2} \log \left( \frac{e}{2\pi} \frac{\varepsilon^2}{\sigma^2} \right)$
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: \( \Psi(\gamma) = \frac{1}{2} \log \left( 1 + c_1 \gamma^2 + \frac{(c_2 - c_1) \Theta_1(\gamma)}{\Theta_2(\gamma)} \gamma^2 \right) \), \( \gamma = \frac{\xi}{\sigma} \)

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

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

- \( d_1, d_2 \): depend on the desired SNR range,
Optical Wireless Communications: Towards the Speeds of Wireline Networks

On-Going Research Directions: Capacity of OWC 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 \( \frac{\sigma^2}{2} \), SNR gap \( 10 \log_{10} \left( \frac{4\pi}{e} \right) = 3.32 \) dB,
Optical Wireless Communications: Towards the Speeds of Wireline Networks

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:
Capacity of OWC Turbulence Channels

Asymptotic Results and Efficient Simulations
On-Going Research Directions: Asymptotic Analysis of Ergodic Capacity

**Unified SNR Statistics**

- **Heterodyne Detection**

  \[ \gamma = \eta_e I / N_0 \]

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

- **IM/DD**

  \[ \gamma = \eta_e^2 I^2 / N_0 \]

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

- **Unified**

  \[ \gamma_r = \eta_e^r I^r / N_0 \]

  \[ \mu_r = \eta_e^r \mathbb{E}_I^r [I] / N_0 \]

  with irradiance \( I = I_a I_p \)
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]

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

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

Optical Wireless Communications: Towards the Speeds of Wireline Networks

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

\[
\mathbb{E} [I^n_R] = \left[ \frac{\Omega}{(k^2 + 1)} \right]^n \Gamma (r n + 1) \ _1F_1 [-r n; 1; -k^2]
\]

\[
\mathbb{E} [\gamma^n_r] = \eta^n_e \mathbb{E} [I^n_R] / N_0^n = \mu^n_r \mathbb{E} [(I_R I_L I_P)^n] / \mathbb{E} [I^n_R I_L I_P]
\]

\[
= \mu^n_r \mathbb{E} [I^n_R] \mathbb{E} [I^n_L] \mathbb{E} [I^n_P] / (\mathbb{E} [I^n_R] \mathbb{E} [I^n_L] \mathbb{E} [I^n_P])
\]

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

\[
\times \exp \left\{ \frac{r n \sigma^2}{2} (r n - 1) \right\} \frac{\ _1F_1 [-r n; 1; -k^2]}{(1 + k^2)^{r n} \Gamma (r n + 1)} \mu^n_r
\]
Optical Wireless Communications: Towards the Speeds of Wireline Networks

On-Going Research Directions: Asymptotic Analysis of Ergodic Capacity

Asymptotic Results

- High SNR

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

- Low SNR

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

**Asymptotic Results**

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

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

\[ I = |I_a| \lambda \]

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

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

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

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]

\[ l_p \approx A_0 \exp \left( \frac{2r^2}{w_{\text{eq}}^2} \right) \]

where \( r = \sqrt{x^2 + y^2} \) 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

\[ E[I^p_n] = E \left[ A_0^n \exp \left( -\frac{2nr^2}{w_{z_{eq}}^2} \right) \right] = A_0^n \mathcal{M}_r 2 \left( -\frac{2n}{w_{z_{eq}}^2} \right) \]

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

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

\[ E[I^n] = E[I^a_n]E[I^p_n] = A_0^n E[I^a_n] \mathcal{M}_r 2 \left( -\frac{2n}{w_{z_{eq}}^2} \right). \]

\( \mathcal{M}_r 2(.) \) 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

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

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

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

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)

\[ P(\gamma < \gamma_{th}) = P(l = l_a I_p < l_{th}) = P(y_a + y_p < \varepsilon) \]

where \( y_a = \log(l_a) \), \( y_p = \log(l_p) \), and \( \varepsilon = \log(l_{th}) \)

- 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 \( y^*_k(\cdot) \sim f^*_y(\cdot) = \frac{f_{y_k}(\cdot)}{w_{y_k}(\cdot)}, \quad k = a, p \)
IS Exponential Twisting

• Weighting Choice: \( w_{y_k}(x) = e^{-\theta x} M_{y_k}(\theta) \)
where \( M_{y_k}(.) \) is the MGF of \( y_k \)

• IS Estimator:

\[
I^* = \frac{1}{N^*} \sum_{n=1}^{N^*} 1_{(y_{a,n}+y_{p,n}<\epsilon)} e^{-\theta(y_{a,n}+y_{p,n})} M_{y_a}(\theta)M_{y_p}(\theta)
\]

\( M_{y_a}(\theta) = E[h_a^\theta] = \exp(\frac{1}{2} \theta(\theta - 1) \sigma^2_R) \) (LN fading)

\( M_{y_a}(\theta) = E[h_a^\theta] = \frac{(\alpha\beta)^{-\theta} \Gamma(\alpha+\theta)\Gamma(\beta+\theta)}{\Gamma(\alpha)\Gamma(\beta)} \) (G-G fading)

\( M_{y_p}(\theta) = E[h_p^\theta] = E[h_p^\theta] = \frac{\xi_x \xi_y A_0^\theta \exp\left(-\frac{2\theta}{w_{zeq}} \frac{\mu_x^2 \xi_x^2 + \mu_y^2 \xi_y^2}{\xi_x^2 + \theta + \xi_y^2 + \theta}\right)}{\sqrt{(\xi_x^2 + \theta)(\xi_y^2 + \theta)}} \)
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:
  \[
  \log(A_0) + \frac{\sigma_R^2}{2} (2\theta - 1) - \frac{\xi_x^2 + \xi_y^2 + 2\theta}{2(\xi_x^2 + \theta)(\xi_y^2 + \theta)} - \frac{2\theta}{w_{zeq}} \left[ \frac{\mu_x^2 \xi_x^4}{(\xi_x^2 + \theta)^2} + \frac{\mu_y^2 \xi_y^4}{(\xi_y^2 + \theta)^2} \right] = \epsilon
  \]

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

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

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

\( \sigma_y = \sigma_x \)
\( \sigma_y = 1.5 \sigma_x \)
\( \sigma_y = 2 \sigma_x \)
Mirror-Aided Non-Imaging Receiver for Optical MIMO Systems

New Designs for VLC Systems
Optical Wireless MIMO in VLC

- MIMO systems in FSO typically exploit diversity gain over fading due to the atmospheric turbulence.
- In VLC, MIMO schemes are now considered in some applications to increase the data rates (exploiting multiplexing gain).

Indoor MIMO-VLC  Short-range MIMO-VLC  Multi-user MIMO-VLC
Limitation in Optical MIMO

• High Channel Correlation
  – Usually, the IM/DD channels do not provide rich scattering environment.
  – In this case, spatial-multiplexing MIMO remains a challenge because of the resulting highly correlated (ill-conditioned) channel matrix.
  – For example
    • In a symmetric scenario, when the channel matrix is $H = \begin{bmatrix} 1 & 0.9 \\ 0.9 & 1 \end{bmatrix}$, two eigenvalues are 1.9 and 0.1.
Advanced Receiver Structure

• To reduce the channel correlation

[Ying et al., JSAC’2015]
Advanced Receiver Structure

All existing receivers focused on reducing the channel gain in specific directions to reduce the correlation!

Motivation

- To further reduce the channel correlation, we would like to decrease the channel gains in one specific direction, while increasing those in other specific directions.
- Mirror at the receiver can block the light beams in one specific direction, while reflecting into photodetectors in other specific directions.

Goal

Design a new receiver exploiting a mirror.
System Model

- Two-dimensional 2×2 indoor MIMO-VLC system

Channel gain

\[
h_{ji} = \frac{(m+1)A_{ji}}{2\pi d_{ji}^2} \cos^m \alpha_{ji} \cos^k \beta_{ji}, \quad |\alpha_{ji}| \leq \frac{\pi}{2}, \quad |\beta_{ji}| \leq \frac{\text{FoV}}{2}
\]
Mirror Diversity Receiver

- Proposed receiver is equipped with double-sided mirror between two PDs.
  - Double-sided mirror can destructively reduce the channel gain from a specific direction by blocking the light as well as constructively enhance that from other directions by receiving the reflected lights in the mirror.
  - Considering effective active area where is affected by a mirror, channel gain of each path can be computed.
Performance of MDR in MIMO-VLC

• Using classical capacity formula

\[
C = \frac{1}{2} \log_2 \det \left| I + \rho \tilde{H} \tilde{H}^T \right|
= \frac{1}{2} \log_2 \prod_{m=1}^{2} (1 + \rho \lambda_m)
= \frac{1}{2} \log_2 \left( 1 + \rho(\xi_1 \tilde{A}_{11} + \xi_2 \tilde{A}_{22}) + \rho^2 \xi_1 \xi_2 (\tilde{A}_{11} \tilde{A}_{22} - \tilde{A}_{12} \tilde{A}_{21}) \right)
\]

• Using bit error rate formula for $M$-ary PAM

\[
BER \approx \frac{M - 1}{M} \sum_{m=1}^{2} Q \left( \sqrt{\frac{6\rho \lambda_m \log_2 M}{(M^2 - 1)}} \right)
\]

<table>
<thead>
<tr>
<th>Notation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$</td>
<td>average electrical signal-to-noise ratio (SNR) per LED</td>
</tr>
<tr>
<td>$\lambda_m$</td>
<td>eigenvalues of the channel matrix</td>
</tr>
<tr>
<td>$\xi_t$</td>
<td>$\frac{(m+1)}{2\pi r^2} \cos^m \alpha_t \cos^k \beta_t u_t$</td>
</tr>
<tr>
<td>$u_t$</td>
<td>$\begin{cases} 1, &amp; \text{if }</td>
</tr>
</tbody>
</table>
Numerical Results for Capacity

Experiment for MDR

Consider all receivers, i.e., SSR, LBR, ADR (facing each LEDs) and proposed MDR.

Experimental Result for BER

The bit error rate as a function of the electrical SNR per LED in SSR, LBR, ADR, and the proposed MDR at position $x = 0$. 
Angle-aided Mirror Diversity Receiver

• MDR can be combined with an angle diversity receiver

AMDR exploits the angle diversity by tilting the receiver plane with the elevation angle $\beta_\alpha$ as well as the mirror diversity by deploying the mirror with the height $h_M$. 
Numerical Results for BER

Bit error rate as a function of electrical SNR per LED $\rho$ in LBR, ADR, MDR and the proposed AMDR at the receiver position at $x = 0$. It corresponds to the case 1 in Table.

Bit error rate as a function of electrical SNR per LED $\rho$ in LBR, ADR, MDR and the proposed AMDR at the receiver position at $x = 1$. It corresponds to the case 4 in Table.
Discussion

• Extension to general MIMO-VLC

  – We can arrange our proposed MDR isotropically to obtain directivity and then place the mirrors in the middle of multiple PDs.
  
  – Analysis of the channel matrix and system performance in a general MDR model will be our next project.
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

ctl.kaust.edu.sa