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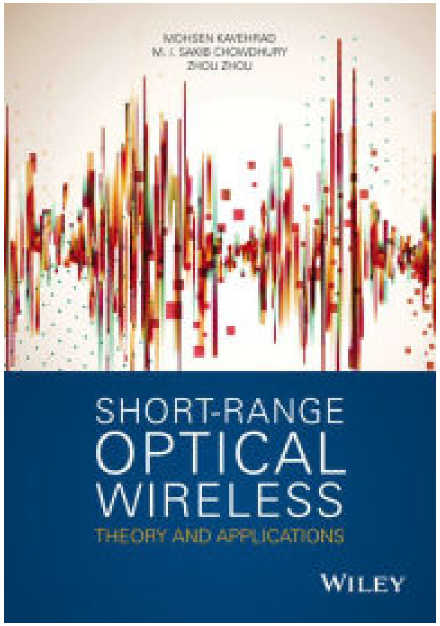
Optical Wireless: Theory and Applications



Mohsen Kavehrad (FIEEE)
Center on Information and Communications Technology
The Pennsylvania State University
Electrical Engineering Department
University Park, PA, 16803
mkavehrad@psu.edu

2015 IEEE International Conference on Wireless for Space and Extreme Environments
Orlando, Florida
December 2015

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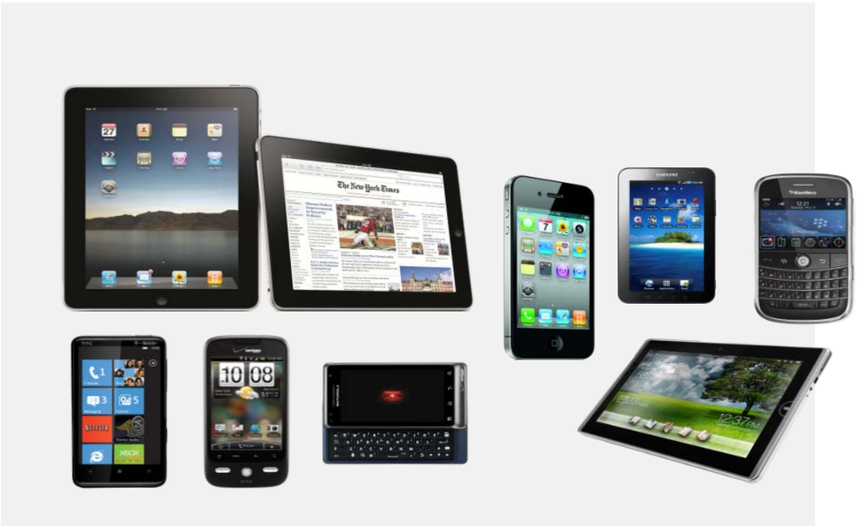
Mobility, Video and cloud computing are CHANGING COMMUNICATIONS FUNDAMENTALLY



Mobility

Cloud Computing

181% TABLET GROWTH

Gartner predicted that tablet sales will grow 181% in 2011 to 54.8M, many of which are built to take advantage of mobile 3G and 4G networks.

1B MOBILE DEVICES

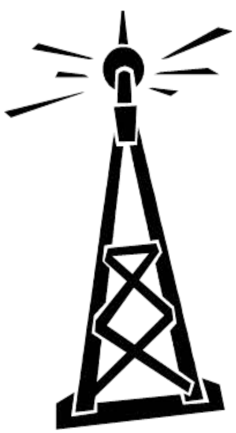
According to IDC we will reach 1 billion mobile devices in 2013. Morgan Stanley tells us we will reach 10B mobile devise in 2050.

62% CLOUD SERVER REVENUE INCREASE

According to IDC's cloud computing survey, server revenue in the private cloud category will grow from $7.3 billion in 2009 to $11.8 billion in 2014, or about 62 percent.

600 Terabytes of Wireless Data per Month !

1.4 Million Base Stations



5 Billion Cell Phones

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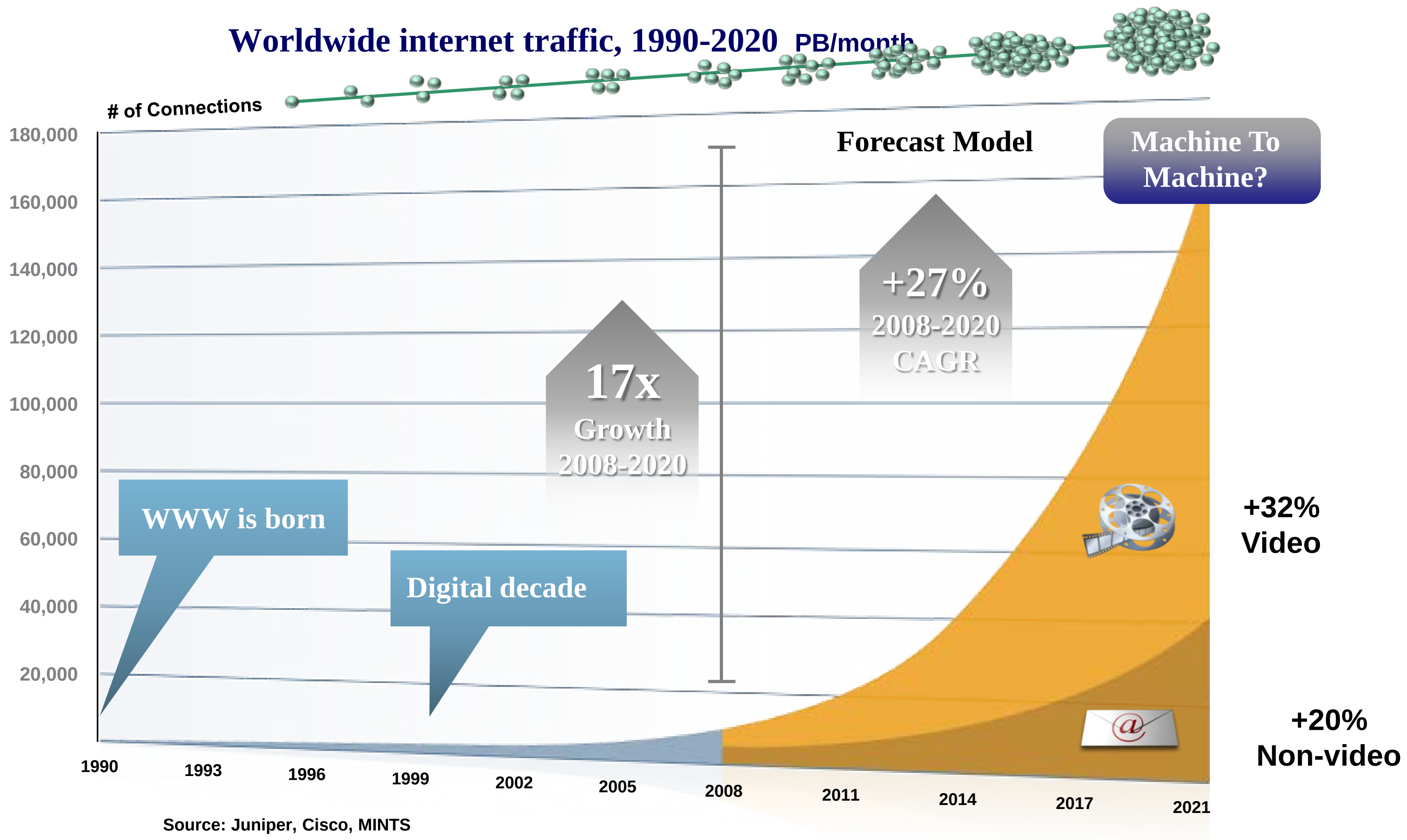
THE PROBLEM: UNPRECEDENTED TRAFFIC



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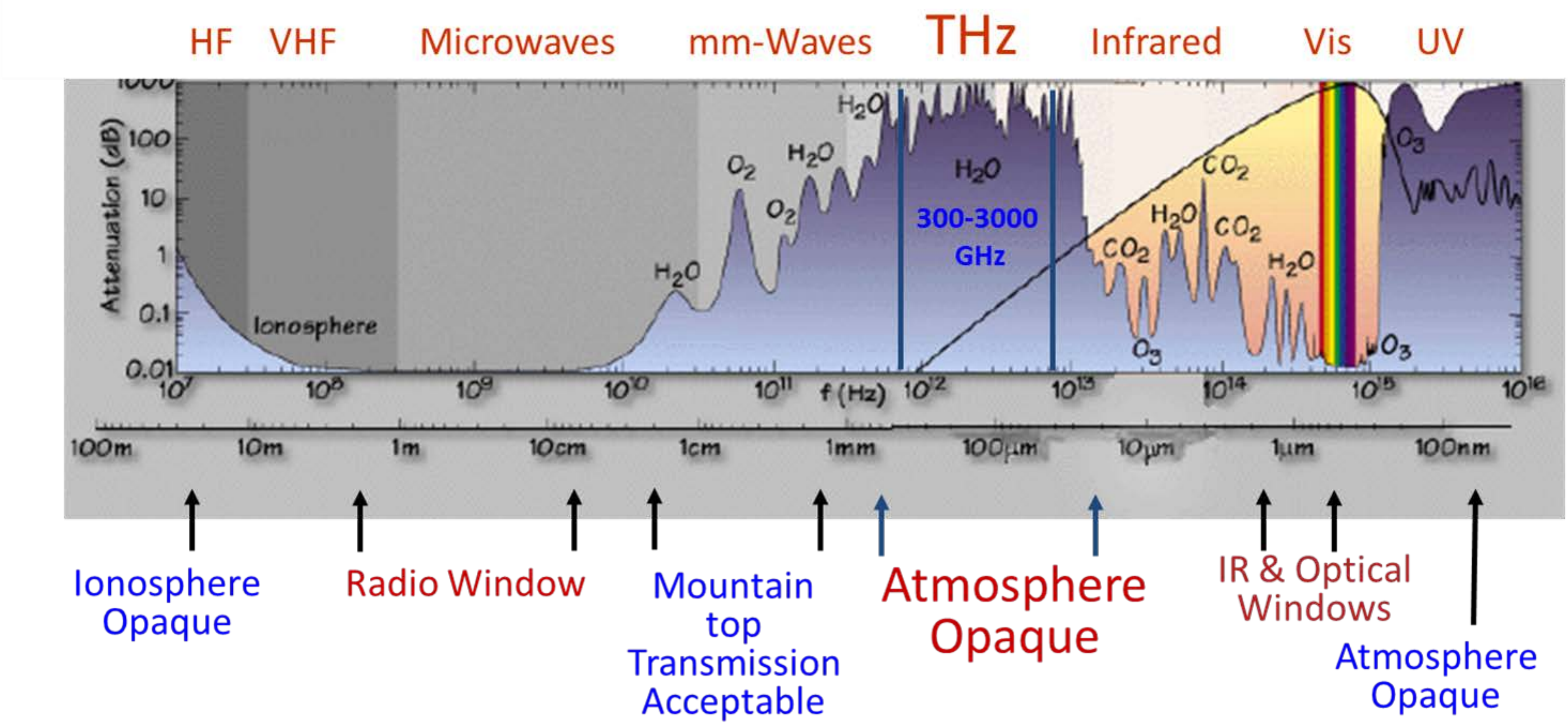
Atmospheric Transmission



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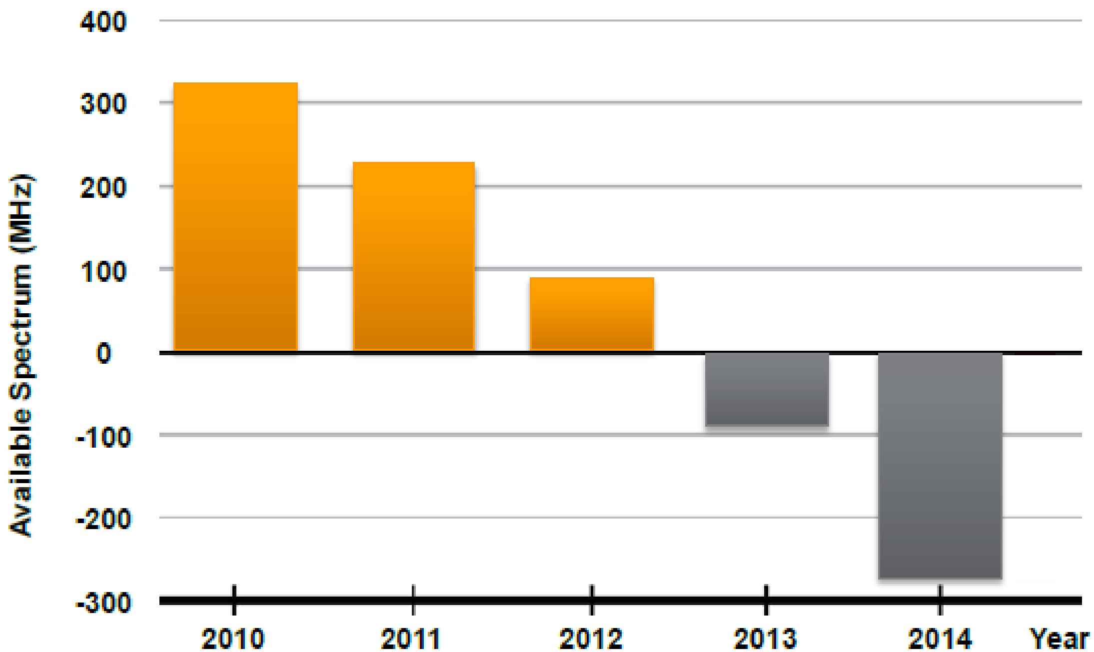
The Point of Wireless Disconnect



The FCC projects a spectrum deficit for wireless communications by 2013

Source: GIIC Point of View: Wireless Point of Disconnect, San Diego, Oct. 2011

Approaches to solutions

- Cognitive radio
- Use of microwave & lower THz-spectrum
- Use of unregulated bandwidth in the upper portion of the EM spectrum

→ Optical wireless communication (OWC)

→ Infrared, visible and ultraviolet light

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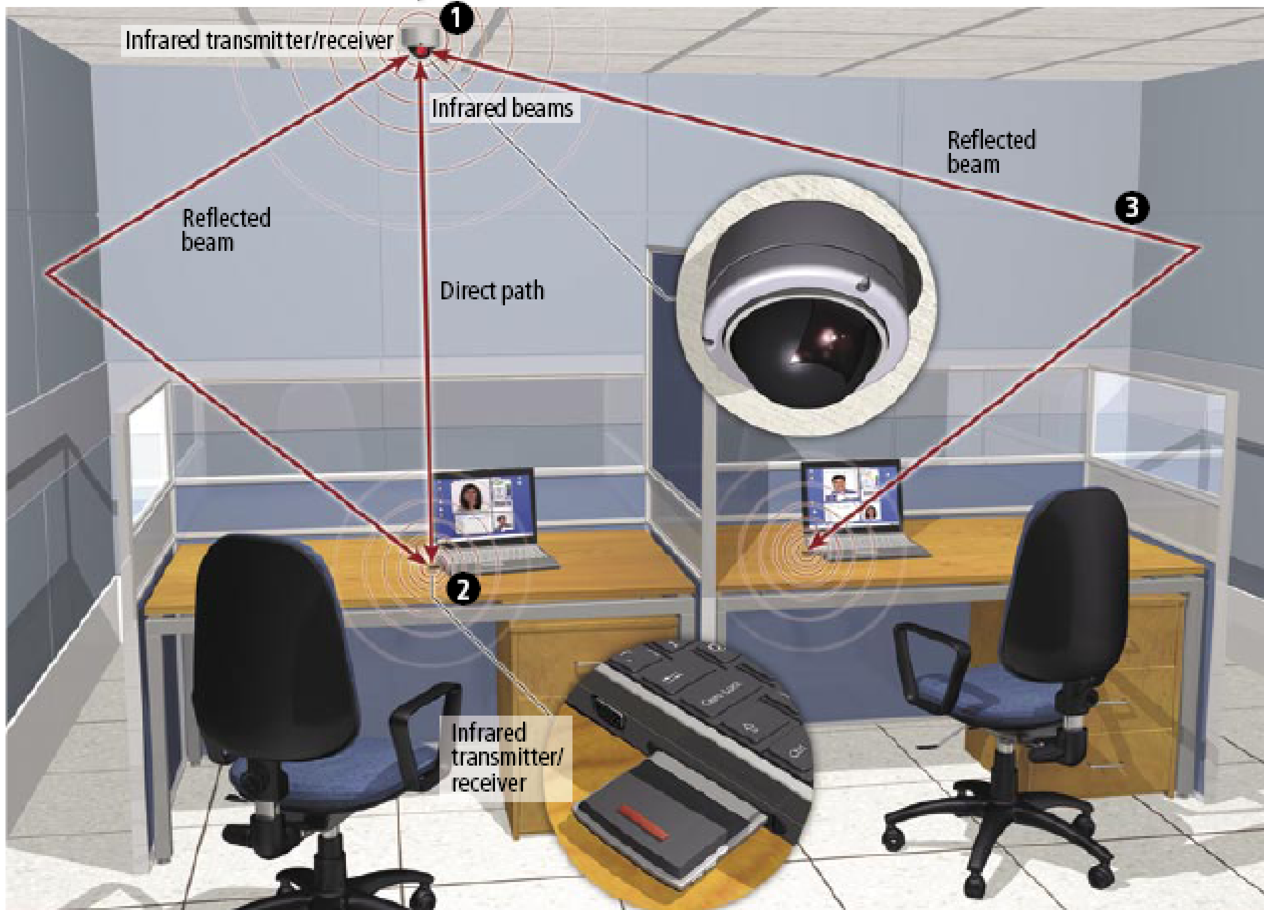
Visible Light and IR Wireless Communications

[HOW IT WORKS]

Optical Wireless Network

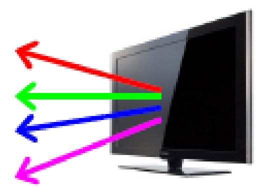
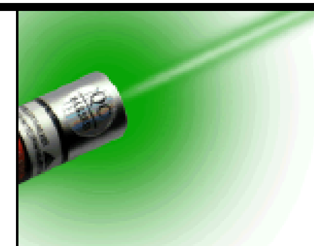
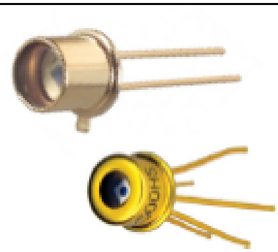
In contrast to radio-wave-based technology, such as Wi-Fi or the new WiMAX systems, optical wireless networks can connect multiple indoor portable devices to the Internet at broadband speeds using infrared light. Inexpensive infrared transmitters/receivers beam signals into a room ❶ to link with devices fitted with plug-in cards that can both receive and transmit the coded infrared light ❷. Because light signals do not interfere with one another—as radio signals can—and offer greater bandwidth, many more devices can share the optical network. Barriers such as partitions do not halt reception because beams reflect off room surfaces ❸. Engineers are working on similar systems that use white LED lamps, flickering in code faster than the human eye can detect.

Data link to and from Web



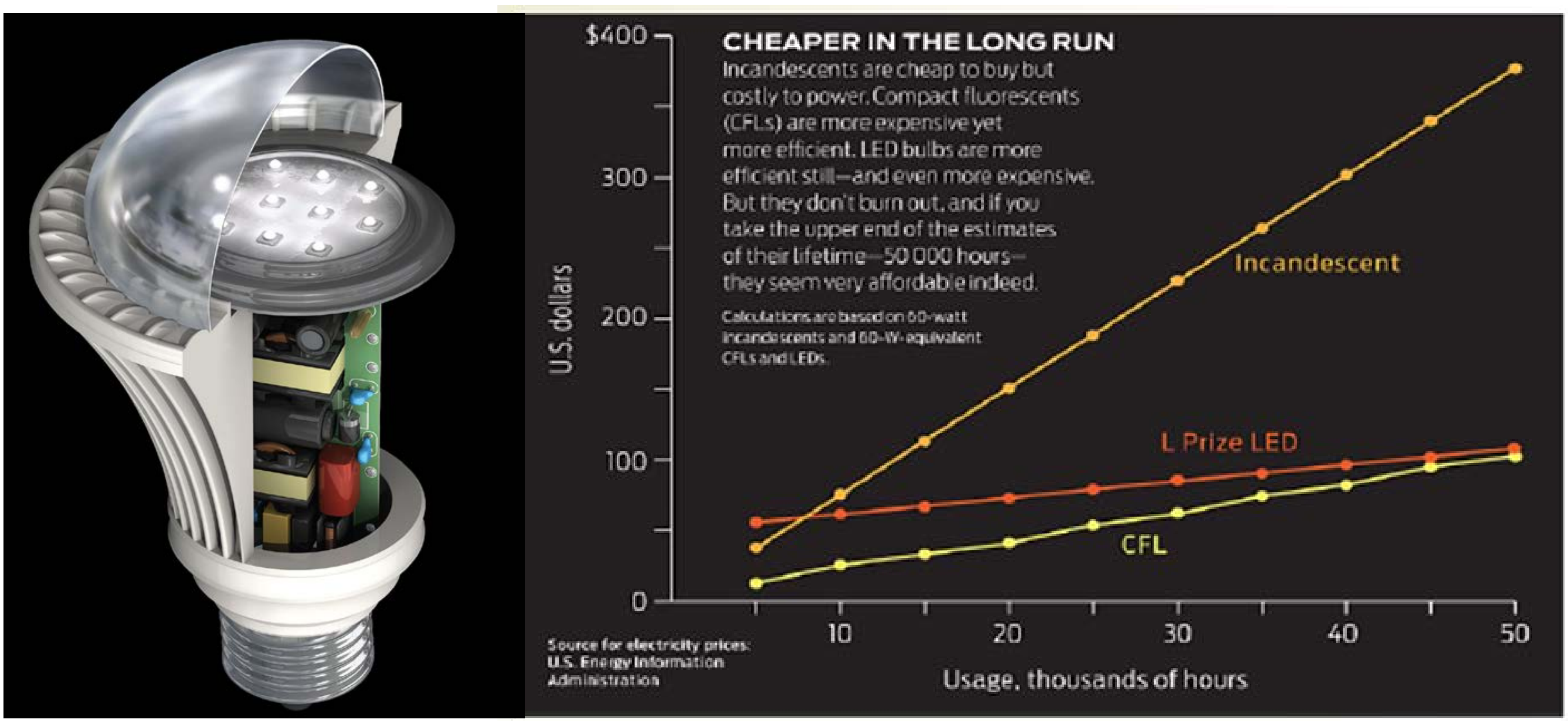
M. Kavehrad, "Broadband Room Service by Light," Scientific American Journal, July 2007

Classification by Optical Frontend

<table>
<tr><td>Transmitter / Receiver</td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td rowspan="2">Very low speed, dominated by the transmitter</td><td colspan="3">Low speed, dominated by the receiver</td></tr>
<tr><td></td><td>Medium speed</td><td>High speed</td><td>Very high speed</td></tr>
</table>

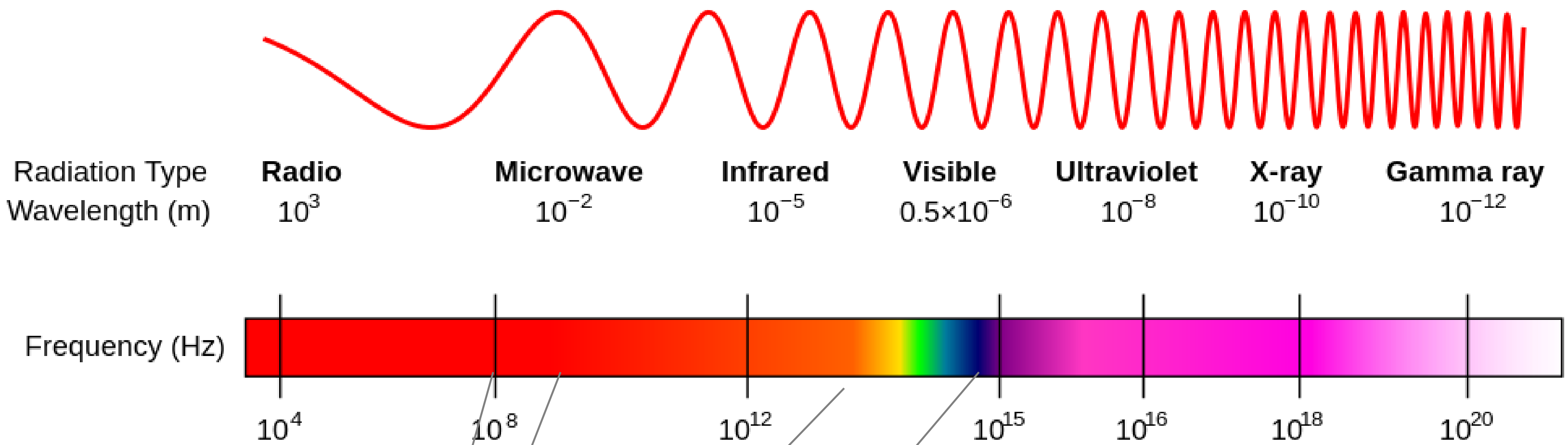
Solid State Lighting

IEEE Spectrum: January 2012

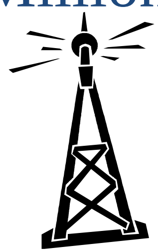


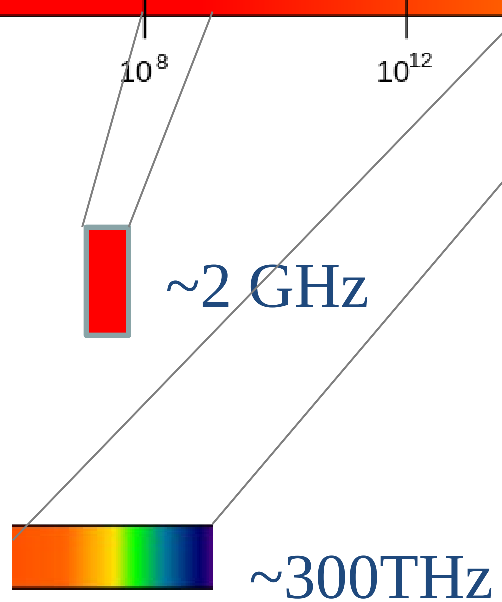
US $2000 Cost of ridding a room of the mercury from a broken CFL

Technology and Economic Impact



1.4 Million





14 Billion

Deployed units Number

Bandwidth Available

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SMART LIGHTING

Smart LED bulbs control from mobile device anywhere

- **Welcome home**
  Turn on your lights automatically as you go home

- **Stay connected**
  Receive lighting notifications during the day

- *Auto respond to sunset/sunrise*
- *Dim control to watch a movie*
- *Turn it off after you leave home*
- *Create custom lifestyle schedules*

- **Set the mood**
  Escape the daily grind
  Experience a different ambience

Smartphone control multi-color, energy efficient LED bulbs

- **Ease into your day**
  Wake up naturally with automatically increasing light

Commercial

Retail

Hospitality

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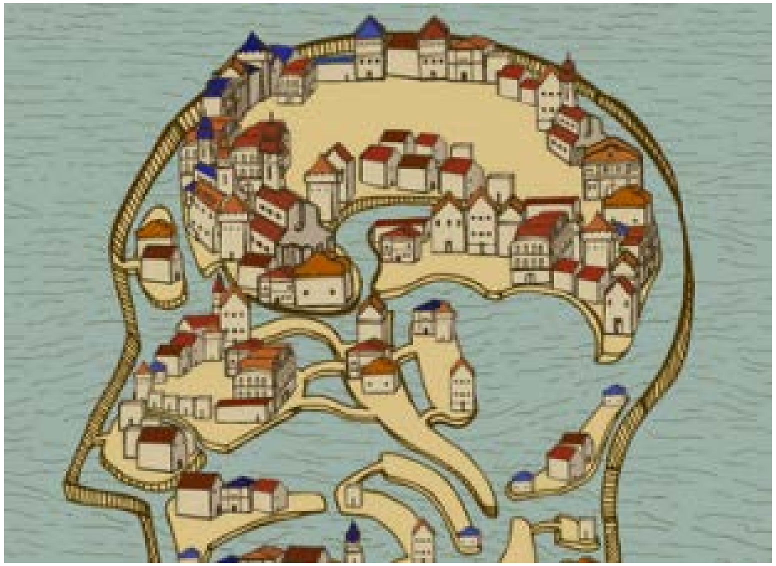
Smart City through Networked Street Lights



The IPv6-Addressable Light Bulb Goes On Sale

Silver Spring Networks leverages streetlights to build on the internet of "important things"

[http://www.greentechmedia.com/articles/read/How-Networked-Streetlights-Will-Make-Your-City-Smarter?utm_source=Daily&utm_medium=Headline&utm_campaign=GTMDaily]

April 26, 2013

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Sensity: One Network, One Platform, Many Apps

Video Camera

Retail Analytics

Parking System

+ 100's of additional Apps

1 Network

No Trenching!

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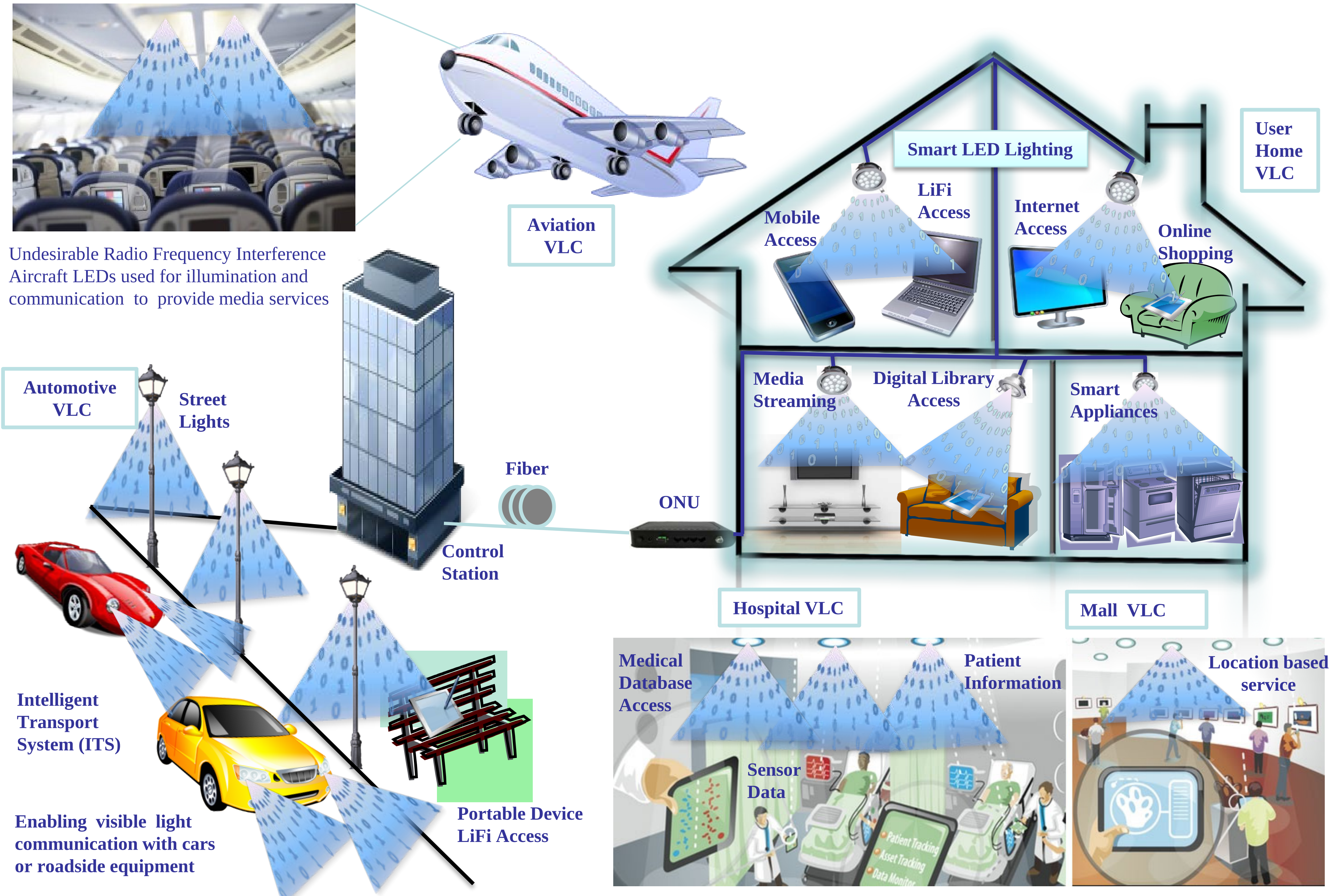
VISIBLE LIGHT COMMUNICATIONS



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VLC Applications Areas

IT Security

RF-sensitive Areas, e.g. Hospitals

Private Households

Mechanical Engineering

Advertising, Messaging

Tradeshows, Museums

In-flight Entertainment

Underwater Communications

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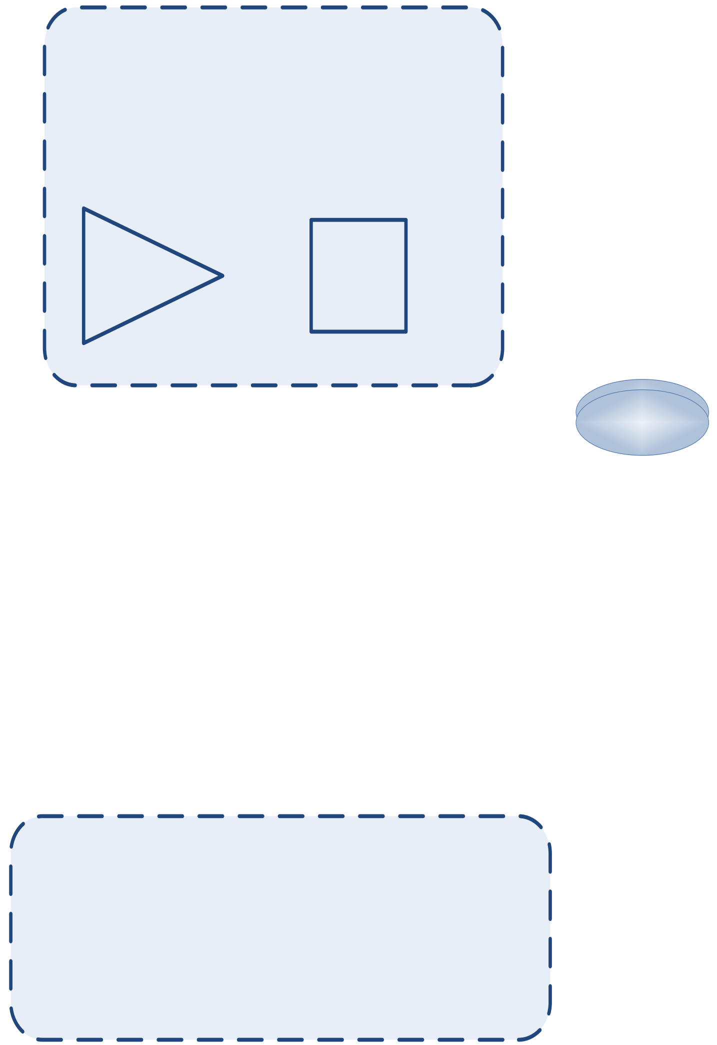

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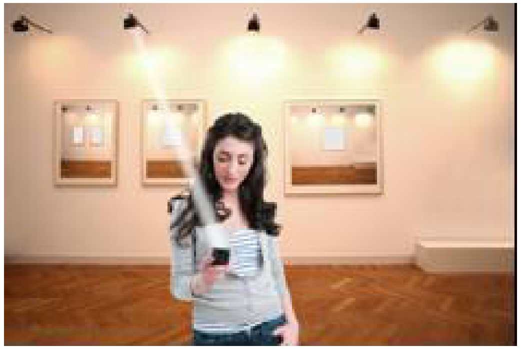
R&D Indoor Localization & Navigation

- Determination of local (indoor) position by means of lighting
- Attractive for medical areas, goods depots, complex buildings (guidance etc.), …
- Goal: 1 cm resolution, support of objects moving at walking speed
- Low-speed uplink, e.g. for system control (logging) via local access point



R&D in progress at several places

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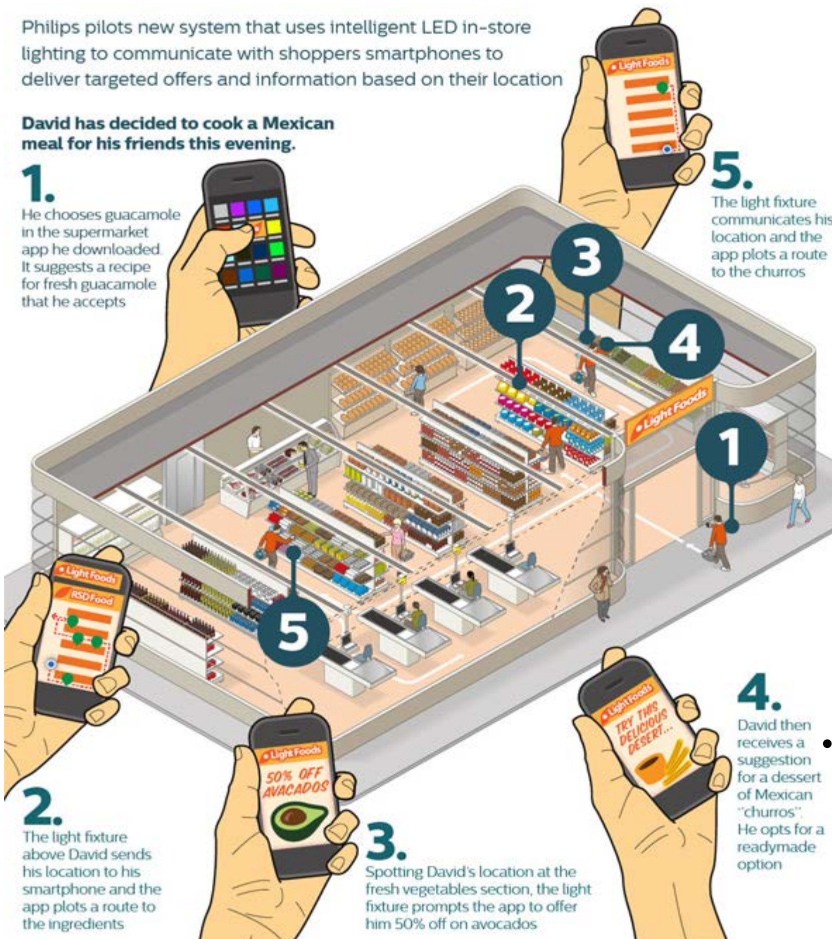
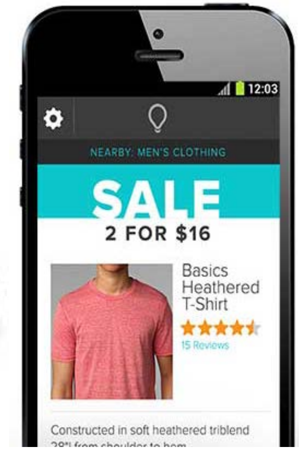
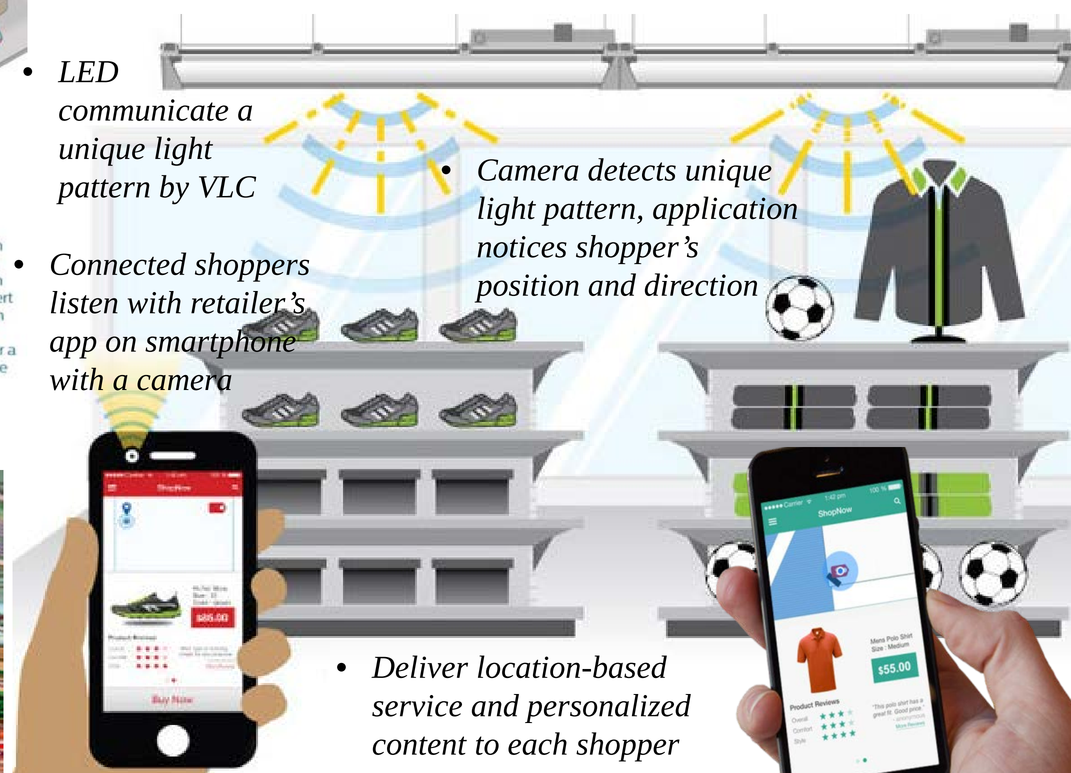
VISIBLE LIGHT POSITIONING



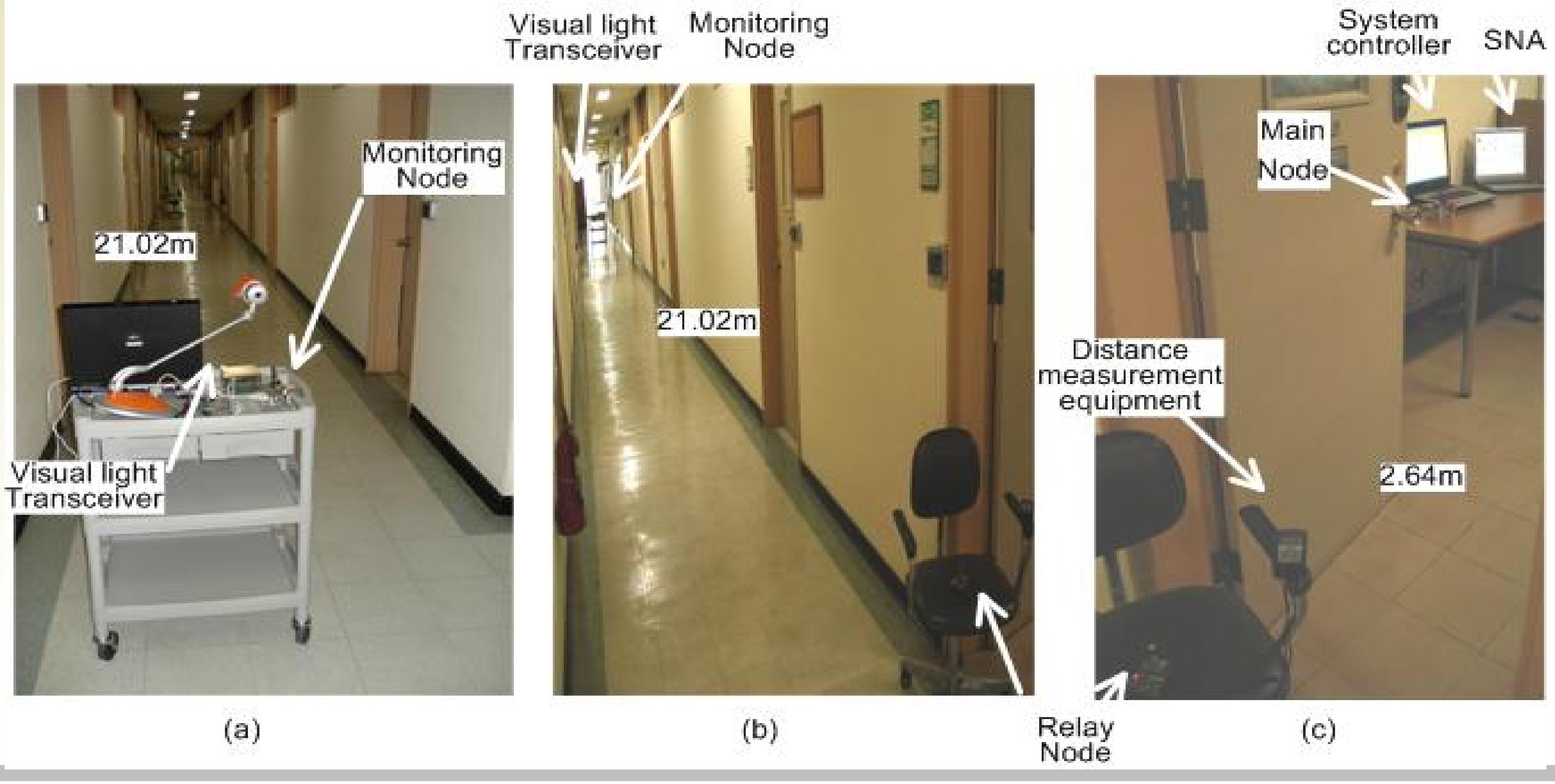




- *LED communicate a unique light pattern by VLC*
- *Connected shoppers listen with retailer's app on smartphone with a camera*
- *Camera detects unique light pattern, application notices shopper's position and direction*
- *Deliver location-based service and personalized content to each shopper*

Positioning System Implementation

- **Hybrid RF/VLC Positioning Experiment** multi-hop wireless networking: with 24m distance between a target (i.e., monitoring node of Fig. (a)) and an observer (i.e., main node of Fig. (c)).



Y. U. Lee, M. Kavehrad," Long-range Indoor Hybrid Localization System Design with Visible Light Communications and Wireless Network," IEEE Photonics Society Summer Topical Conference – Optical Wireless Systems Applications, Seattle, July 2012.

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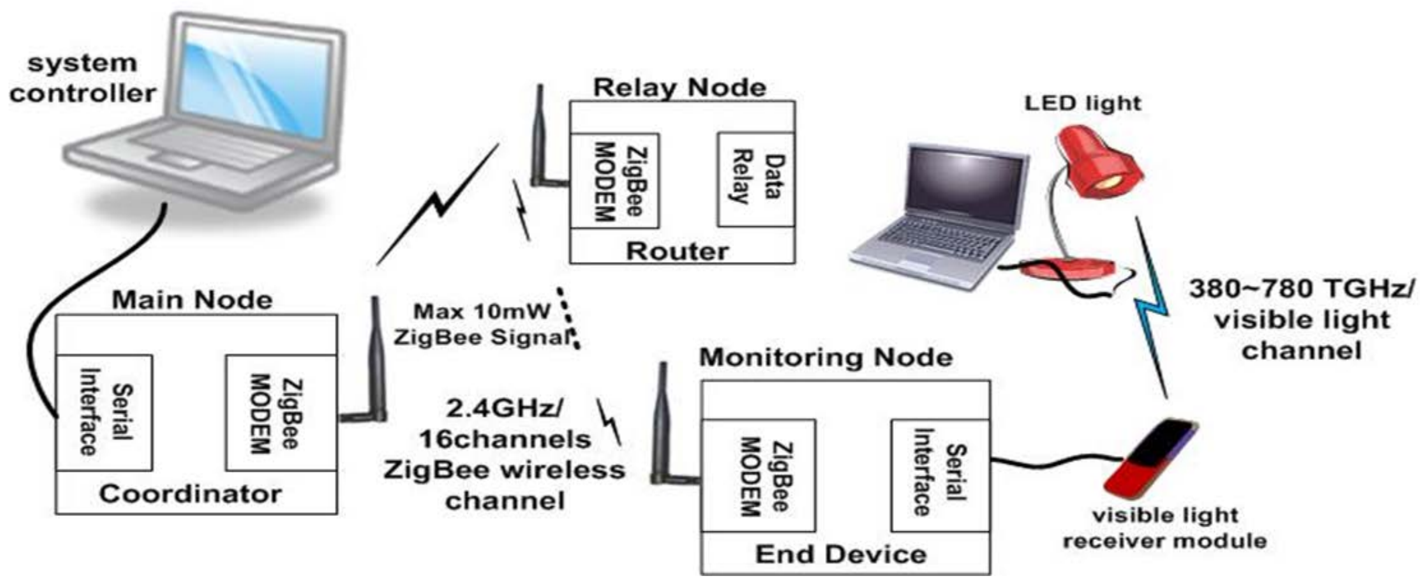
Hybrid Positioning with Lighting LEDs and Zigbee Multihop Wireless Network

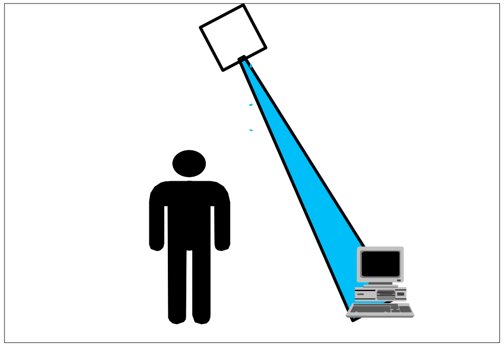
ScienceDaily®
Your source for the latest research news

"LED lights are becoming the norm," said M. Kavehrad, W.L. Weiss Chair Professor of Electrical Eng. and director of the NSF COWA at Penn State. "The same lights that brighten a room can also provide location information."
January 2012

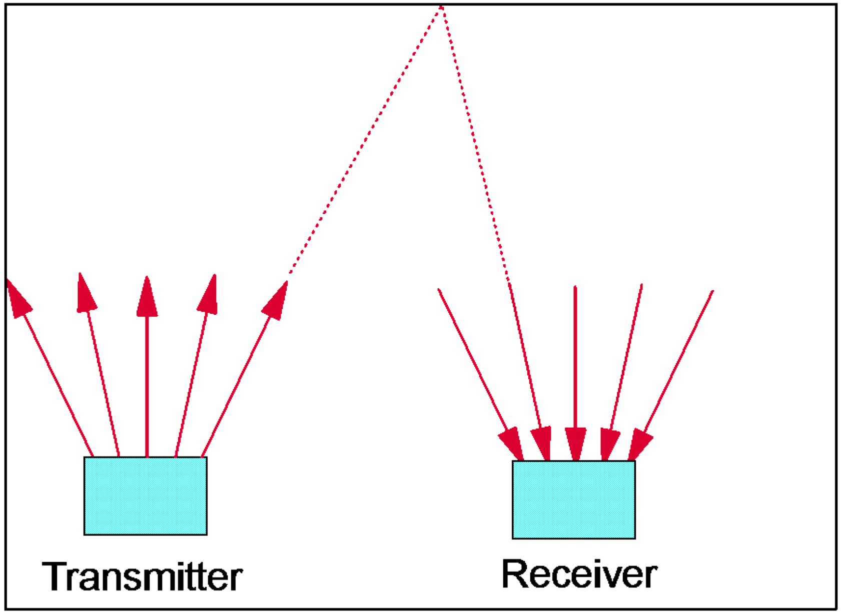


Architectures Suitable for Ultra High-Speed Indoor Wireless Communications

- Line of sight
  - Blocking
  - Require Base Station
- Spot diffusing
  - Robust to blocking
  - Do not require infrastructure
  - More challenging link budget due to intermediate surface



Each receiver element has narrow field of view-receives signal from small 'spot' therefore no multipath



•G. Yun, M. Kavehrad, "Spot-Diffusing and Fly-Eye Receivers for Indoor Infrared Radio Comm.," IEEE Int. Conf. on Selected Topics in Wireless Communications, Vancouver, June 1992.

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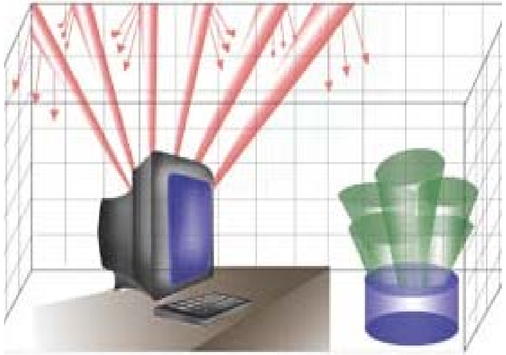
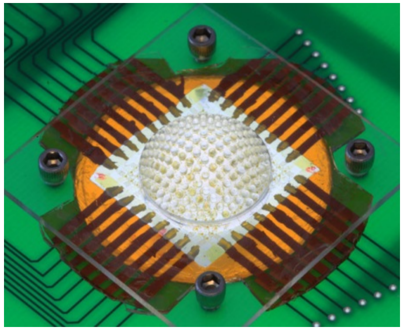
High-Speed MIMO Communications



Fly-Eye Hemispheric Imaging Receiver

- One-to-many and many-to-one communications No alignment
- High data rate
- No multipath induced distortion
- Tolerance to shadowing and blockage (Rx consists of multiple elements)
- Better ambient light rejection (due to narrow FOV)

- G. Yun, M. Kavehrad, "Spot-Diffusing and Fly-Eye Receivers for Indoor Infrared Radio Comm.," IEEE Int. Conf. on Selected Topics in Wireless Communications, Vancouver, June 1992.



Insect-Eye Camera Offers Wide-Angle Vision for Tiny Drones

- Engineers make a tiny compound eye

BY: JEREMY HSU / **WED, MAY 01, 2013**

Biomimicry: The 160-degree, 180-pixel eye is inspired by an insect's compound eye

Photo: University of Illinois and Beckman Institute **Eye See You:** Composites of hard and soft materials and circuits make up an electronic version of an insect's compound eye.

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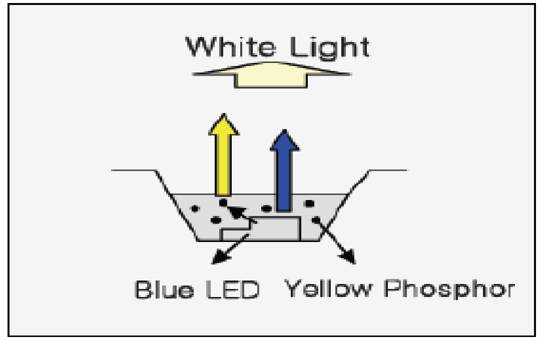
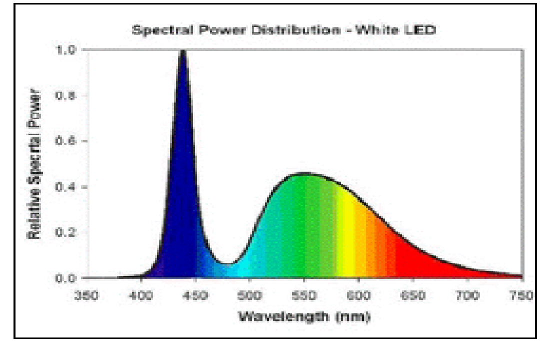
Key Elements: LEDs and Lasers for Solid-State Lighting

Blue LED + Phosphor

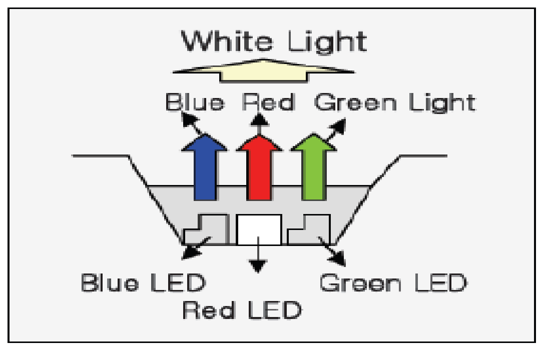
- Low-cost
- Simple driving
- Few MHz bandwidth (Phosphor)
- “Blue” filtering @Rx → 20 MHz

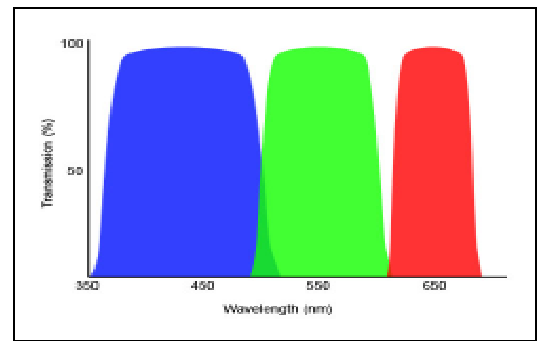




R G B LED

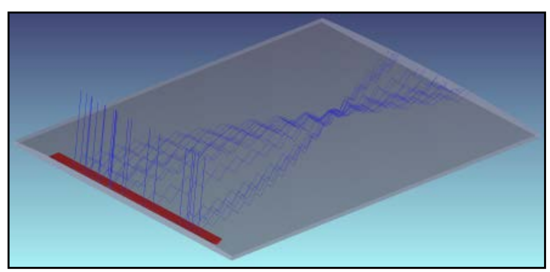
- Higher cost
- ~15 MHz per LED chip
- Enables WDM (using 3 drivers)

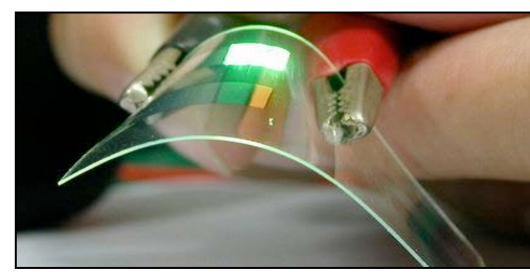




Organic LED

- Modulation Bandwidth >20 MHz





CMOS-controlled color-tunable GaN-based micro-LEDs pixels in smart displays have a modulation bandwidth of 100 MHz, providing a wavelength-agile source for high-speed VLC. OLEDs on top of the LEDs would act as a color conversion layer, multiplexing the signals into other colors.

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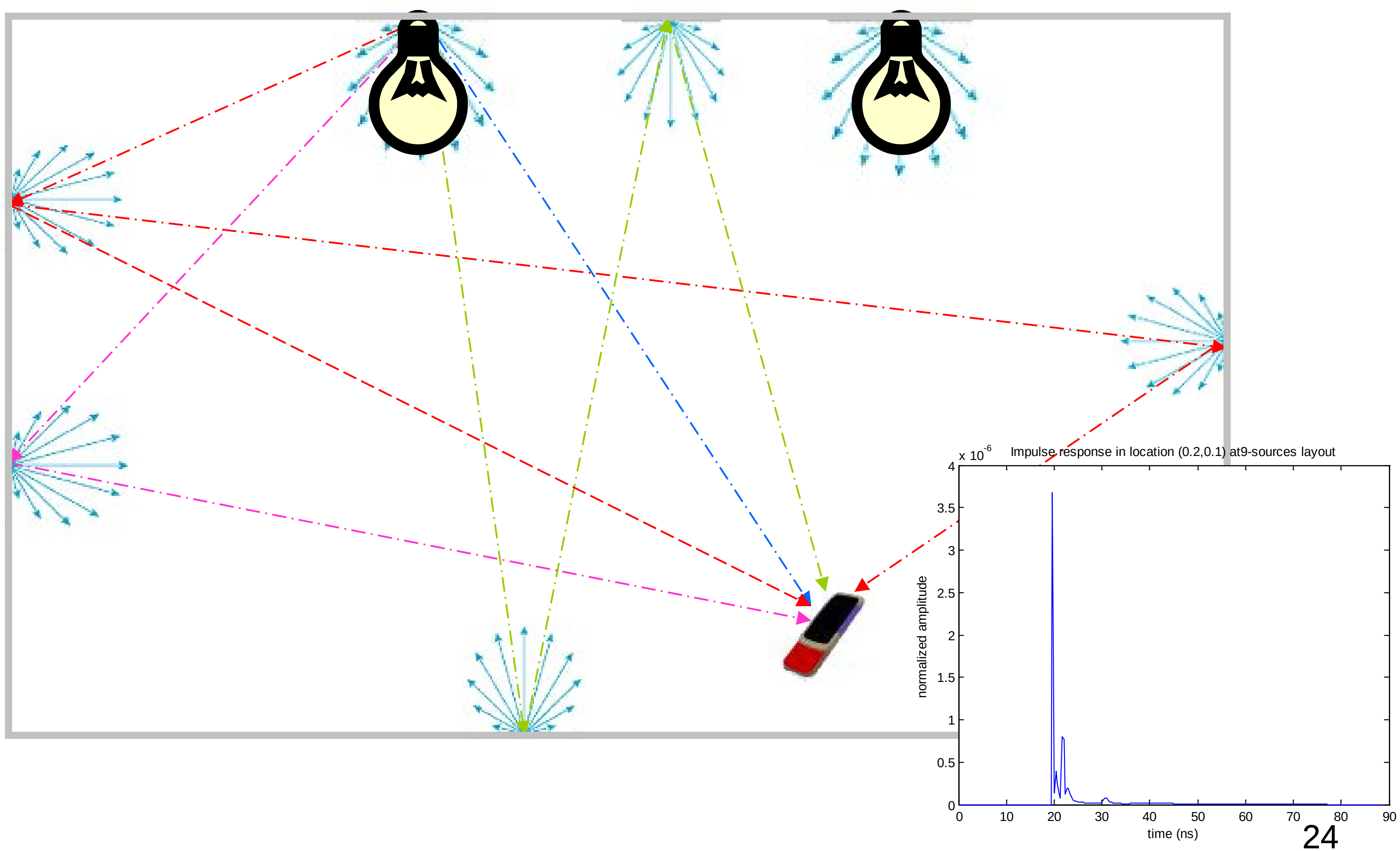
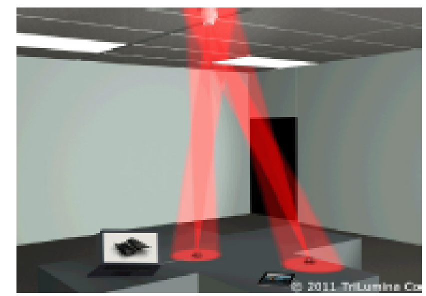
VLC To Address Mobility:
Diffuse MIMO Communications



Goals of IrDA: 5 and 10 Giga-IR

- Wavelength range 830 … 1550 nm
- Powers up to 1 W, always IEC class 1
  → extended optical sources
- Range 1 cm … 10 m, various radiation angles
- Final spec. were expected by end of 2012
- 1 Gb/s module recently demonstrated @ FhG-IPMS, Dresden

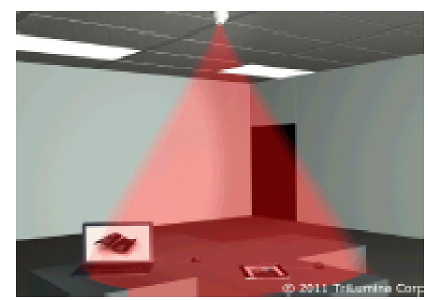


MIMO

Docking

Spotting

Beaming



Shower

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Multi-Gigabit LAN

FEBRUARY 11, 2010

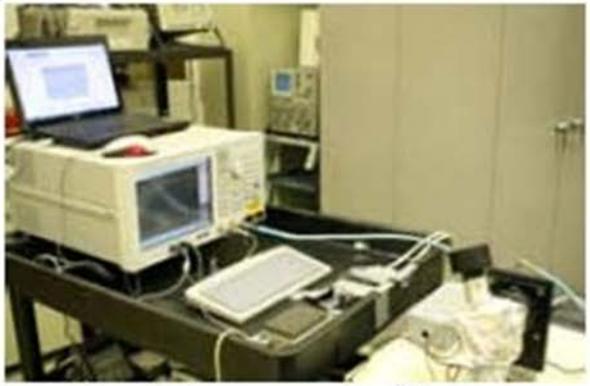
Technology Review PUBLISHED BY MIT

Beaming broadband across the room

Wireless optical networks could provide gigabit-per-second data transfer.

By: Erika Jonietz

A wireless network that uses reflected infrared light instead of radio waves has transmitted data through the air at a speed of one gigabit per second--six to 14 times faster than the fastest Wi-Fi network. Penn State graduate student Jarir Fadlullah and Mohsen Kavehrad, professor of electrical engineering and director of the university's Center for Information and Communications Technology Research, built and tested the experimental system. Their setup sent data across a room by modulating a beam of infrared light that was focused on the ceiling and picking up the reflections using a specially modified photo-detector. The pair says that their measurements show the system could support data rates "well beyond" the one gigabit per second they are currently claiming.



This experimental system can transfer data at one gigabit per second. An infrared laser is used to transmit the data.

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Ultra High-Speed Wireless Communications

- **Pointed links:**
  - Data-Centers
  - Entertainment systems

- **Diffuse links:**
  - Home/office usage
  - Mobility requirements

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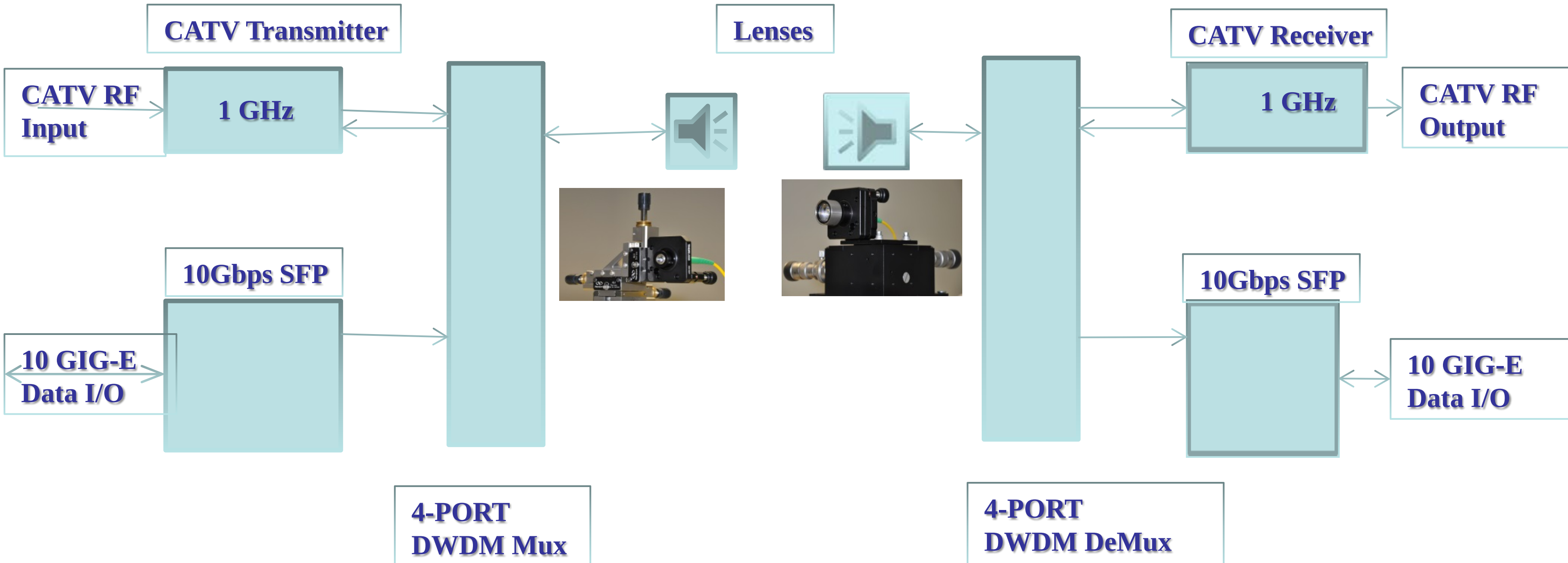
Single-Mode Fiber band over 1550 nm IR Optical Wireless Link for Data Centers

June 2013

Pennsylvania State University – CICTR Labs.



http://www.youtube.com/watch?v=_BCaX5ex90s&feature=youtu.be

M. Kavehrad, M.I.S. Chowdhury, W. Zhang "CATV Transmission over a 1550 nm IR Indoor Optical Wireless Link," To appear in the OSA Optics Letters Journal.

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What can you do with an LED Light Bulb that has its own IP Address?

Add a Node to the Global Network: INTERNET

The IPv6-Addressable Light Bulb Goes On Sale GreenWave Reality and NXP launch 6LowPAN mesh-networked LED bulbs and home energy control platform.

Summary

"The most compelling story of how ***Internet of Light*** will transform our world is the one still being written: the future of lighting, communications, sensing and the birth of a new enterprise lighting network.“

Ample Opportunities

- Optical spectrum is huge, secure and unregulated.
- OWC emerges as a new wireless technology with many useful applications.
- UV-C spectrum is unique
- Several standards already available, e.g. IEEE, JEITA, IrDA, VLCC.
- High-speed OWC technology is about to enter the market.

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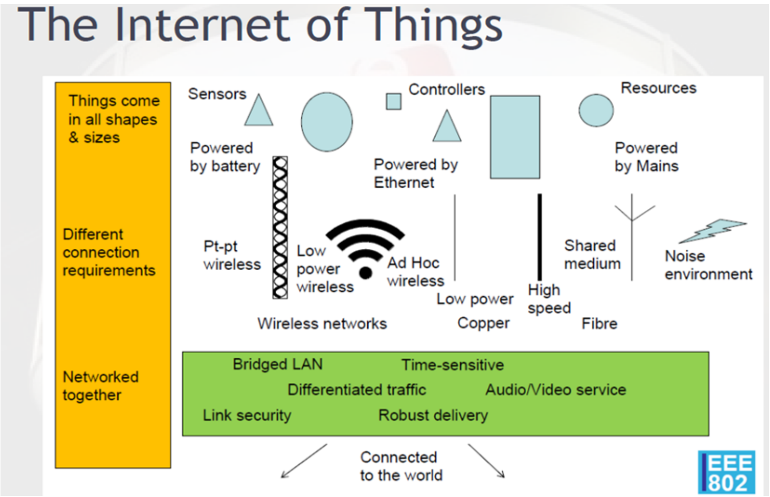
An Eye on the Future - Information Superiority

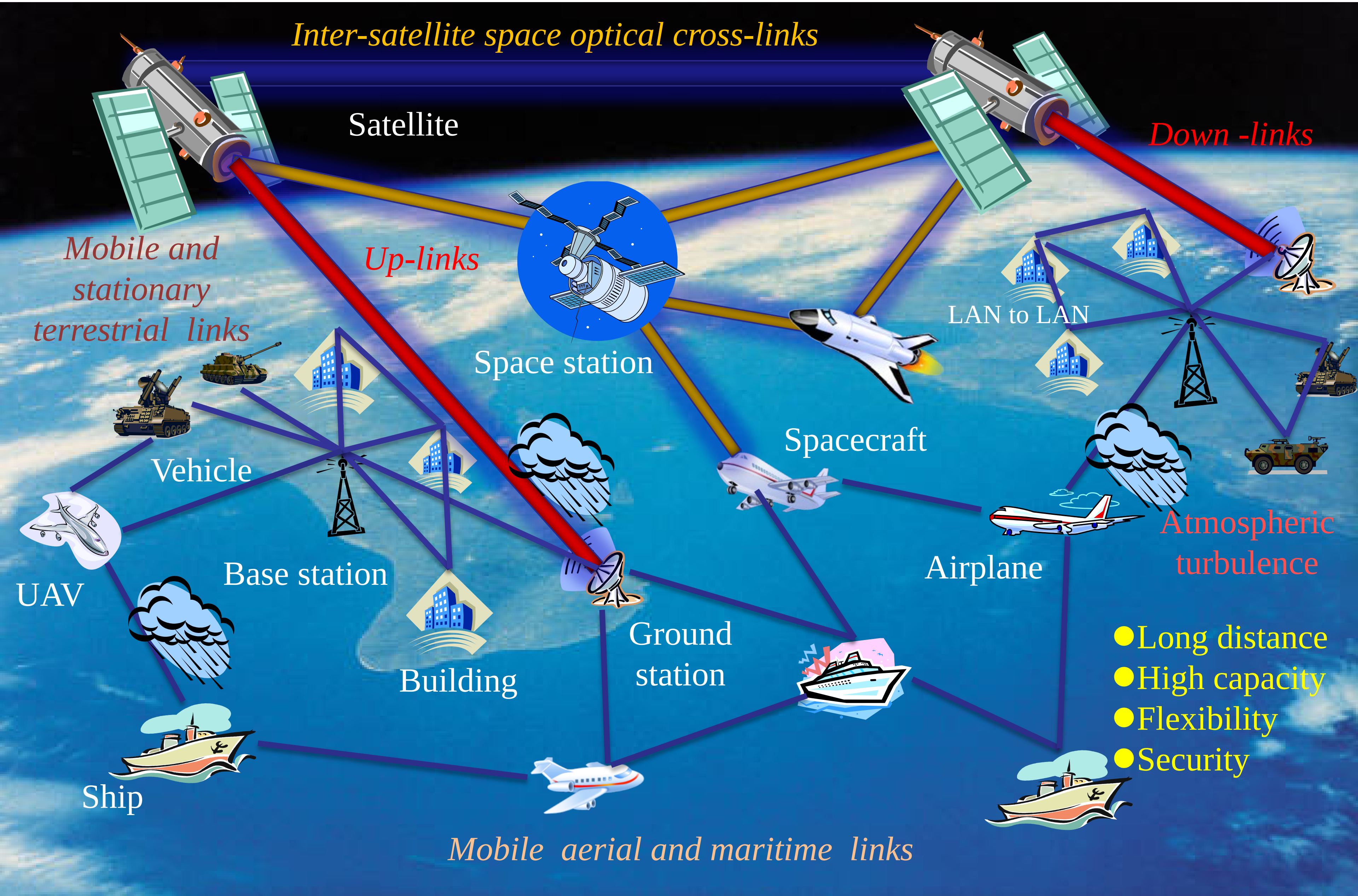
- The “Internet-of-Things” and “Big Data” are here.



- SM-Fiber optics give you all the bandwidth you need, but cannot provide “Global Connectivity”.

- Information superiority through global-connectivity will re-define the “**Have’s**” and the “**Have not’s**”.

Free Space Optical Communications



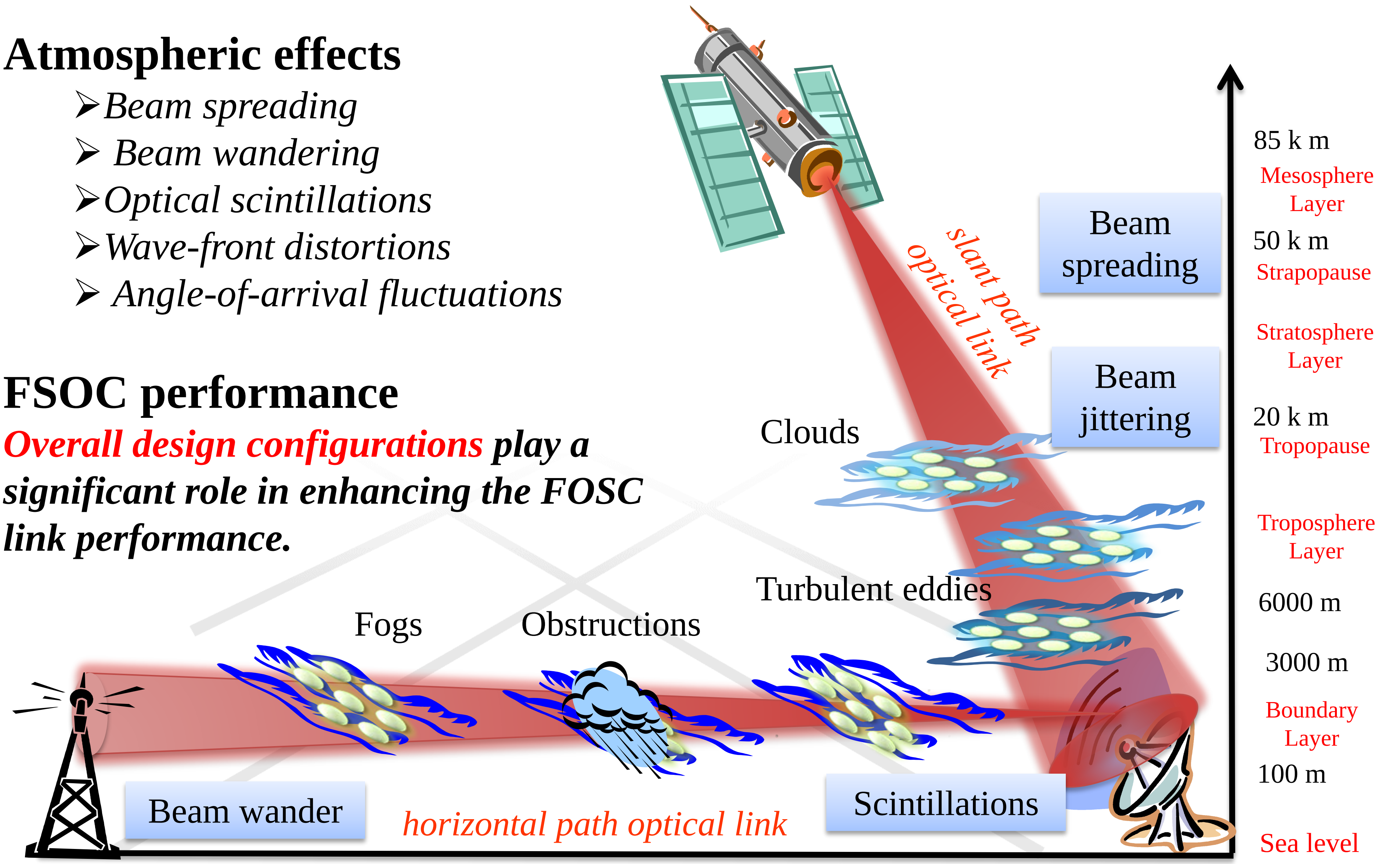
Atmospheric Effects on Free Space Optical Communications

Atmospheric effects

- *Beam spreading*
- *Beam wandering*
- *Optical scintillations*
- *Wave-front distortions*
- *Angle-of-arrival fluctuations*

FSOC performance

Overall design configurations play a significant role in enhancing the FOSC link performance.



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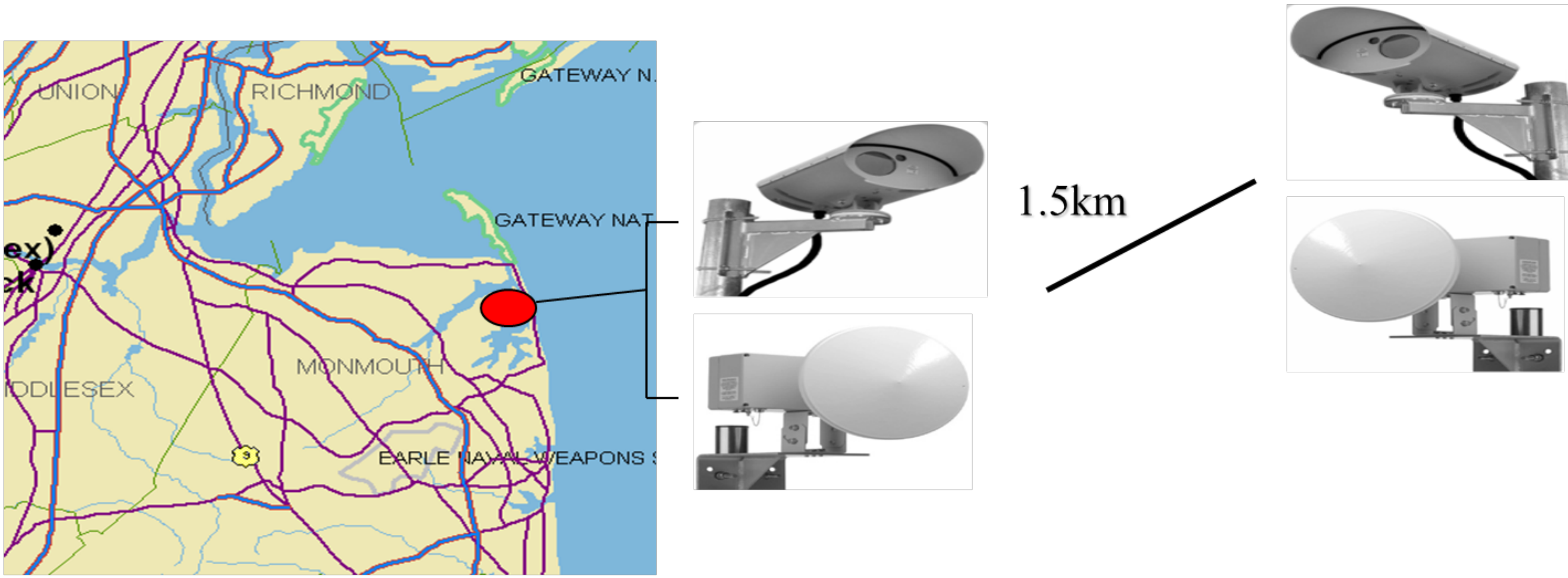
AT&T

Hybrid FSO/RF Great Complements

• M. Kavehrad, "Design and Performance Considerations for the Hybrid Atmospheric Optical/Digital Microwave Network Systems," Technical Memorandum, Bell Laboratories, December 1987.

•M. Kavehrad, “A Countermeasure to Improve Outage Performance of Interference-Limited Microwave Radio Links,” Canadian Journal of Electrical & Computer Engineering, Vol. 16, No. 1, January 1991.



– Full-Duplex Radios:

60 GHz: ASK Data (~ 100 Mbps)

FSO: ASK Data (~ 100 Mbps)

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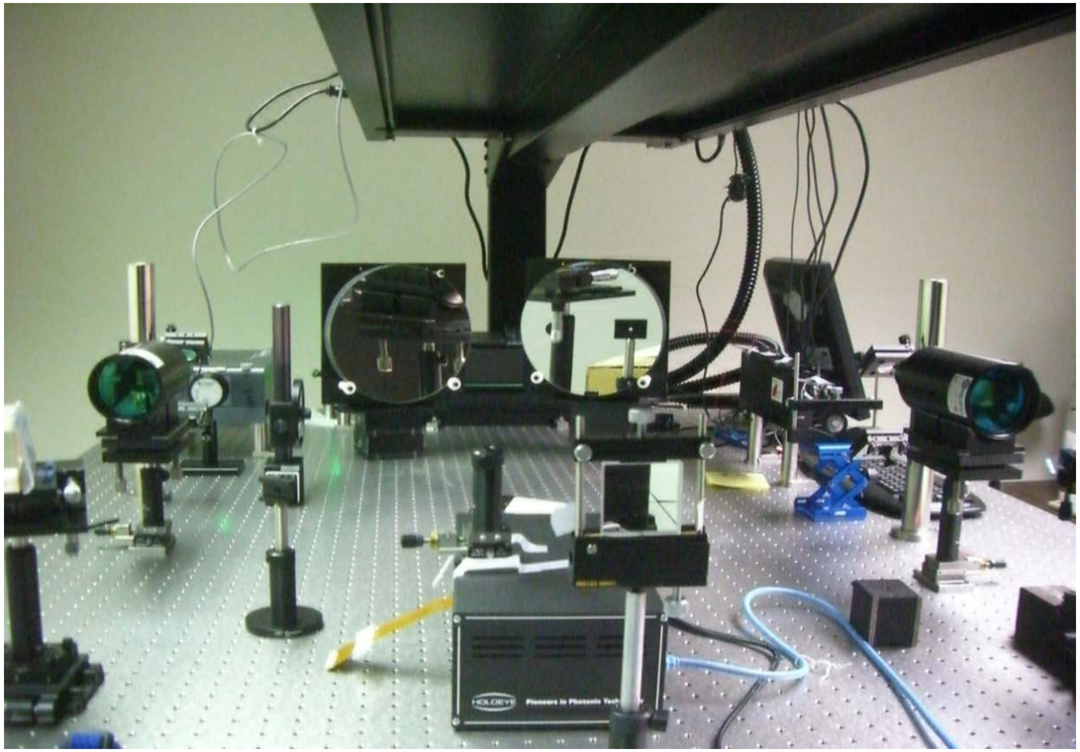
Ultra-short Pulse Laser Technology

- Ultra-fast switching times and ultra-high transmit powers enable communication capabilities that far exceed anything available today. These pulses shaped through signal processing can help penetration through clouds.
- A 100 fs pulse at 100 mJ per pulse would produce a peak power of 1 Terawatt per pulse; at 3 Giga pulses per second, this is 300 Mega Watts of average power.



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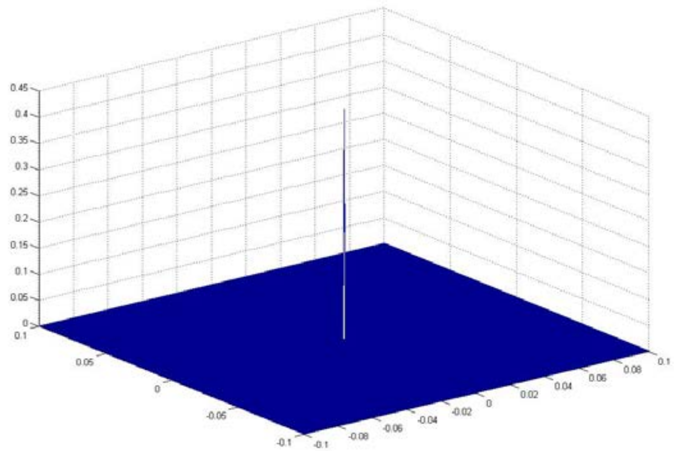
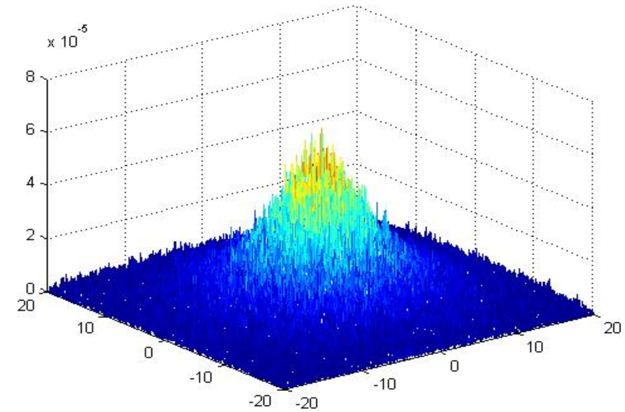
Channel Modeling

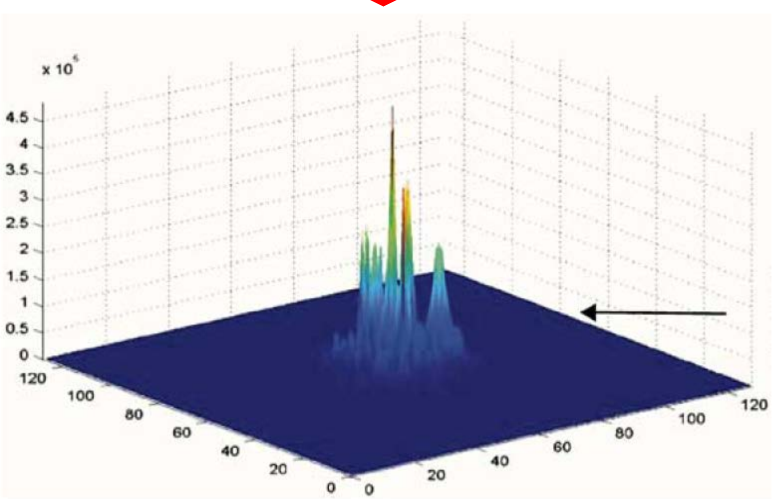
Ideal Point-Spread Function (PSF) or Spatial Impulse Response

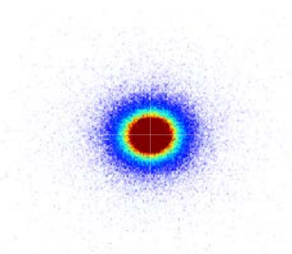


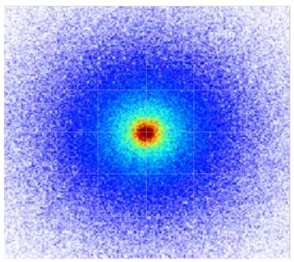
Scattering



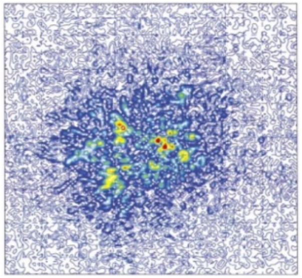
Turbulence

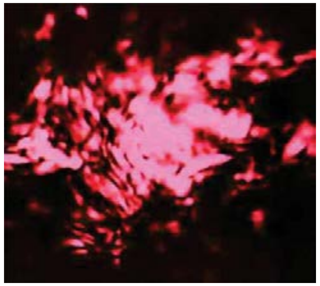






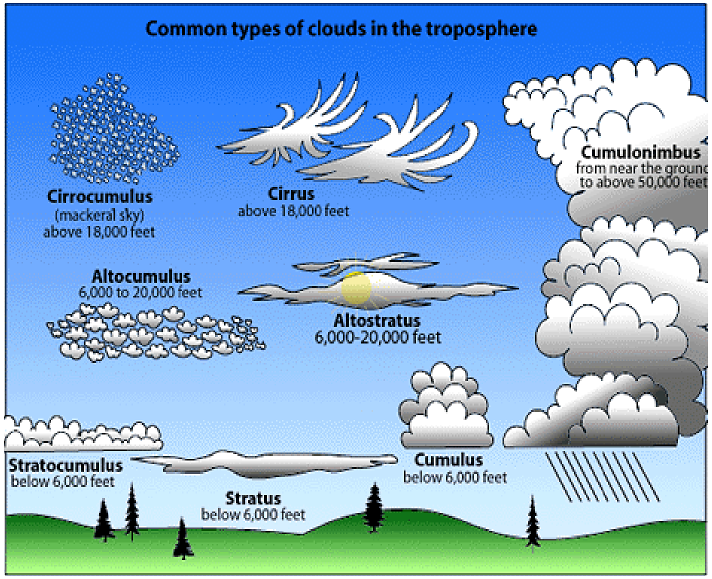
300

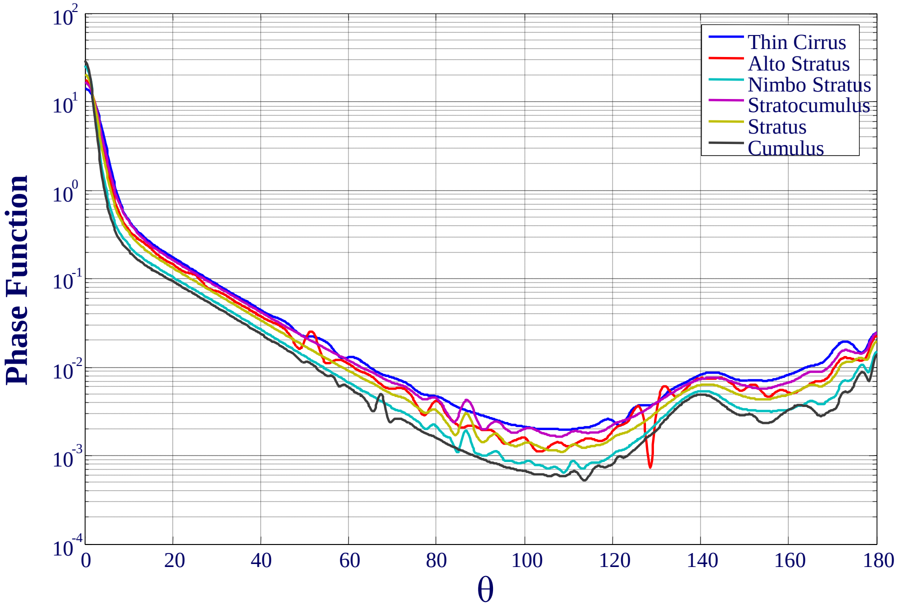




Clouds Channel Modeling

Scattering Impulse Response





150 ⟷ 1.

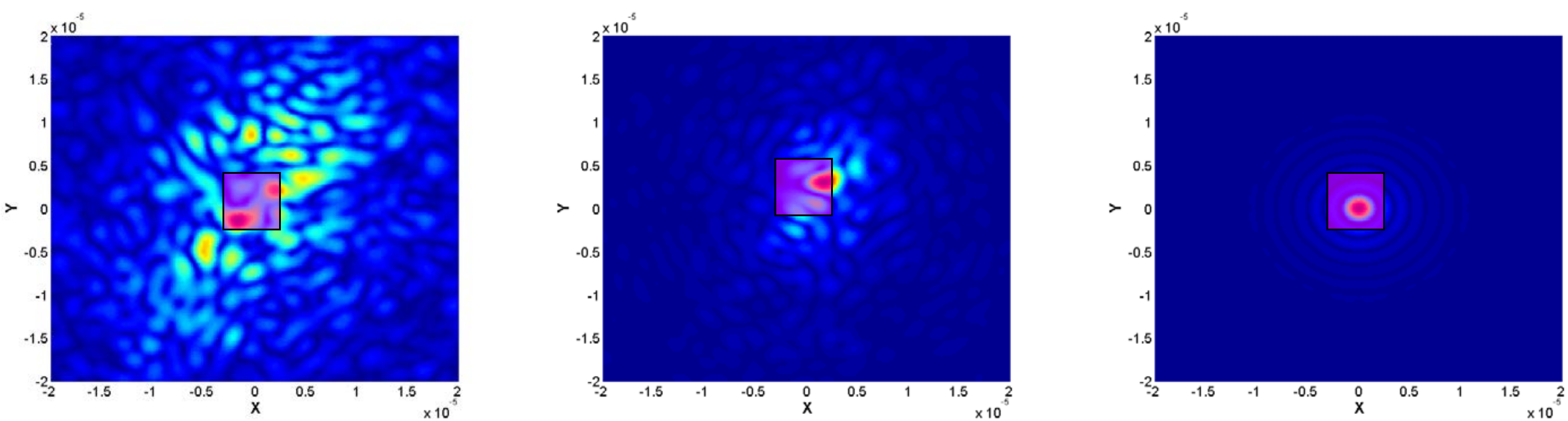
Typical Optical Thickness for 1 Km

- Phase functions take into account the particle size distribution.
- Phase functions of clouds are very similar and are highly peaked in forward direction.

Channel Modeling

Turbulence & Kolmogorov Theory

- **D/r_0 >>1, i.e., a small coherence-length or a large receive aperture. This brings Spatial-Selective Fading, as aperture size has exceeded the coherence-length of channel.**
- Aperture averaging reduces the intensity fluctuations variance.
  - Phase aberrations break up the impinging wave into several spatial modes.
  - PSF is broadened and distorted.
  - Random, time varying distortion of PSF changes the amount of light received by photo-detector and gives rise to attenuation and fading of the signals.



D/r_0=15 **D/r_0=4** **D/r_0<1**

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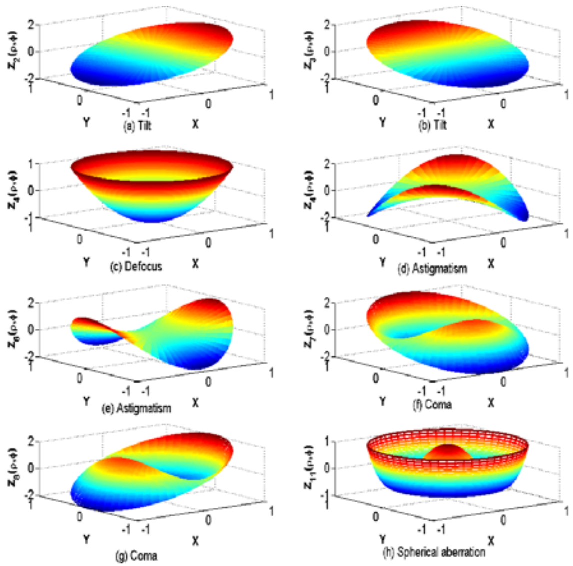
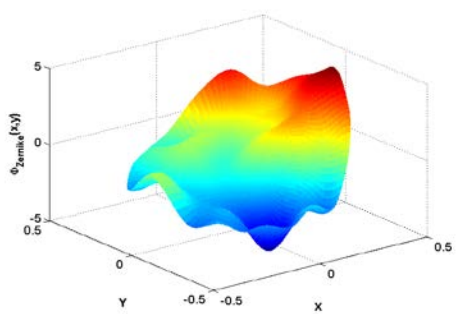
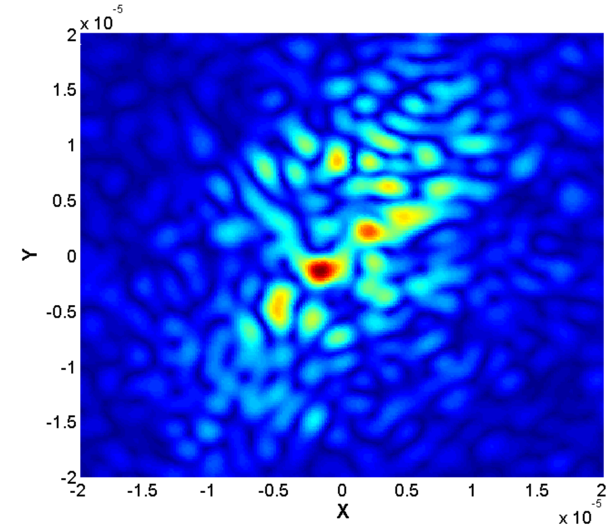
What is the Optimum Receiver ?

- Case where $(D/r_0) >> 1$ results in "Space-Selective (in analogy to frequency-selective RF)" fading or "multi-spatial modes" fading. Now, the optimum receiver is an Adaptive Optics system (Zernike Spatial Tapped-Delay Line) followed by a multi-aperture Maximum-Likelihood receiver (Maximum Ratio Combiner).
- Zernike's provide uncorrelated modes to maximize diversity gain.







$$\psi(\rho,\phi) \approx \sum_{i=1}^{N} a_i Z_i(\rho,\phi)$$

$$a_i \sim N(0,\sigma_i^2)$$

- **This is true, if performance linearly scaled with transmission link length – however, it does not !**

Wide Field-of-View Optical Receivers

- Typically FSOC receiver employs acquisition, tracking and pointing (ATP) mechanisms to point the receiver's narrow field-of-view (FoV) at the small divergence transmitted beam.

- This approach is impractical for many mobile applications requiring small size and low weight.

- A wide FoV optical receiver is needed to replace bulky, gimbals-based mechanisms.

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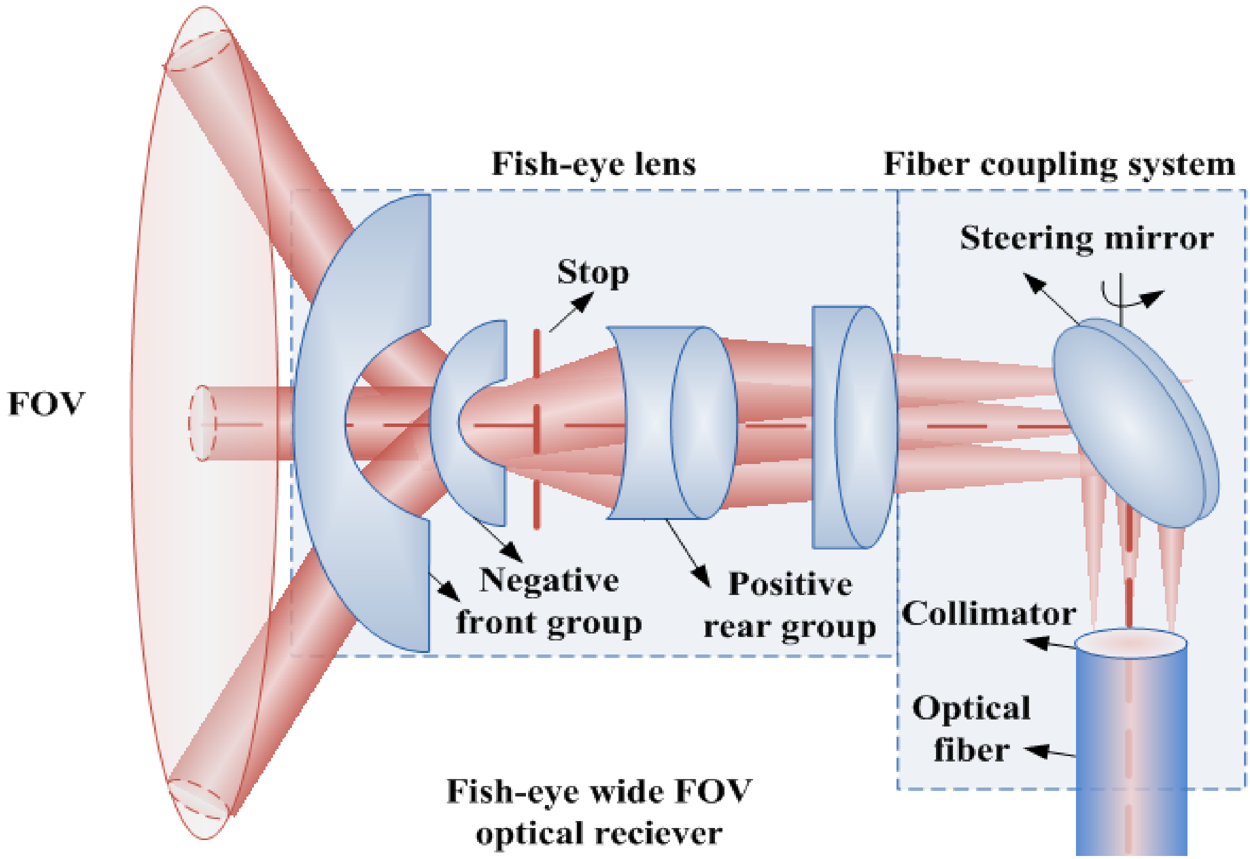
Fish-Eye Optical Receiver



Fish-eye lens group

Collect the wide field beam

Steering mirror

Couple the beam into a multi-mode fiber (imaging)

Inherent motion environment requires tracking accuracy for fiber coupling system

P. Deng, X. Yuan, M. Kavehrad, M. Zhao and Y. Zeng, "Off-axis catadioptric fisheye wide field-of-view optical receiver for free space optical communications," ***Optical Engineering*** *51(6), 063002 (2012)*

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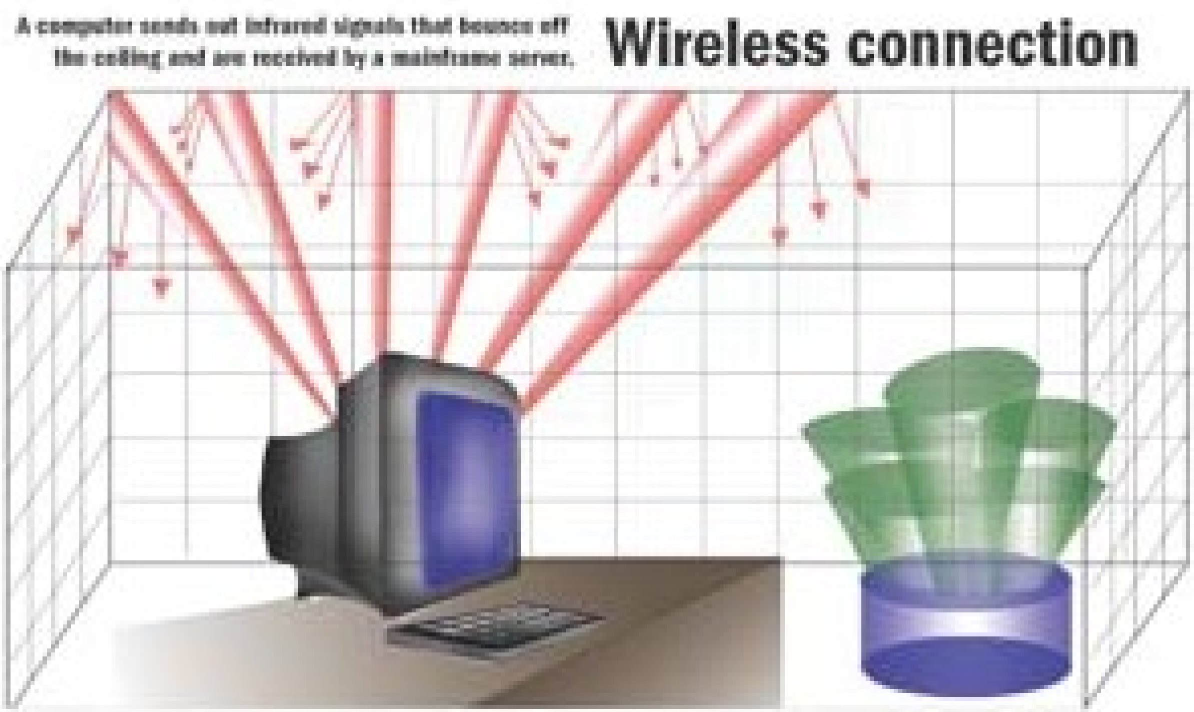
Multi-Beam Quasi-Diffuse Transmitter and Fly-Eye Imaging Receiver



G. Yun, M. Kavehrad, "Spot-Diffusing and Fly-Eye Receivers for Indoor Infrared Radio Communications," IEEE Int. Conf. on Selected Topics in Wireless Communications, Vancouver, June 1992.

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Spatial Diversity based on MIMO

- **Spatial Diversity**
  - Scintillation reduction
  - Fading compensation with inherent redundancy
  - Multiple beams significantly reduce the potential for temporary blockage of the laser beam by obstructions.

- **Limitation**
  - Beam array suffers significant scintillation increase if the spatial separation of beamlets deviates from the optimal value
  - Low received energy exists in beam arrays unless the constituent beamlets are inclined to overlap at the receiver plane
  - An optimal inclination could be difficult to achieve over long propagation distances

MIMO FSOC with Diversity Receivers

Fish-Eye SISO

Single Input Single Output
Multiple Input Multiple Output

Fly-Eye MIMO

Wide FoV diversity optical receiver

MIMO Assumptions

Aperture diameter of each receiver in the array is less than the spatial correlation width of the irradiance fluctuations

Array elements are spatially separated by a sufficient distance that each acts independently of the others

A large FoV is considered for each receiver multiple transmitters are observed

MIMO System Model

Assuming on-off keying (OOK), the signal from M transmitters and N receivers apertures is:

$$r_n = \frac{x\eta}{MN}\sum_{n=1}^{N}\sum_{m=1}^{M} I_{mn} + \upsilon_n, n = 1,\ldots N$$

where x represents information bits, η is the optical-to-electrical conversion coefficient υ_n is the AWGN with a zero mean. Fading channel coefficient I_{mn}, X_{mn} are identically distributed normal random variables with mean μ_x and variance σ_x^2

$$I_{mn} = I_0 \exp(2X_{mn})$$

Adaptive Optics based on SLM Compensation and Wavefront Prediction

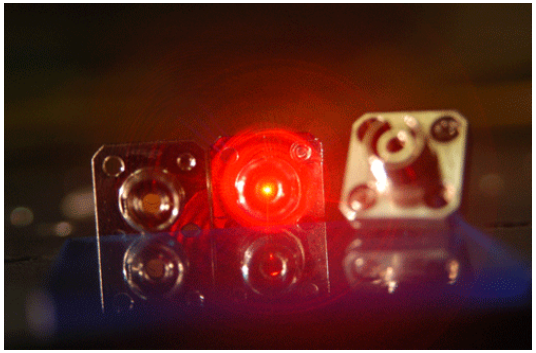
- **Conventional Adaptive optics**
  - **The wave front distortions by the pupil-plane weak atmospheric turbulence can be mitigated with conventional adaptive optics (AO)**
  - **based on wavefront sensor measurements**

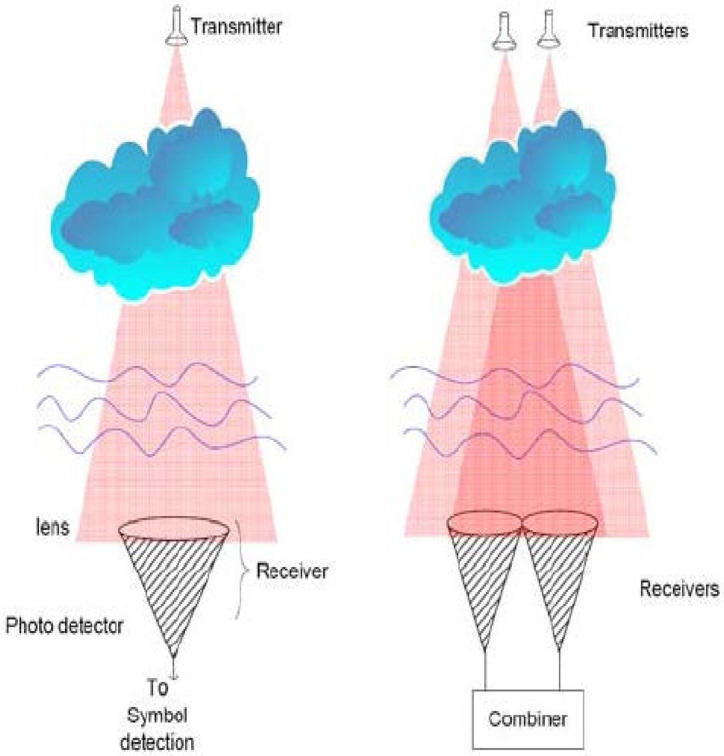
- **Limitation**
  - **strong intensity scintillations in the receiver aperture make wave front measurements difficult due to wave-front dislocations and anisoplanatism in the optical phase**

- **Solution**
  - **Novel adaptive optics approach without wave-front measurements**
  - **based on spatial light modulator (SLM) wavefront corrector**
  - **based on wavefront prediction**
  - **The control algorithm and system performance metric are optimized to compensate the wavefront distortions.**

System Design

- D/r_0 small (either weak turbulence or small aperture):
  - Log-normal intensity fading.
  - Multiple aperture system provides spatial diversity.
- D/r_0 large (either severe turbulence or large aperture):
  - For a single aperture system, PSF is no longer a single spot.
  - Received energy is distributed all over the pupil plane.
  - In equivalent multiple aperture system, each aperture collects smaller number of spatial modes. Hence, PSFs are less distorted compared to a single aperture system.



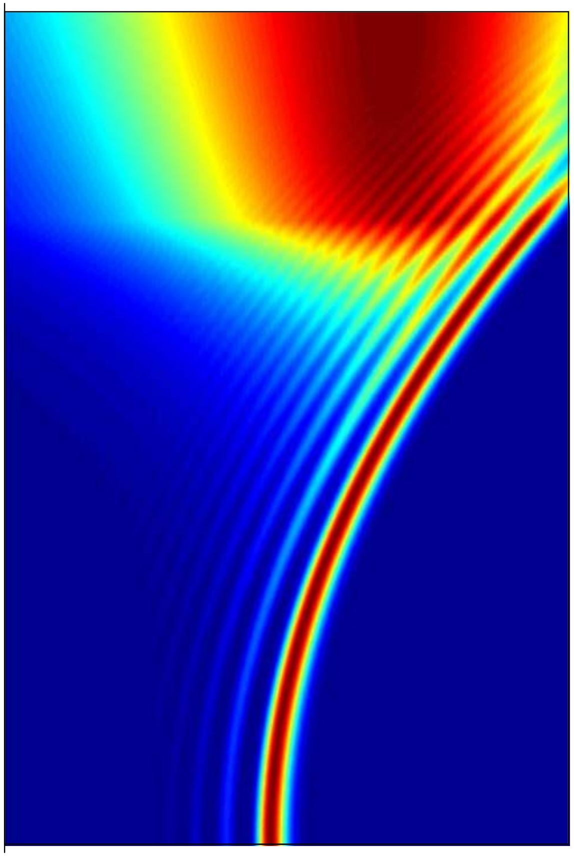


Other Design Configurations with Possible Potential

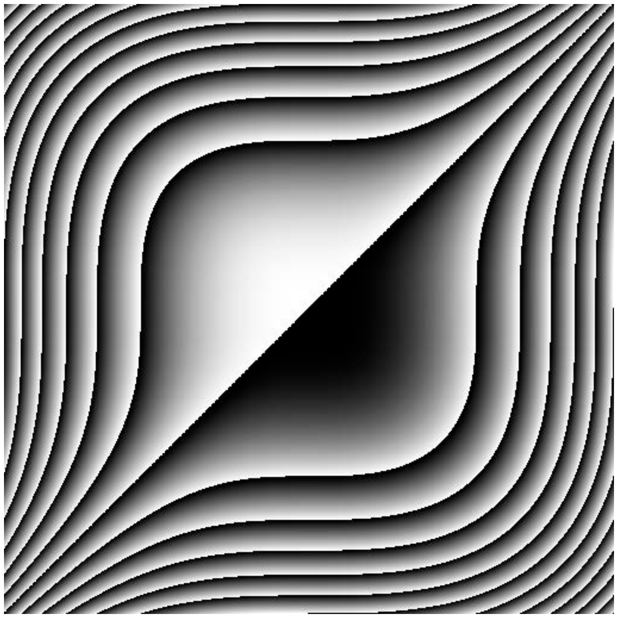
- **Airy beams - spatial bending (self-healing)**
  - Self-bend on propagation and overlap at the receiver plane, making these self-reconstruct after propagating through obstacles.
  - Retain their intensity profiles in turbulent atmosphere.
  - Scintillation of Airy beam arrays is significantly reduced.
- **Partially coherent beams-spatial coherence**
  - A lower scintillation than fully coherent beams, however, a larger angular spread and a relatively large spot
  - Delivering energy through mutually independent coherent modes or beamlets that propagate through statistically independent regions of turbulence.
- **Ultra-short optical pulses - - temporal coherence**
  - Greater bandwidth and improved reliability in high-speed FSO communications.
  - Pulse broadening by multi-scattering.
- **Can we synthesize a system configuration, using partially coherent Gaussian pulse Airy beamlets to mitigate intensity fluctuations?**

Airy Beam

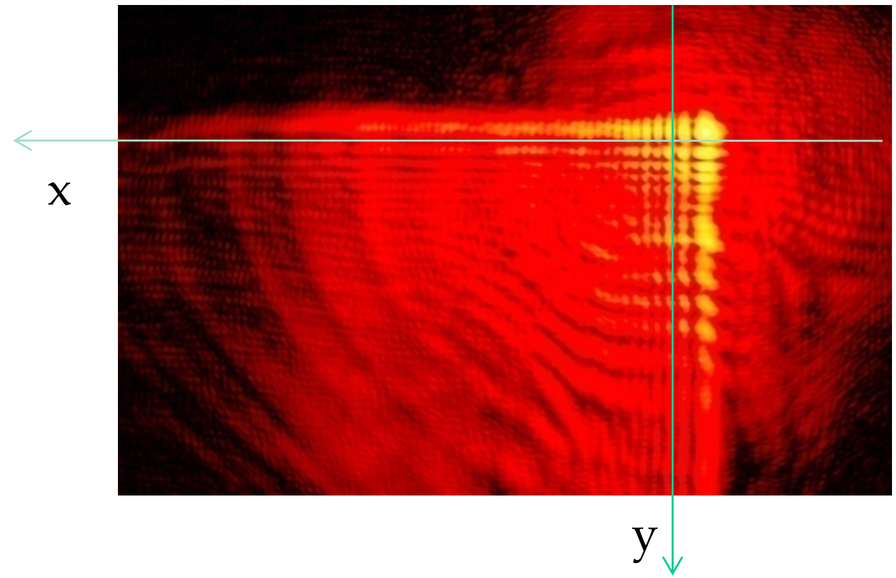
Propagation of a truncated Airy beam in free space



Generation of 2-D Airy Beam



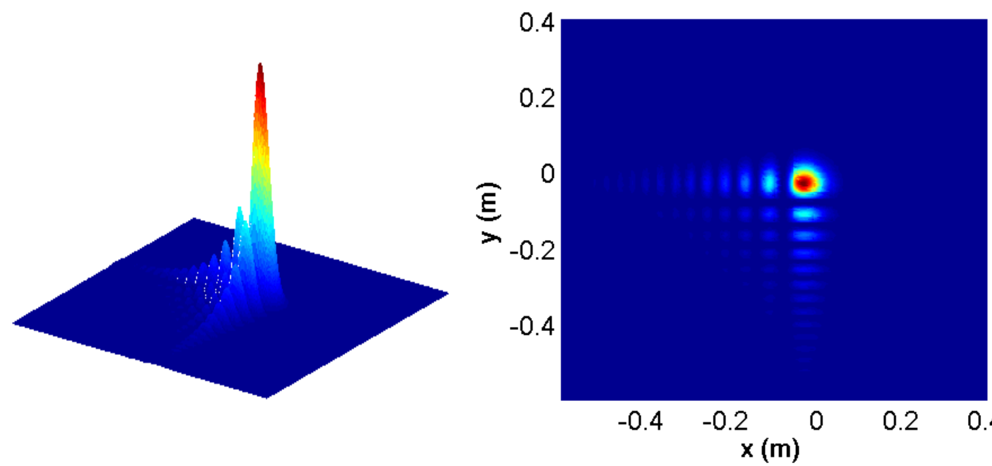
2-D Airy beam phase mask



Experimental intensity distribution

The scalar field of 2-D Airy beam

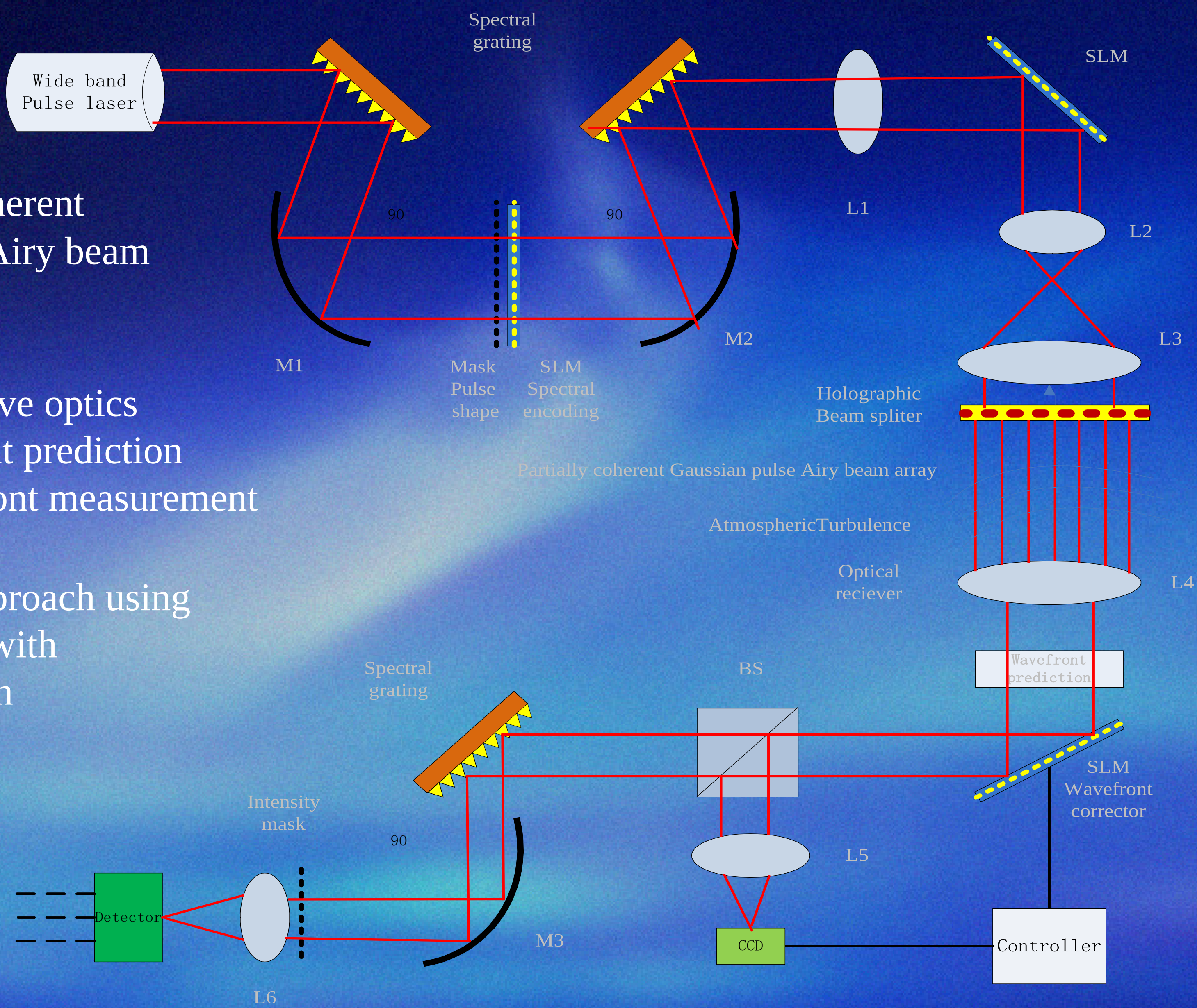
$$u(x,y,z=0) = Ai\left(\frac{x}{x_0}\right)\exp\left(\frac{a_0 x}{x_0}\right) \times Ai\left(\frac{y}{y_0}\right)\exp\left(\frac{a_0 y}{y_0}\right)$$



Theoretical intensity profile

Integration

- Partially coherent Gaussian pulse Airy beam
- Novel adaptive optics using wave-front prediction without wave-front measurement
- Diversity approach using multiple beams with multi-wavelength and multi-rate



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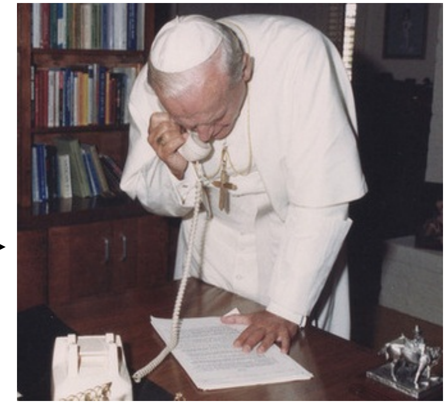
PHYSICAL-LAYER SECURITY

Secret Message



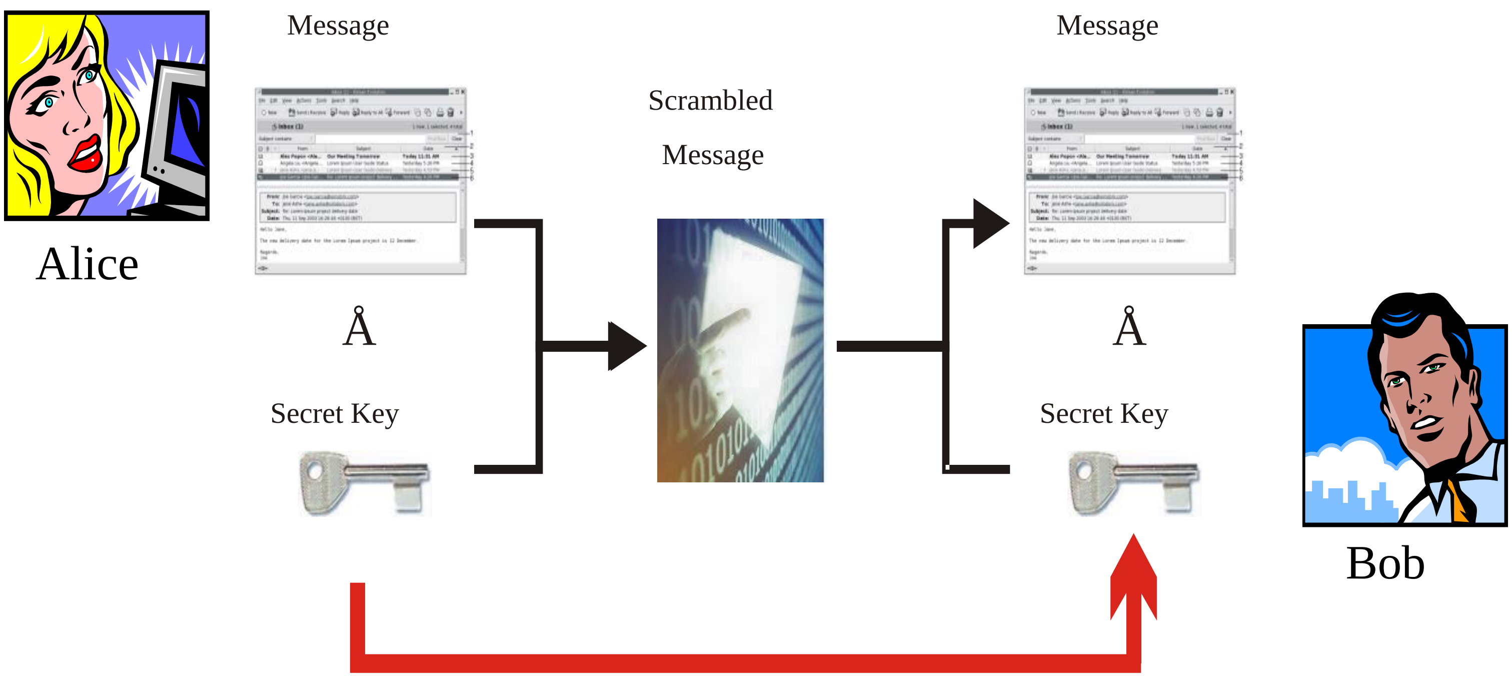
Alice

Bob

Eve (Eavesdropper)

Quantum Communications

Quantum Key Distribution



Secret key exchange by quantum cryptography

Optics at Penn State

Participants at 1st annual ***Symposium on Infrared Materials & Technologies*** (Oct. 2004, PSU)

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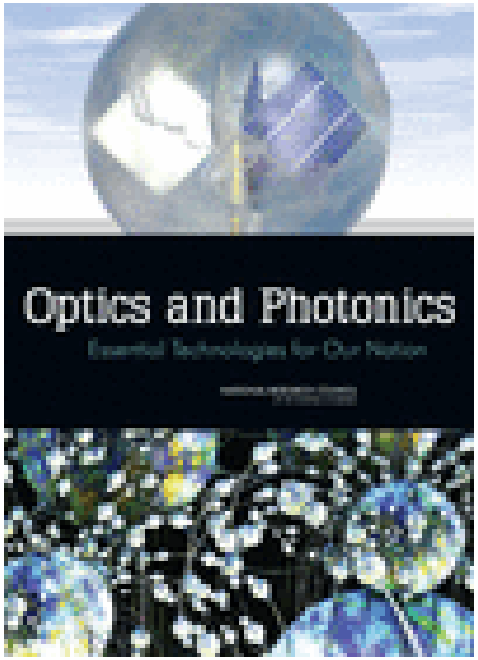
Report on Optics and Photonics - September 2012

A National Research Council (NRC) committee has just released a major report, ***"Optics and Photonics: Essential Technologies for Our Nation."***

The field of optics and photonics is extremely broad in terms of the technical science and engineering topics that it encompasses:

- **COMMUNICATIONS, INFORMATION PROCESSING, AND DATA STORAGE**
- **DEFENSE AND NATIONAL SECURITY**
- **ENERGY**
- **HEALTH AND MEDICINE**
- **ADVANCED MANUFACTURING**
- **ADVANCED PHOTONIC MEASUREMENTS AND APPLICATIONS**
- **STRATEGIC MATERIALS FOR OPTICS**
- **DISPLAYS**



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