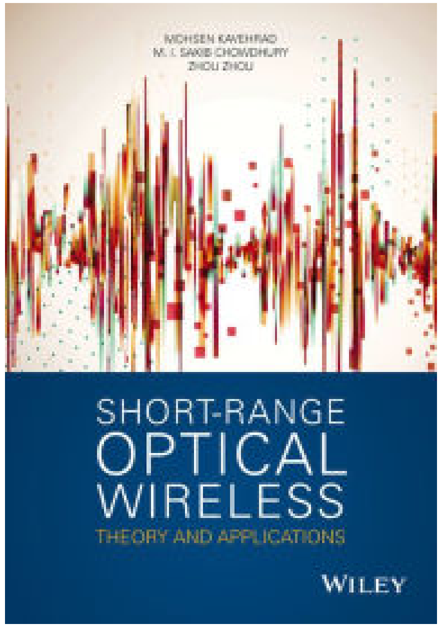
Optical Wireless: Theory and Applications



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ECE Institute
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2017 IEEE DLT
LUXEMBURG
June 2017

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.

Enormous Amounts of Traffic Between Data Centers

Let's assume…

- Servers in datacenter: 400,000
- Server interface rate: 25 Gb/s
- Traffic leaving data center: 10%

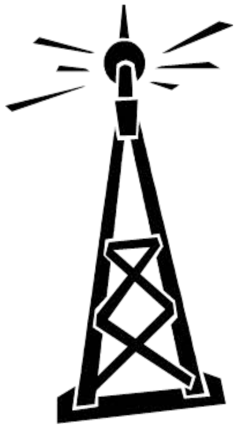
➔ 10,000 x 100G leaving a Mega-Datacenter! (~100 fully loaded WDM systems!)

http://www.google.com/about/datacen

Even if these numbers don't agree with your network, sooner or later they will

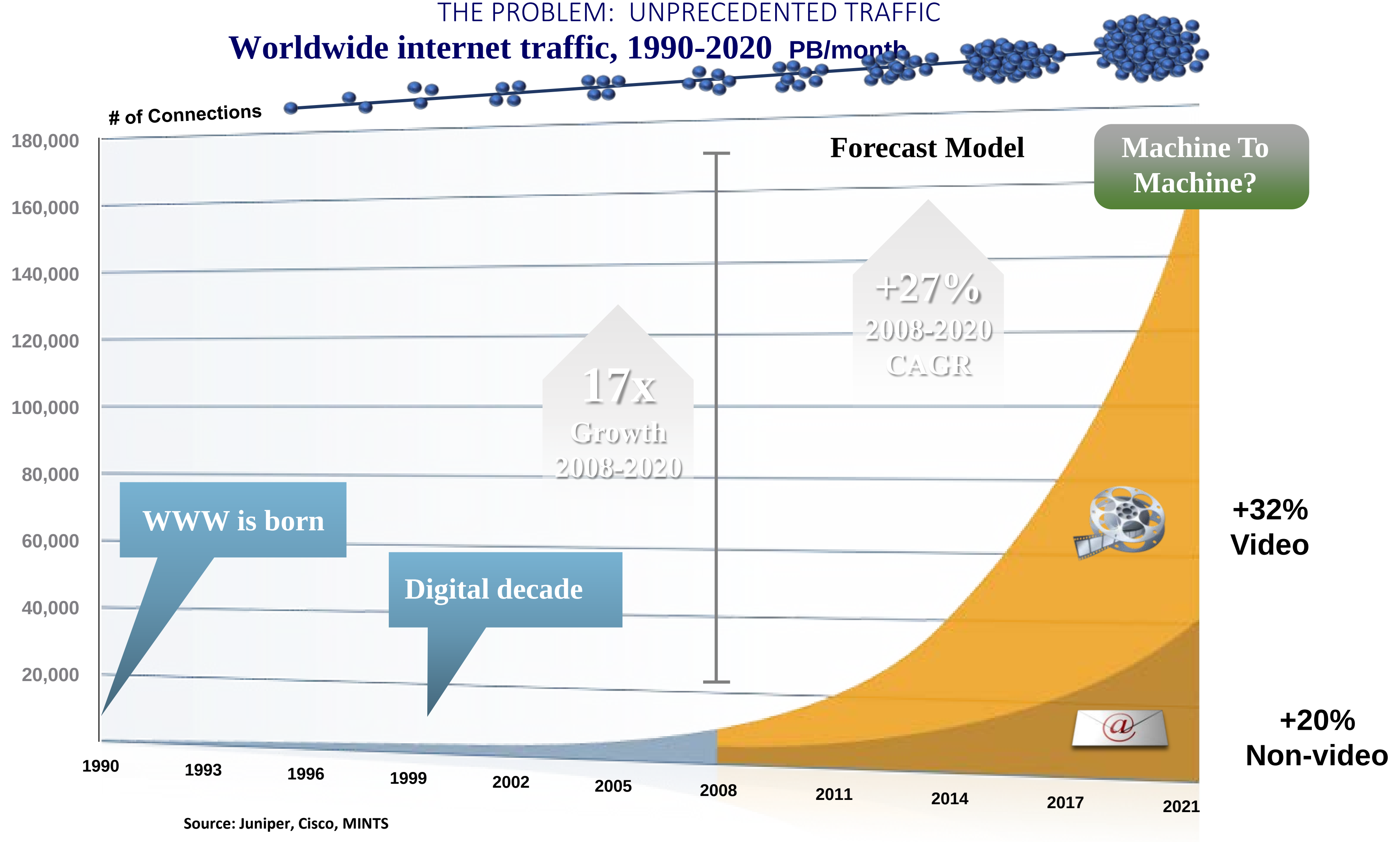
600 Terabytes of Wireless Data per Month !

1.4 Million Base Stations



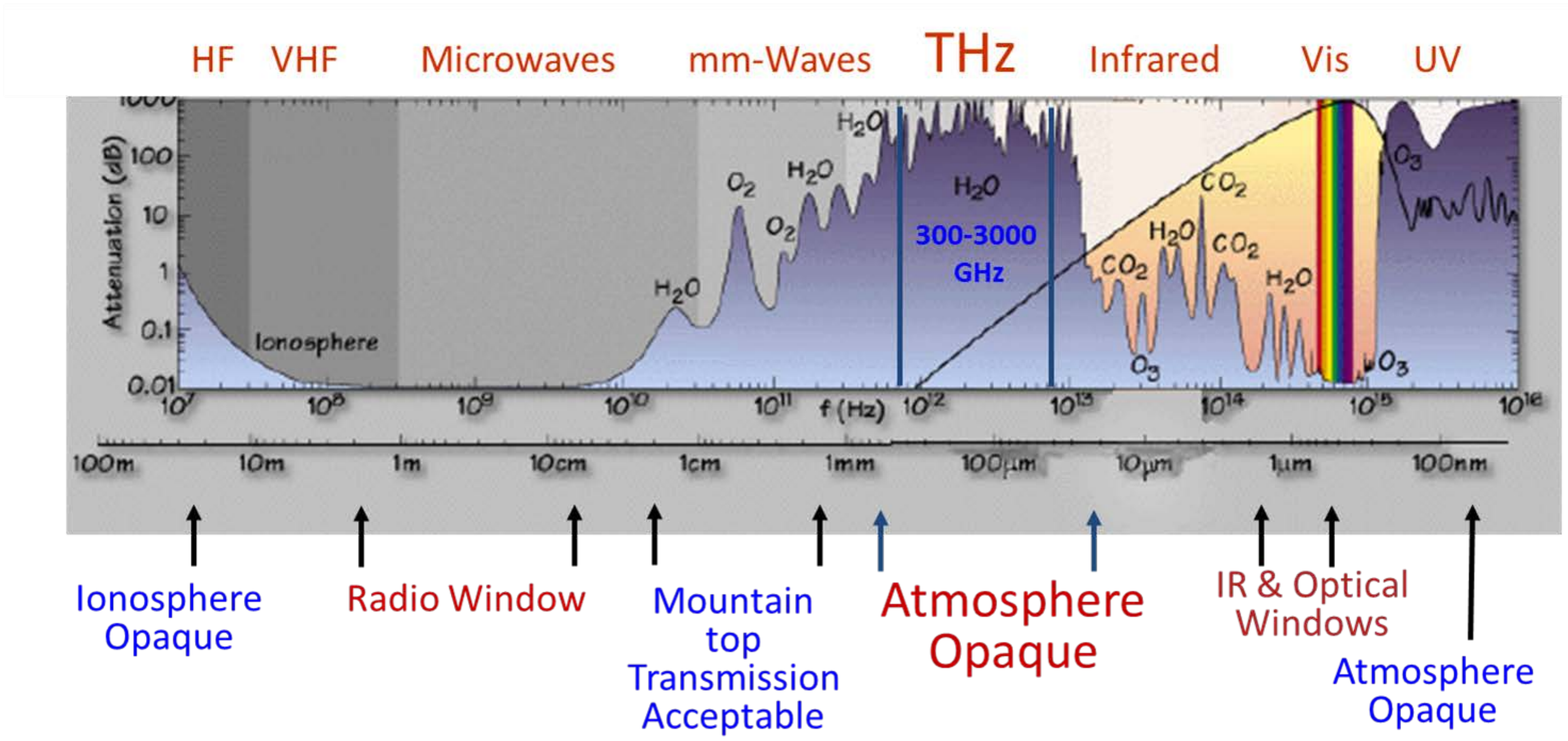
5 Billion Cell Phones

THE PROBLEM: UNPRECEDENTED TRAFFIC

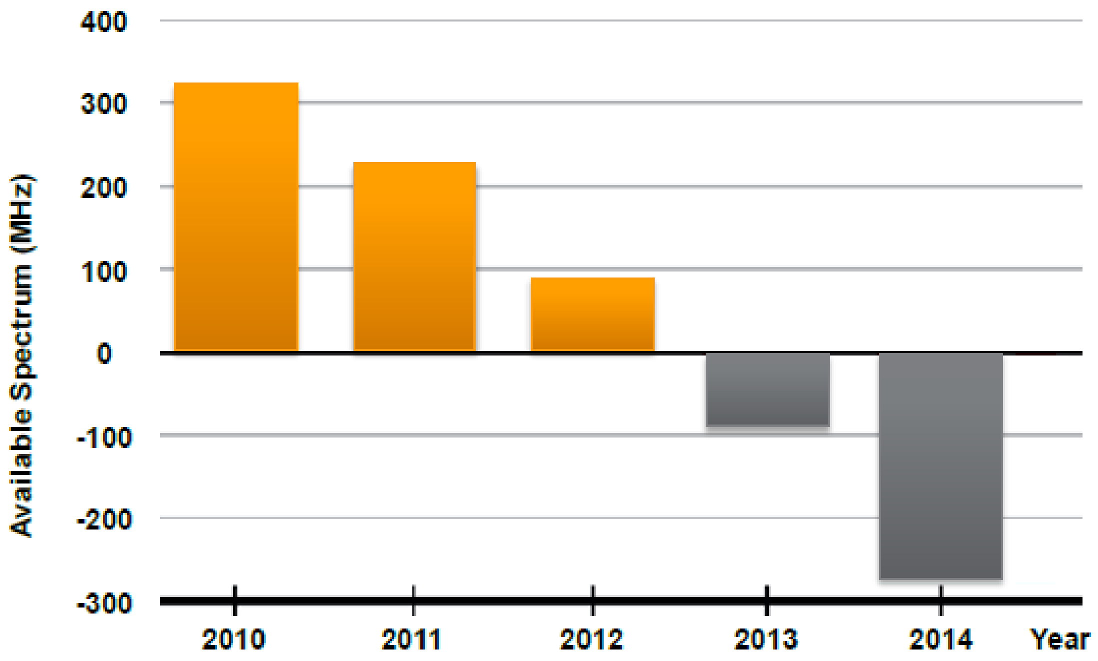


PENNSTATE CICTR

Atmospheric Transmission



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)

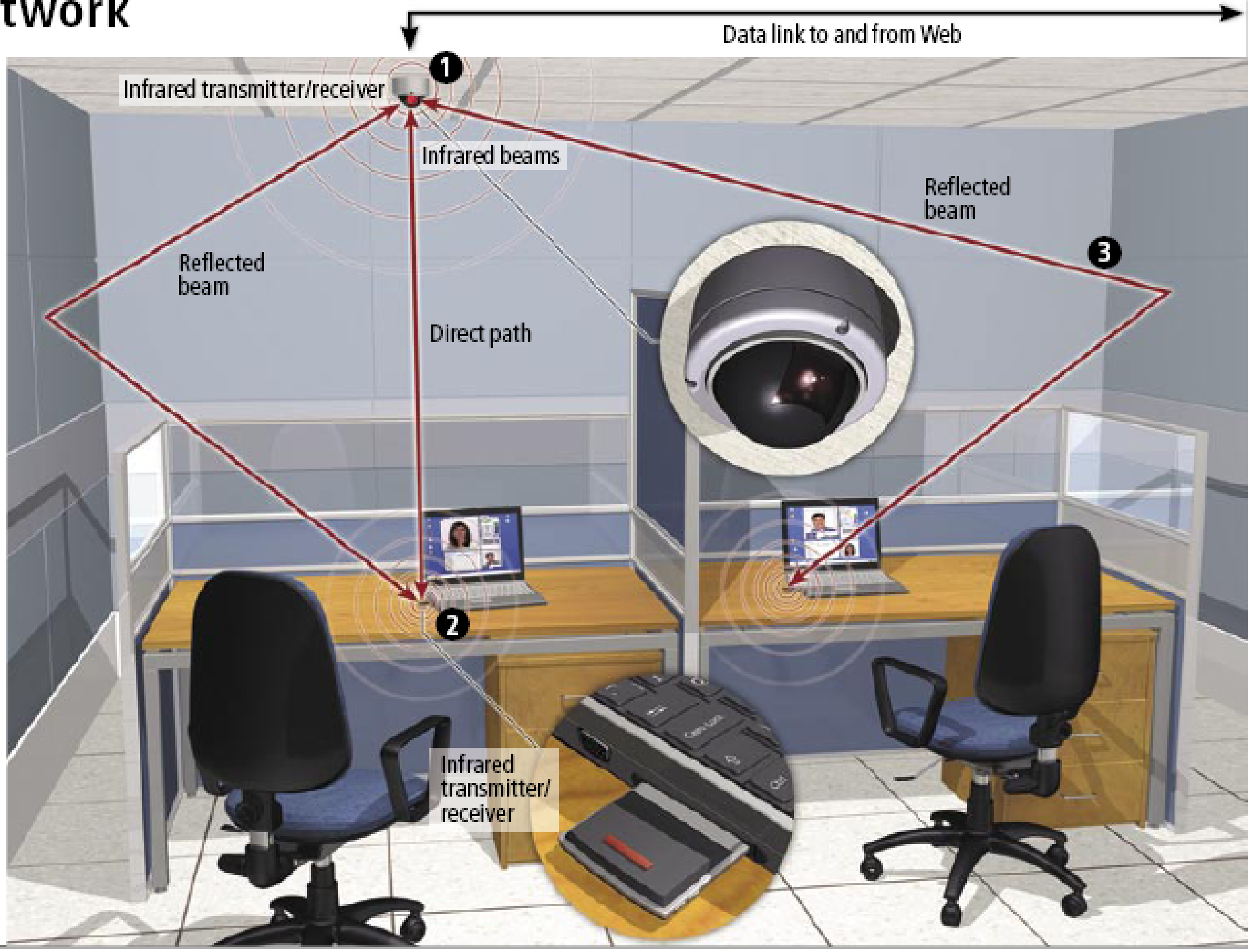
→ Infrared, visible and ultraviolet light

Visible Light and IR Wireless Communications

[HOW IT WORKS]

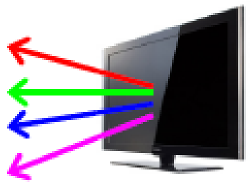
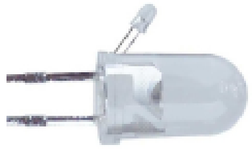
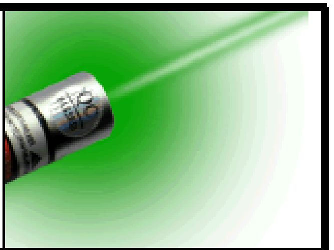
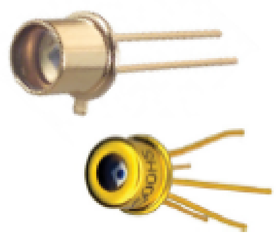
Optical Wireless Network

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.

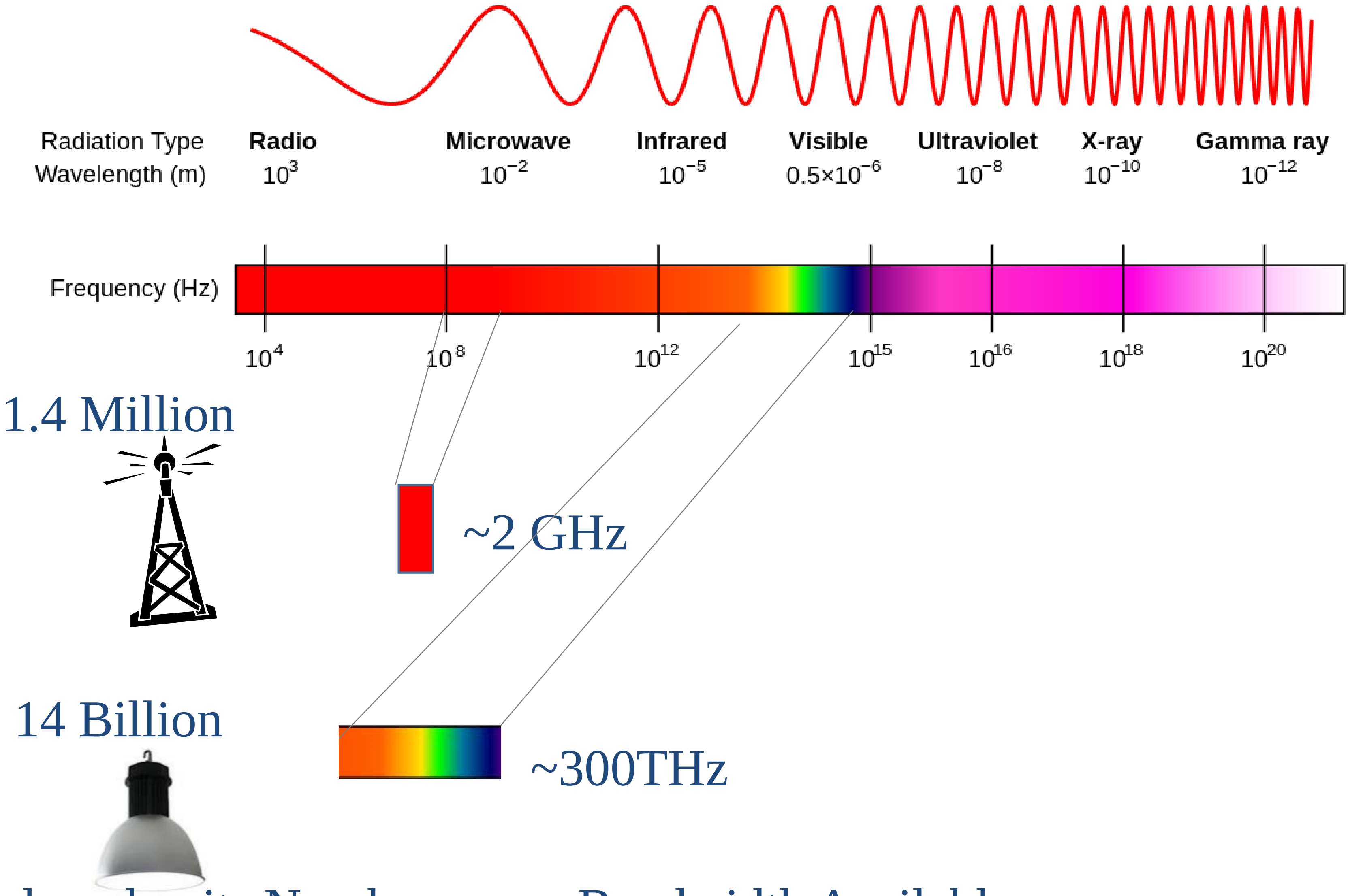


M. Kavehrad, "Broadband Room Service by Light," Scientific American Journal, July 2007

Classification by Optical Frontend

Transmitter / Receiver				
	Very low speed, dominated by the transmitter	Low speed, dominated by the receiver		
		Medium speed	High speed	Very high speed

Technology and Economic Impact

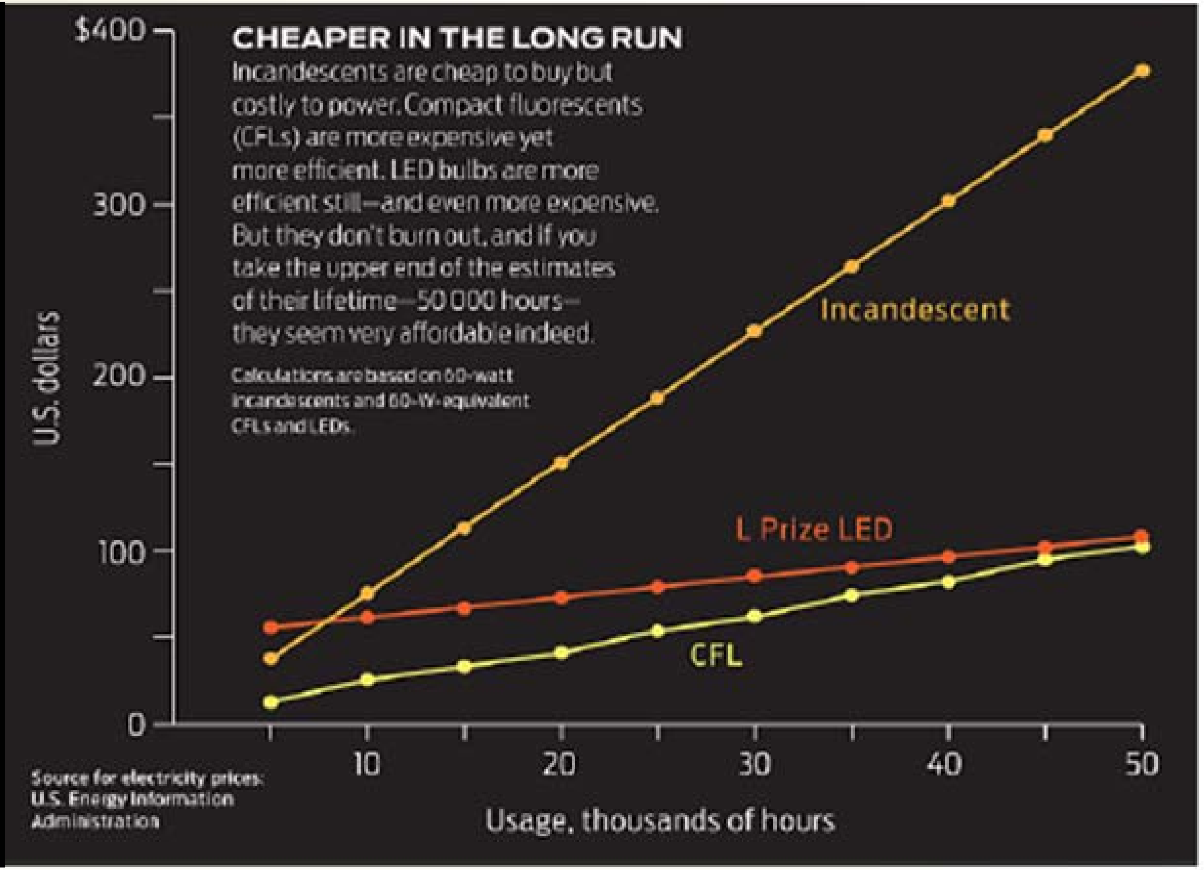


Deployed units Number

Bandwidth Available

Solid State Lighting

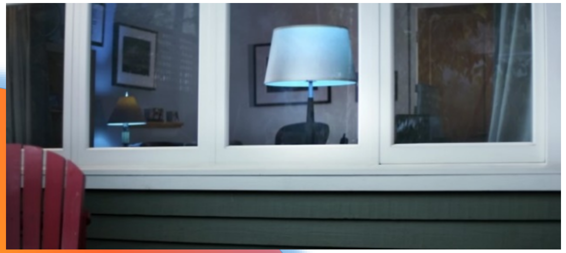
IEEE Spectrum: January 2012



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

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*

- ❑ **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*

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

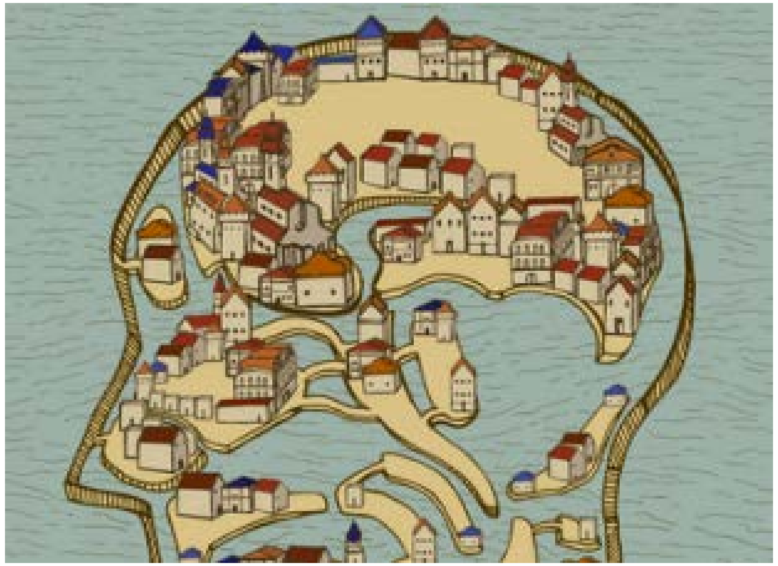
Commercial

Retail

Hospitality

PENNSTATE CICTR

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

Sensity: One Network, One Platform, Many Apps

Video Camera

Retail Analytics

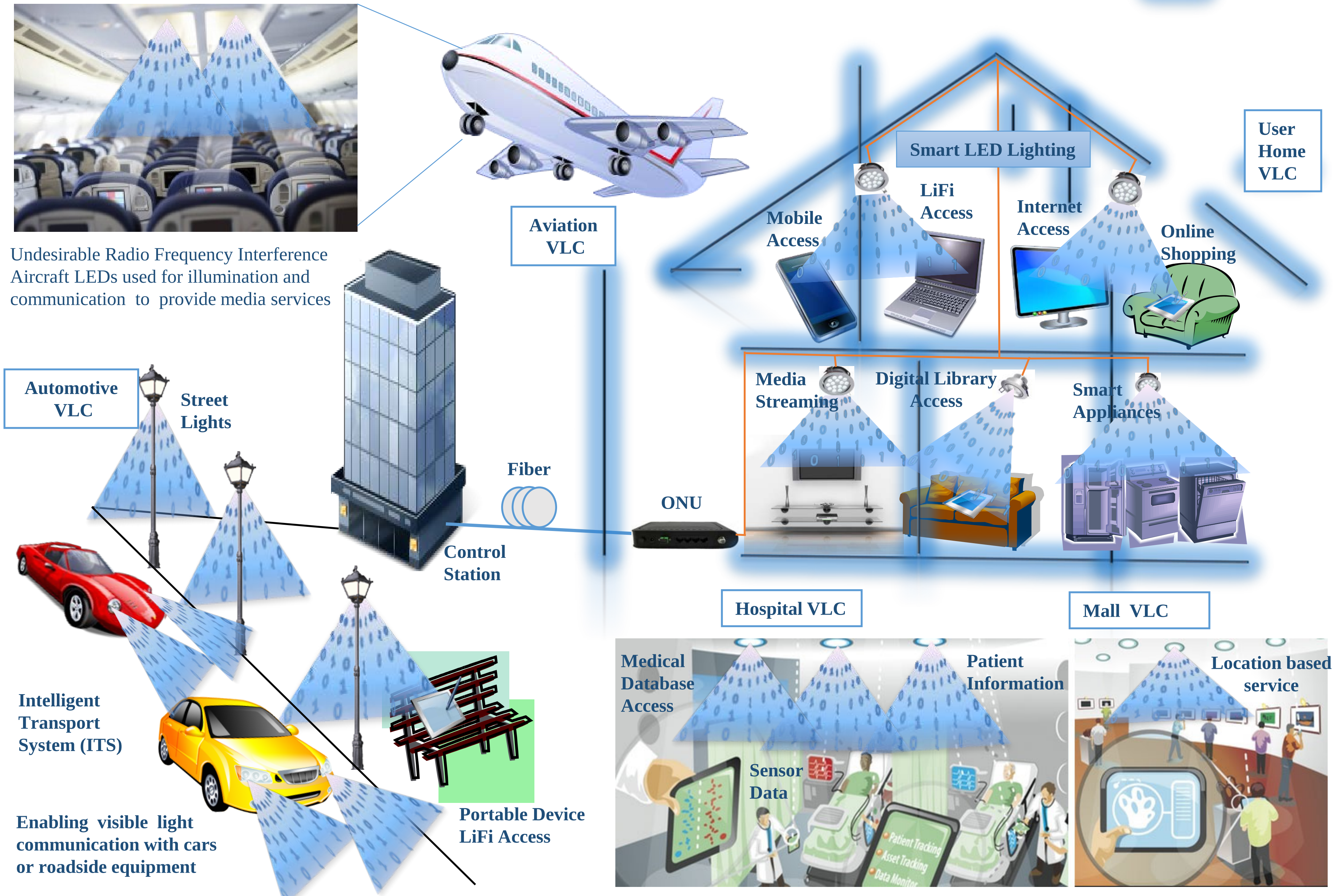
Parking System

+ 100’s of additional Apps

1 Network

No Trenching!

VISIBLE LIGHT COMMUNICATIONS



VLC Applications Areas


IT Security


RF-sensitive Areas, e.g. Hospitals


Private Households


Mechanical Engineering

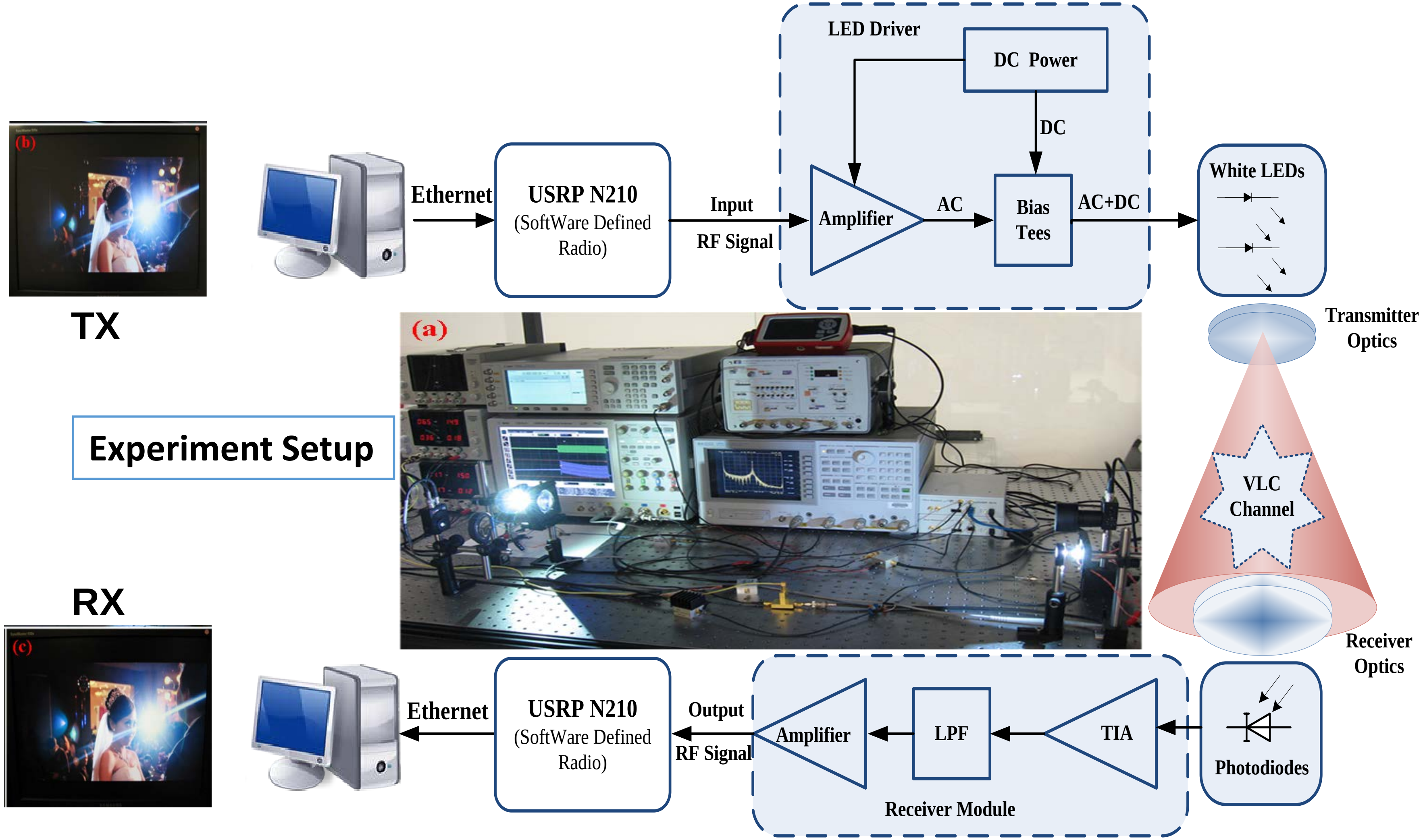

Advertising, Messaging


Tradeshows, Museums


In-flight Entertainment

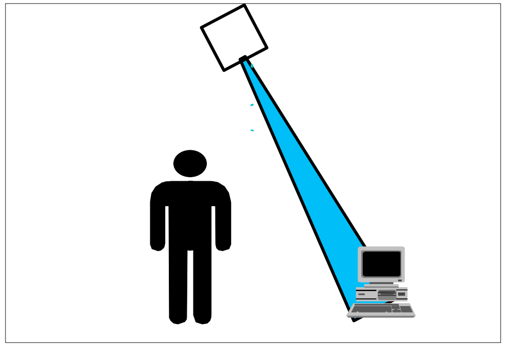

Underwater Communications

Experimental Video Transmission using Visible Light Communications



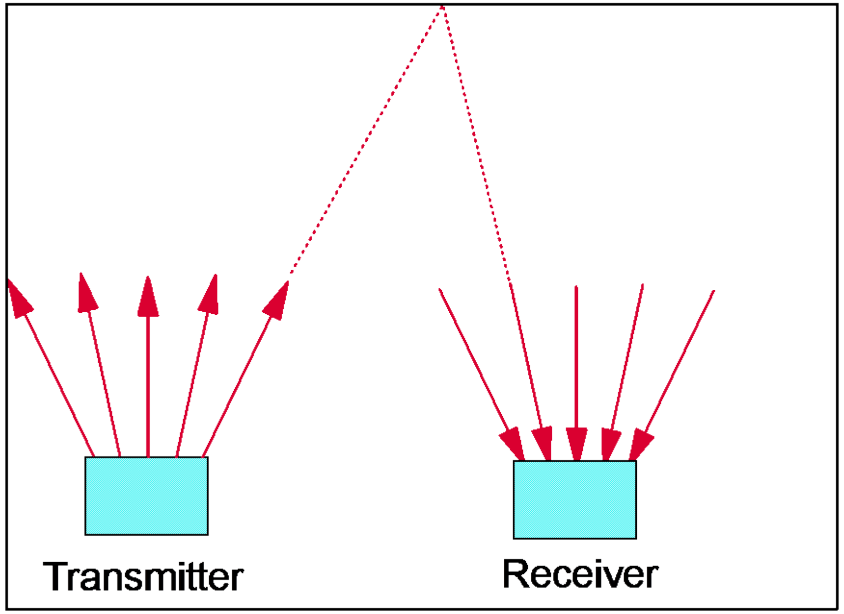
Architectures Suitable for Ultra High-Speed Indoor Wireless Communications

- Line of sight
  - Blocking
  - Require Base Station



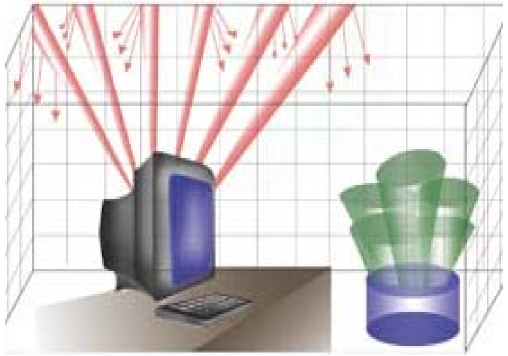
- Spot diffusing
  - Robust to blocking
  - Do not require infrastructure
  - More challenging link budget due to intermediate surface

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.

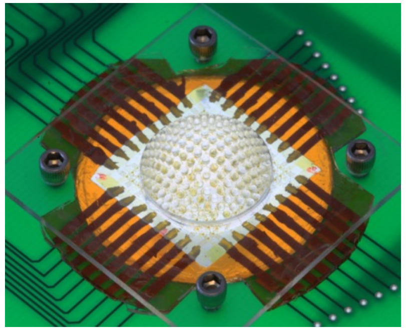
High-Speed MIMO Communications



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**

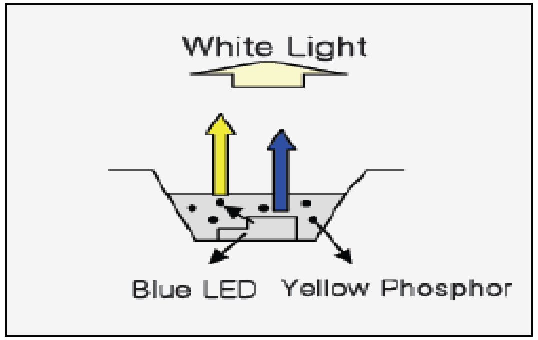
Biomimicry: The 160-degree, 180-pixel eye is inspired by an insect's compound eye

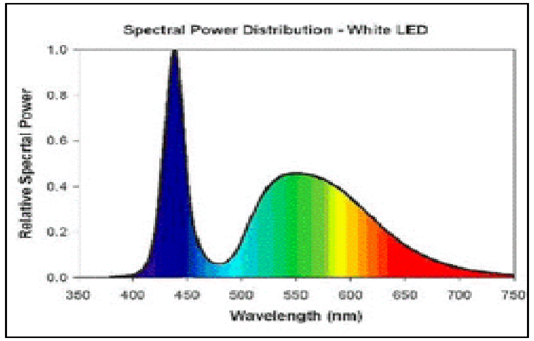
Photo: University of Illinois and Beckman Institute **Eye See You:** Composites of hard and soft materials and circuits make up an electronic version of an insect's compound eye.

Key Elements: LEDs and Lasers for Solid-State Lighting

Blue LED + Phosphor

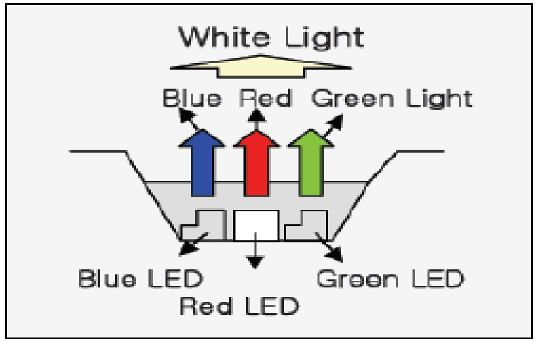
- Low-cost
- Simple driving
- Few MHz bandwidth (Phosphor)
- “Blue” filtering @Rx → 20 MHz

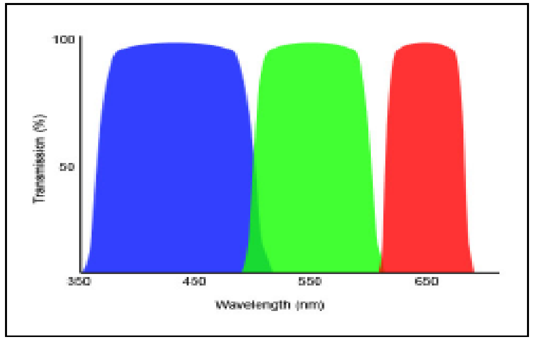




R G B LED

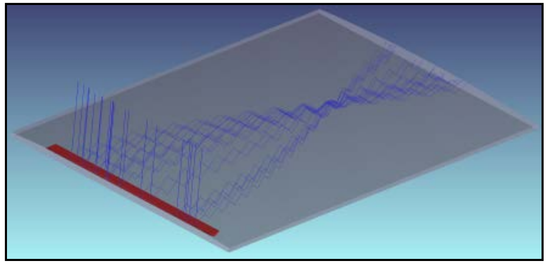
- Higher cost
- ~15 MHz per LED chip
- Enables WDM (using 3 drivers)

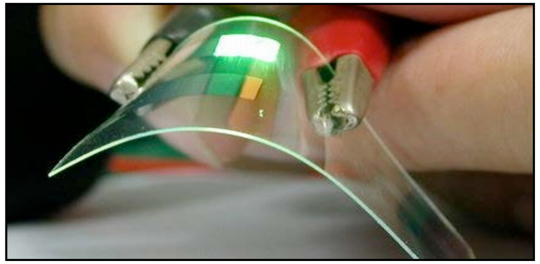




Organic LED

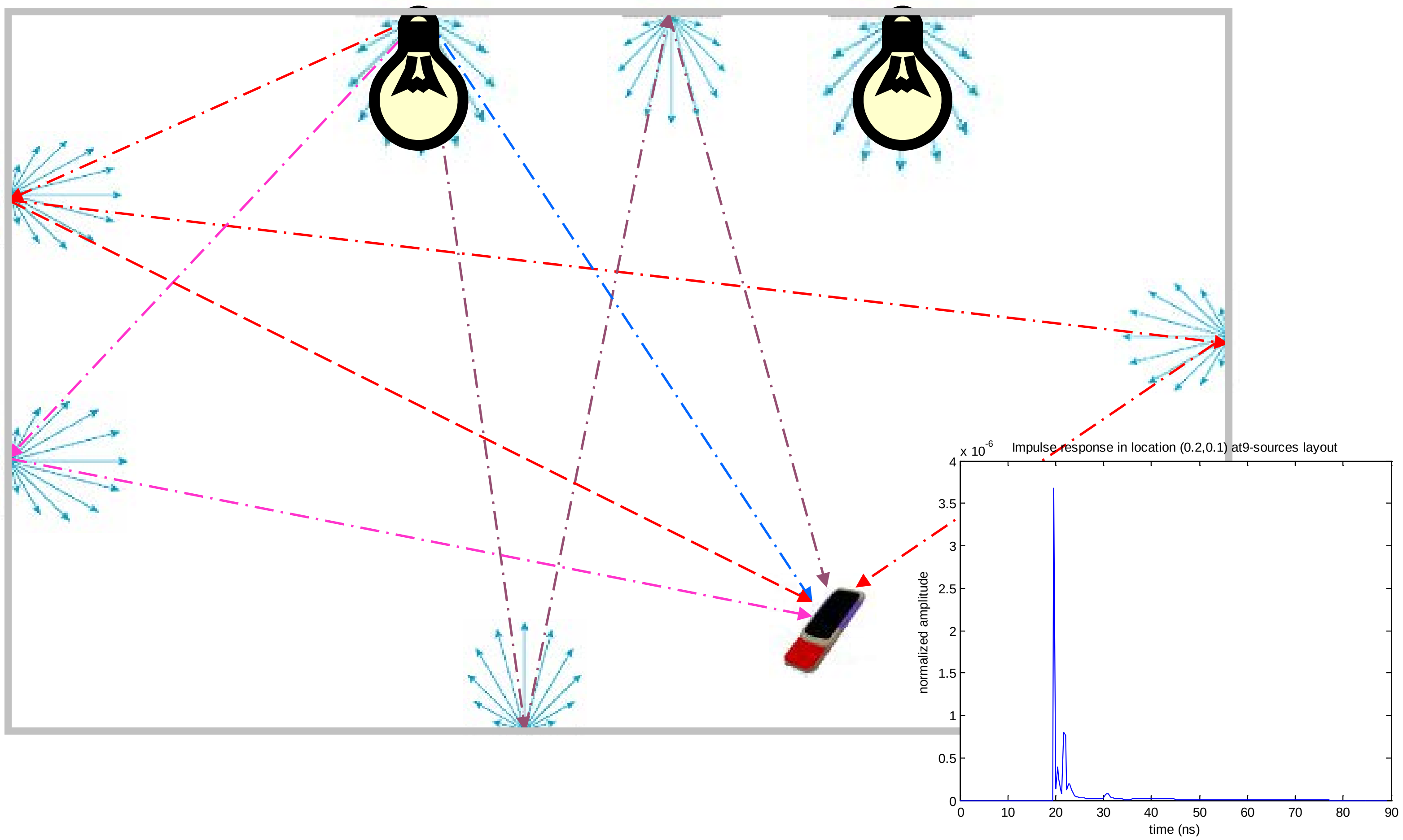
- Modulation Bandwidth >20 MHz





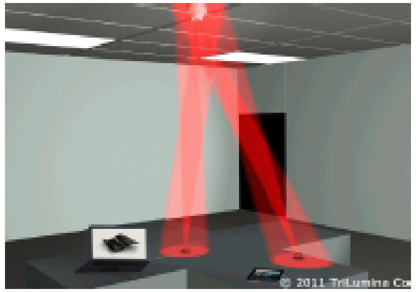
CMOS-controlled color-tunable GaN-based micro-LEDs pixels in smart displays have a modulation bandwidth of 100 MHz, providing a wavelength-agile source for high-speed VLC. OLEDs on top of the LEDs would act as a color conversion layer, multiplexing the signals into other colors.

VLC To Address Mobility:
Diffuse MIMO Communications



Goals of IrDA: 5 and 10 Giga-IR

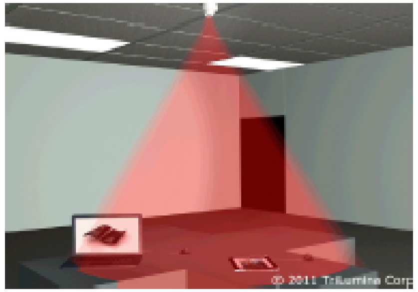
- Wavelength range 830 … 1550 nm
- Powers up to 1 W, always IEC class 1
  → extended optical sources
- Range 1 cm … 10 m, various radiation angles
- Final spec. were expected by end of 2012
- 1 Gb/s module recently demonstrated @ FhG-IPMS, Dresden


MIMO


Docking


Spotting

Beaming


Shower

Multi-Gigabit LAN

FEBRUARY 11, 2010

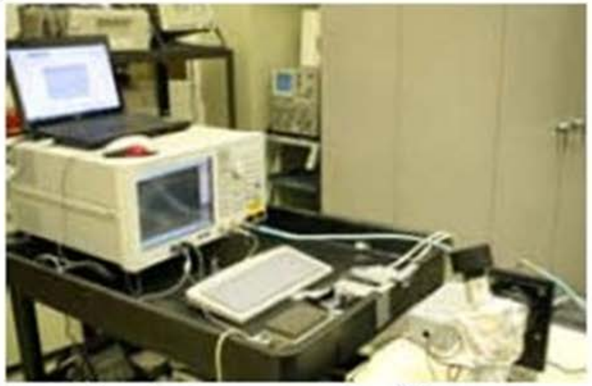
Technology Review
PUBLISHED BY MIT

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.

Ultra High-Speed Wireless Communications

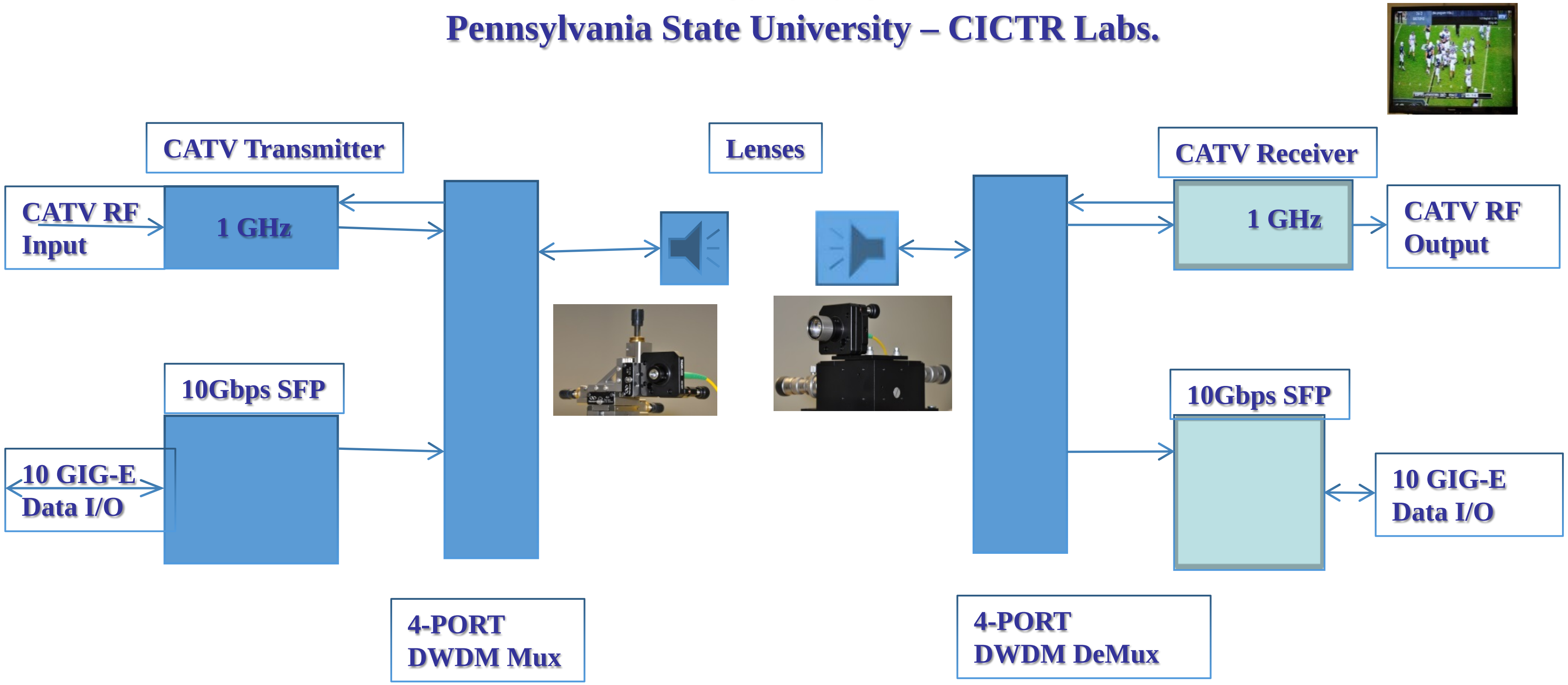
- **Pointed links:**
  - Data-Centers
  - Entertainment systems

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

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

June 2013

Pennsylvania State University – CICTR Labs.



https://www.youtube.com/watch?v=PaxFXNAnU70

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.

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

Add a Node to the Global Network: INTERNET

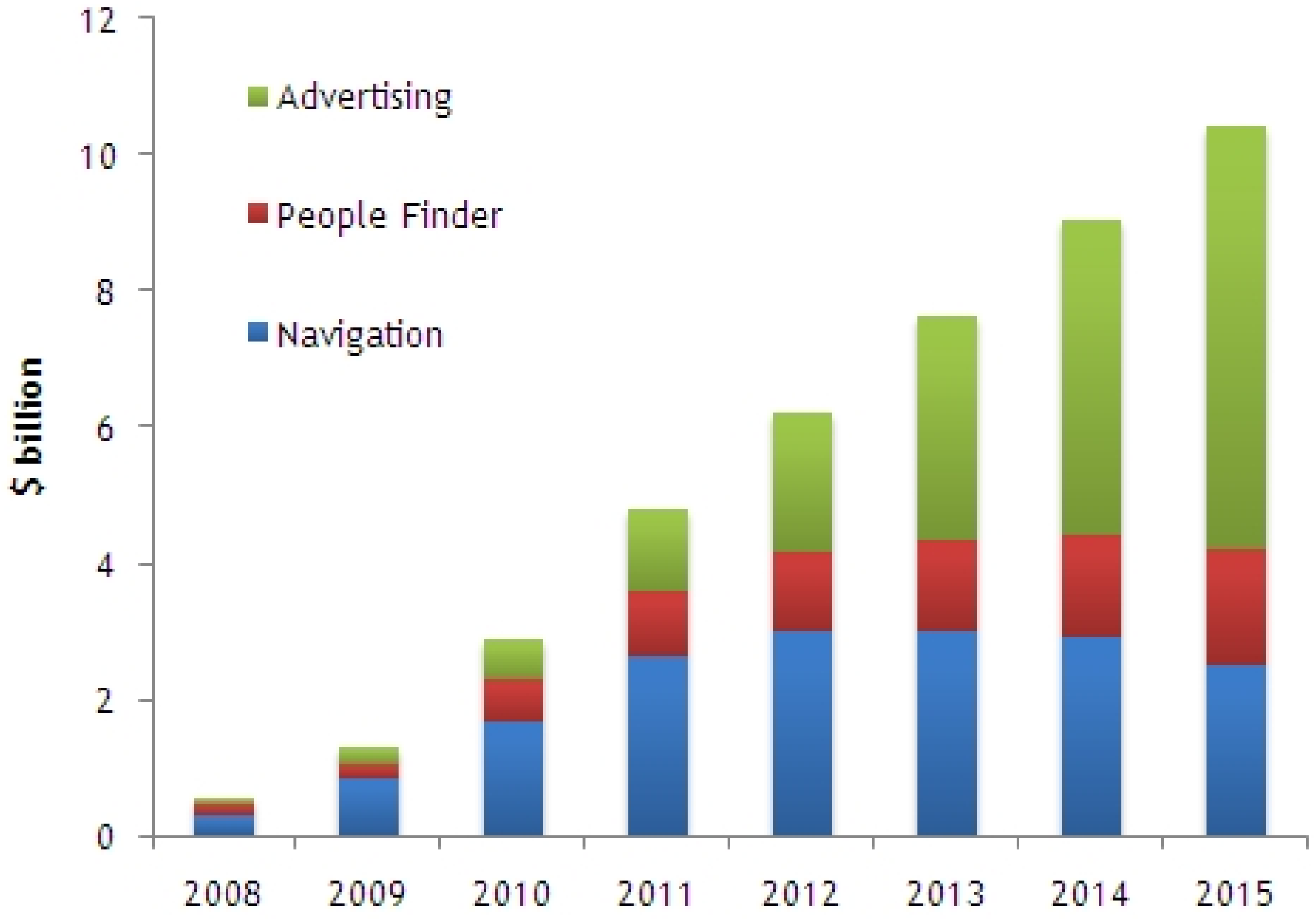
The IPv6-Addressable Light Bulb Goes On Sale GreenWave Reality and NXP launch 6LowPAN mesh-networked LED bulbs and home energy control platform.

Summary

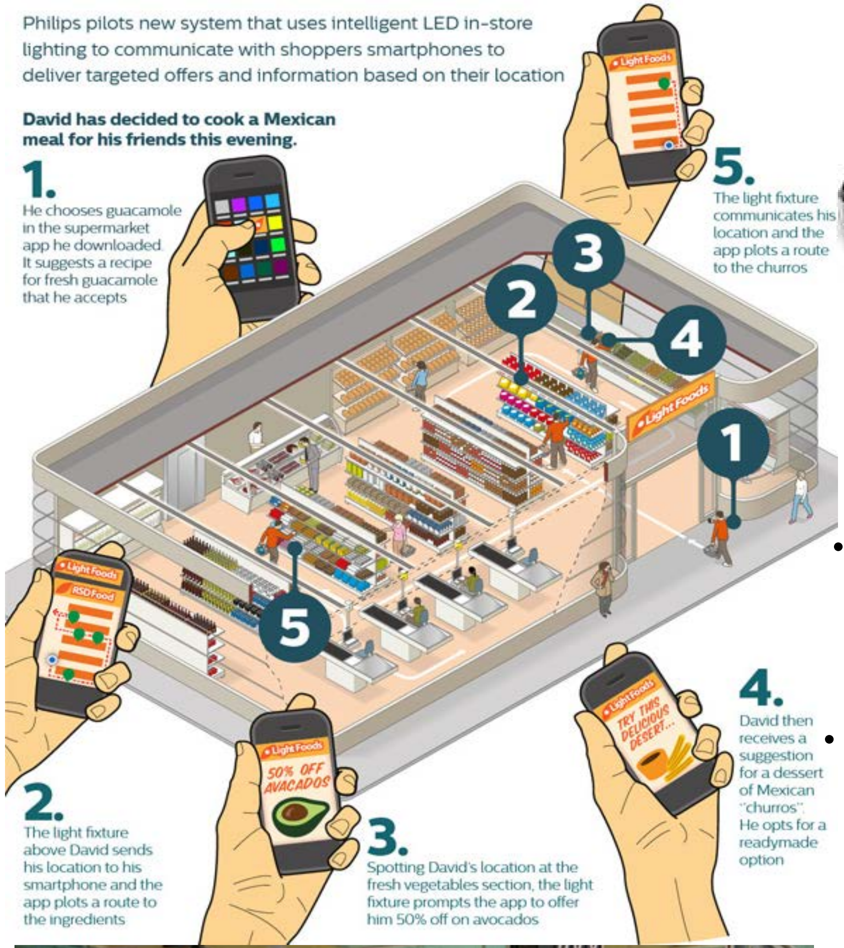
"The most compelling story of how ***Internet of Light*** will transform our world is the one still being written: the future of lighting, communications, sensing and the birth of a new enterprise lighting network.“

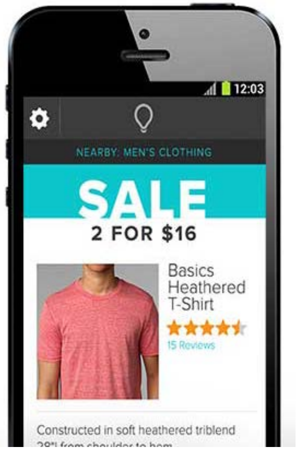
Projected Market of Location-Based Services

(Data source: Pyramid Research)



VISIBLE LIGHT POSITIONING

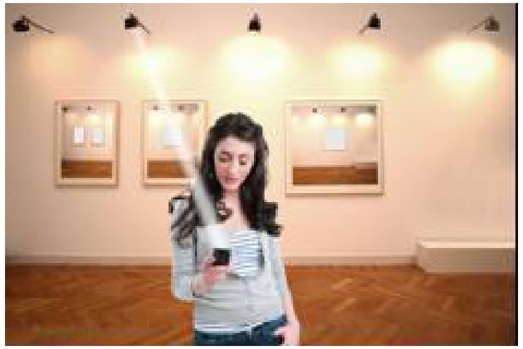


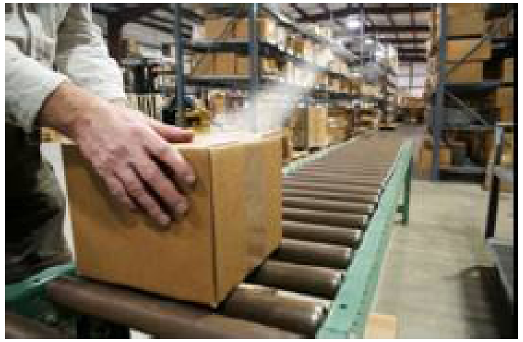


- *LED communicate a unique light pattern by VLC*
- *Connected shoppers listen with retailer's app on smartphone with a camera*
- *Camera detects unique light pattern, application notices shopper's position and direction*
- *Deliver location-based service and personalized content to each shopper*

R&D Indoor Localization & Navigation

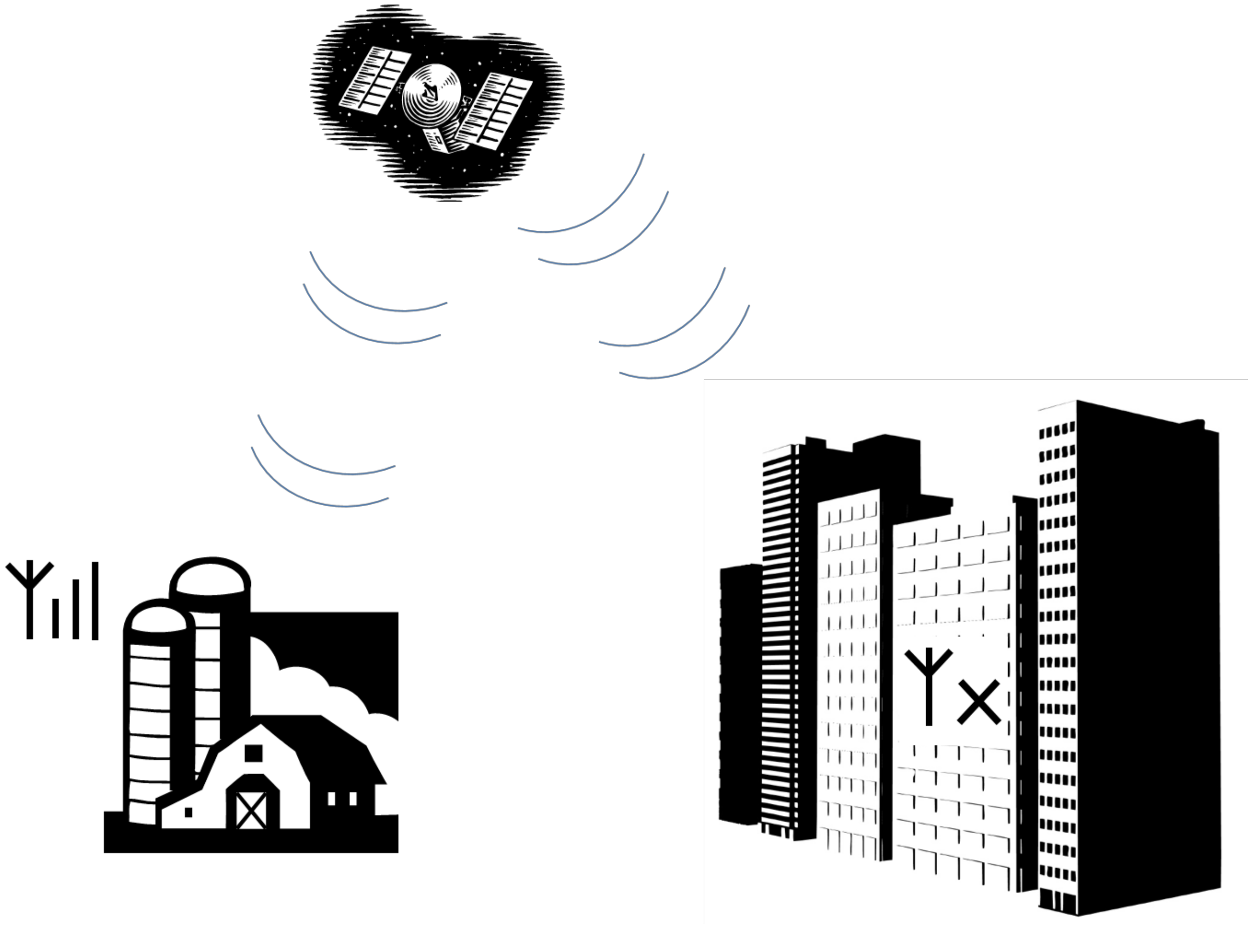
- Determination of local (indoor) position by means of lighting
- Attractive for medical areas, goods depots, complex buildings (guidance etc.), …
- Goal: 1 cm resolution, support of objects moving at walking speed
- Low-speed uplink, e.g. for system control (logging) via local access point





R&D in progress at several places

Motivation



Indoor Coverage Problem of Global Positioning System (GPS)

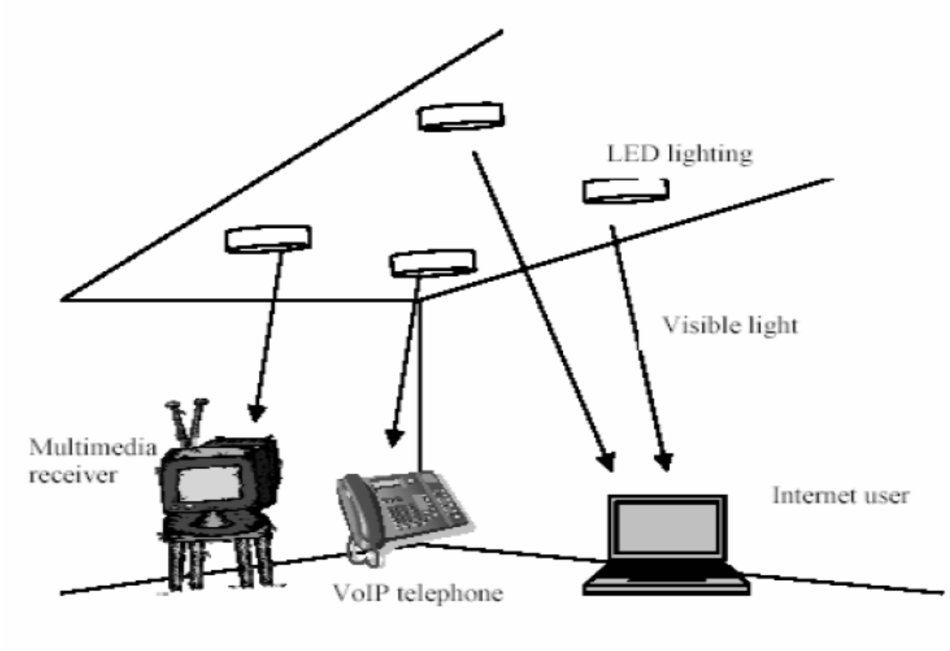
Motivation

- RF approaches (UWB, WLAN, Bluetooth) deliver positioning accuracies from tens of centimeters to several meters.

Positioning Method	Accuracy
Sapphire Dart (UWB)	0.3 m
Ekahau (WLAN)	1 m
TOPAZ (Bluetooth+IR)	2 m
SnapTrack (AGPS)	5 m-50 m
LANDMARC (RFID)	2 m

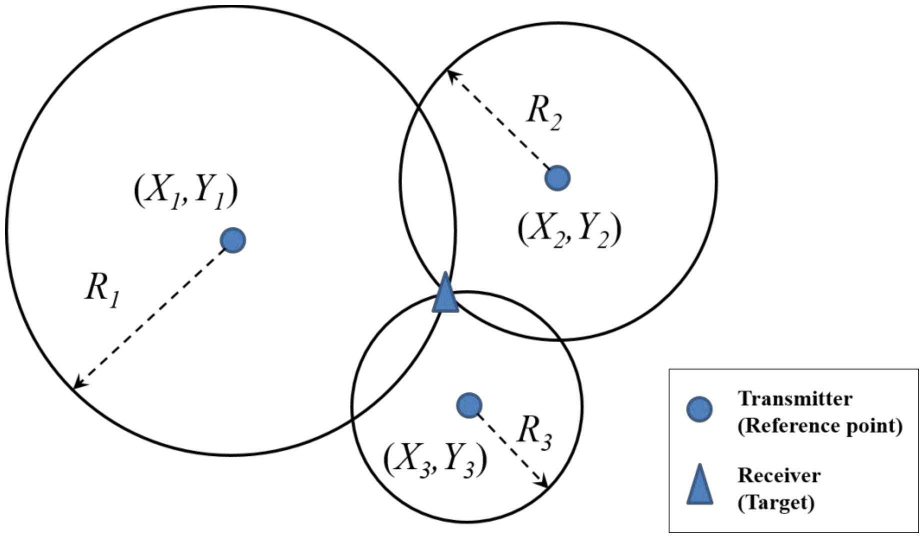
- Besides, more radio-frequency (RF) interference will be generated, congesting the limited mobile band.

Motivation

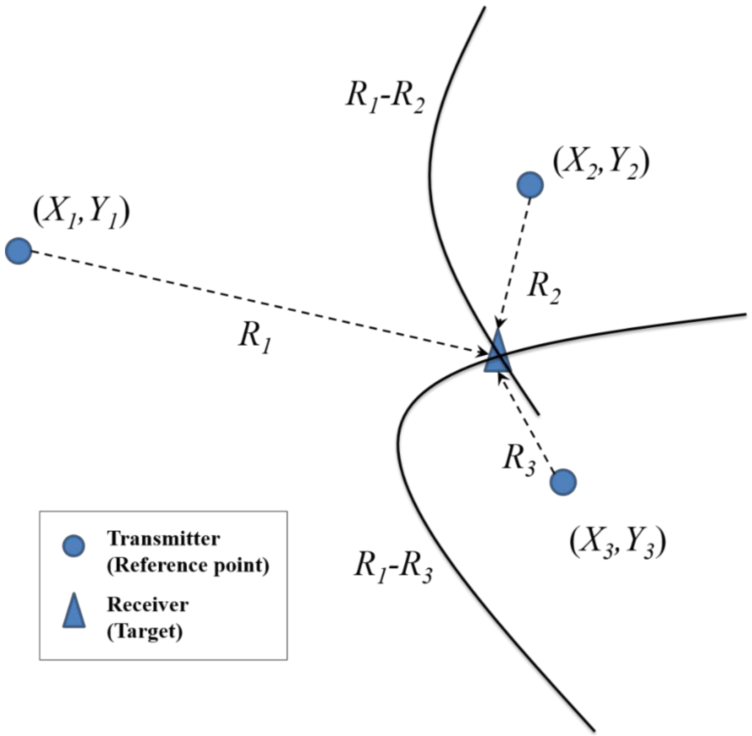


[1] M. Kavehrad and P. Amirshahi, "*Hybrid MV-LV Power Lines and White Light Emitting Diodes for Triple-Play Broadband Access Communications*", 2006.

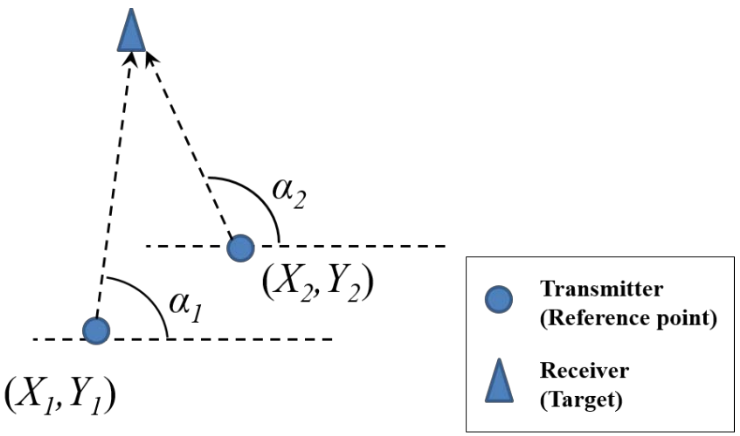
Positioning Techniques



Circular Lateration



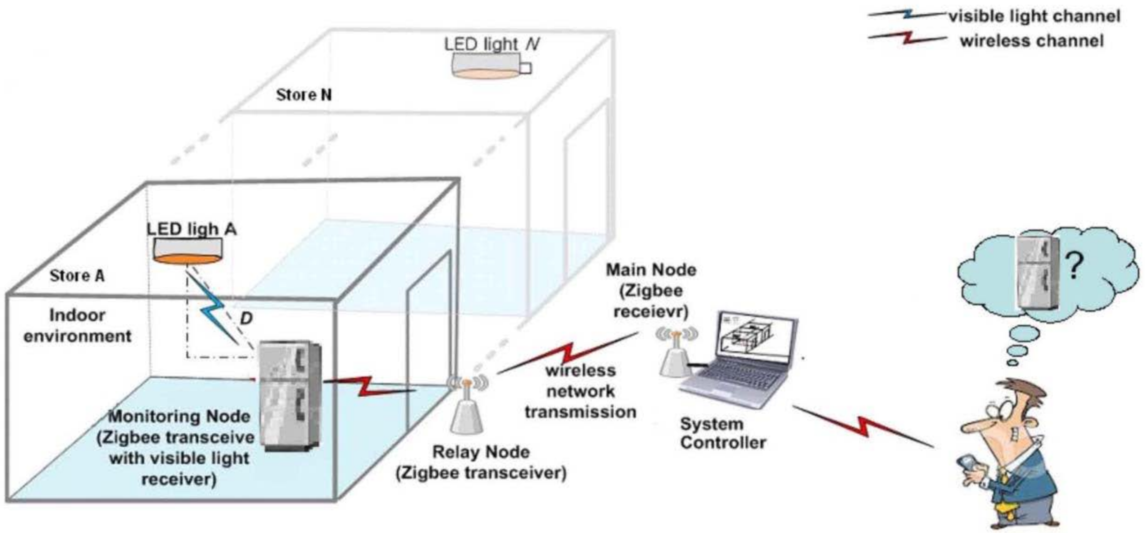
Hyperbolic Lateration

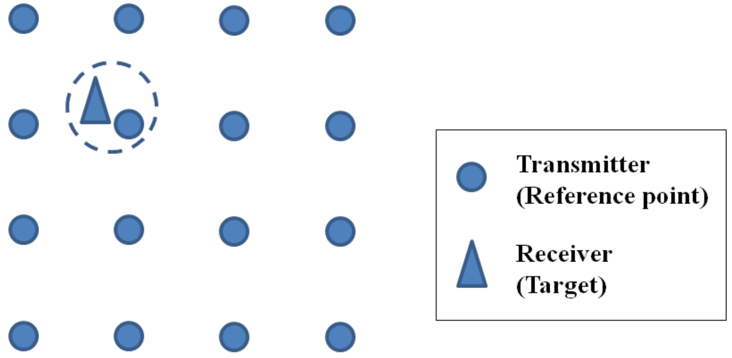


Angulation

Positioning Techniques

Proximity-based Hybrid Positioning using VLC and Zigbee



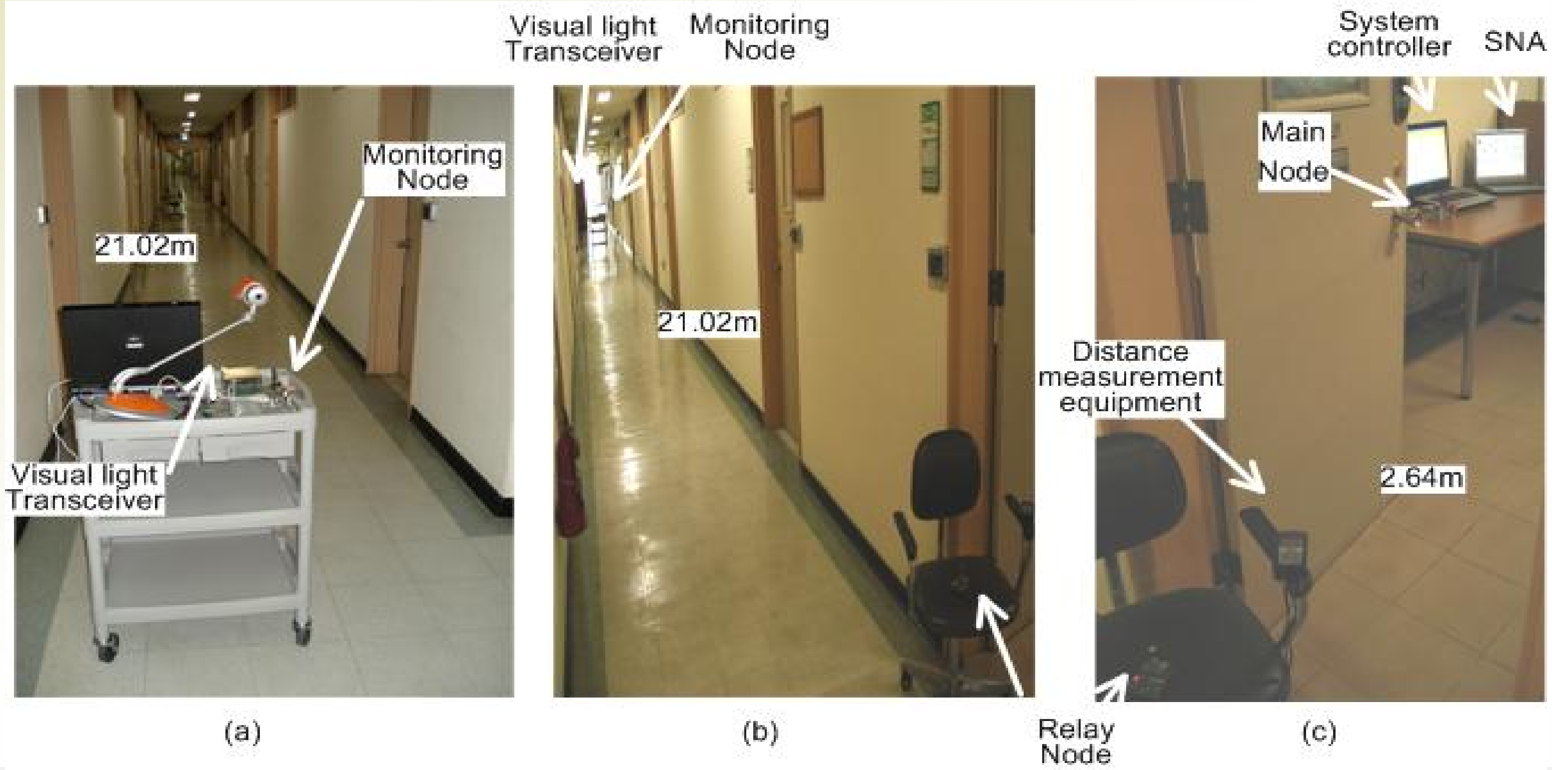


Proximity

- Y. U. Lee and M. Kavehrad,"Two Hybrid Positioning System Design Techniques with Lighting LEDs and Ad-hoc Wireless Network“, 2012.

Positioning System Implementation

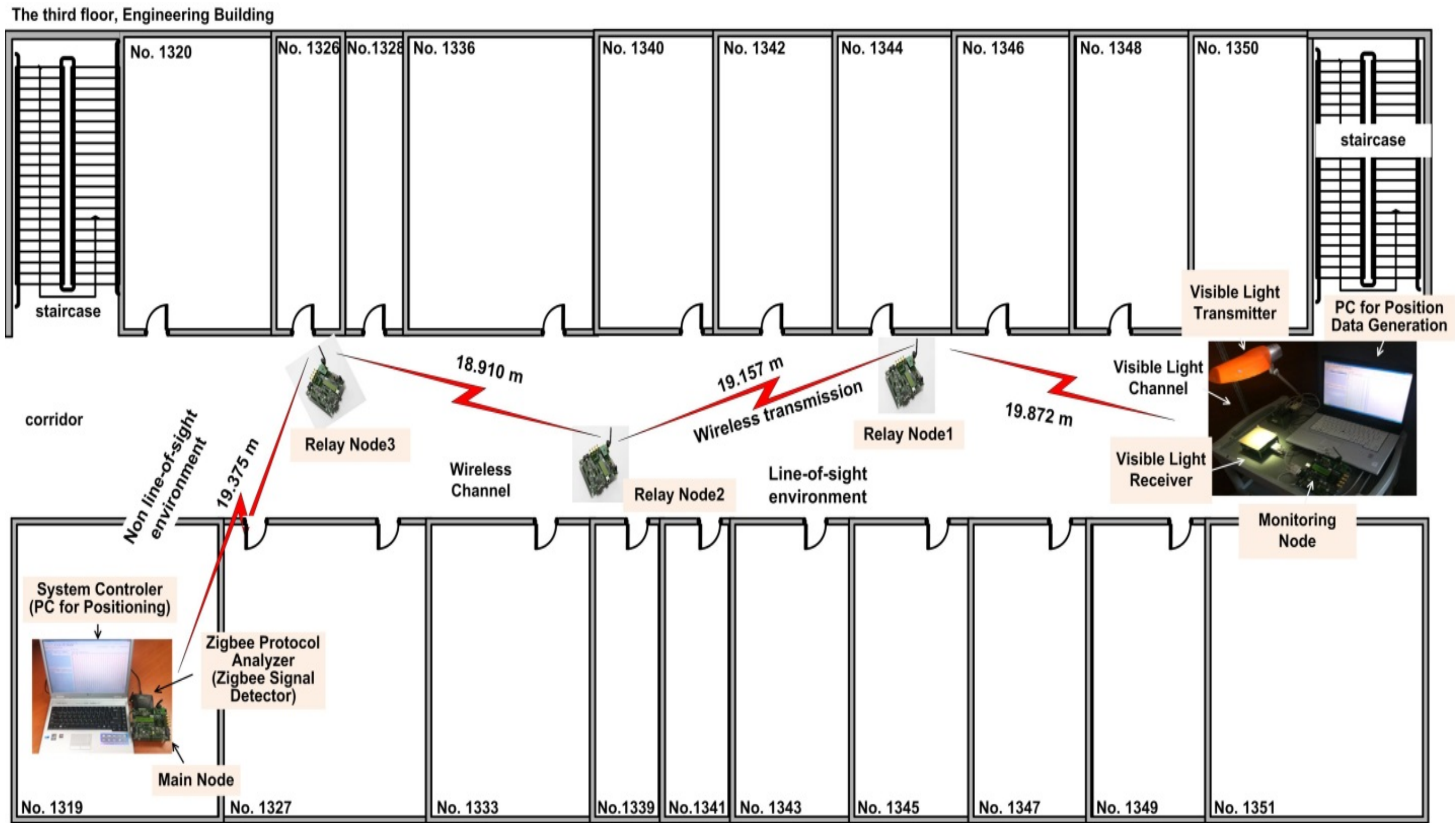
- **Hybrid RF/VLC Positioning Experiment** multi-hop wireless networking: with 24m distance between a target (i.e., monitoring node of Fig. (a)) and an observer (i.e., main node of Fig. (c)).



- 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.

Summary of Work

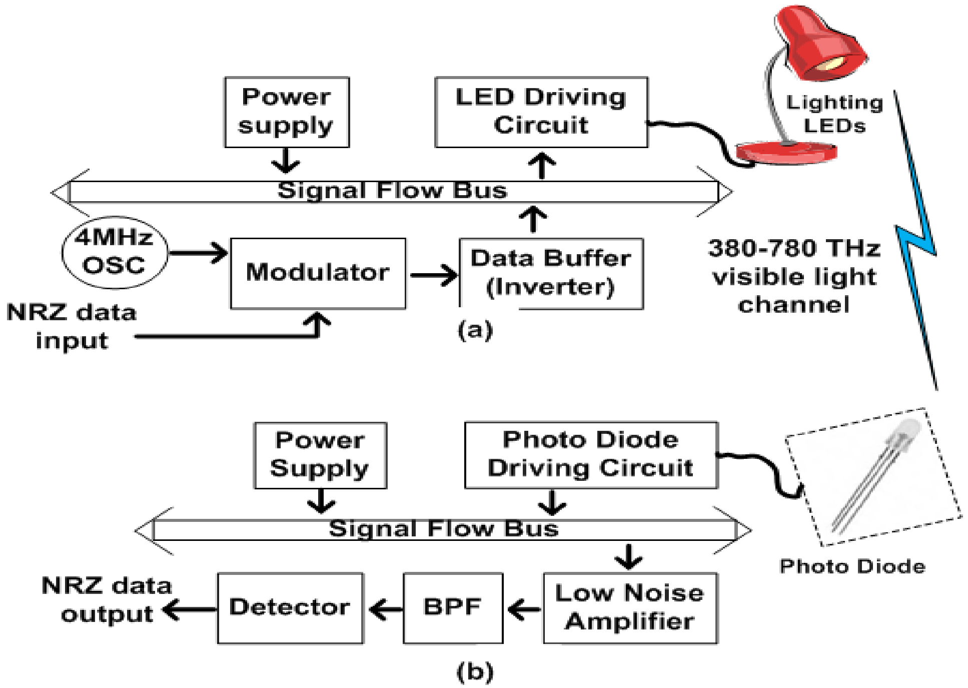
Experimental demonstration of a proximity-based hybrid positioning system



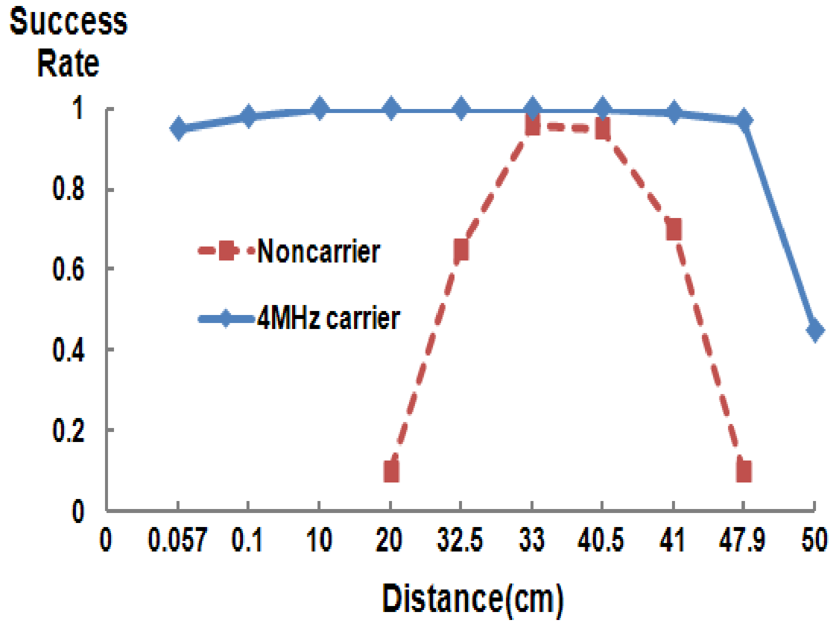
An experimental view of the long-range hybrid positioning with Zigbee wireless network transmission over 77.314 m

Summary of Work

Development of 4 MHz carrier visible light communication (VLC) based transceiver



A 4 MHz carrier VLC based transceiver architecture (a) transmitter (b) receiver



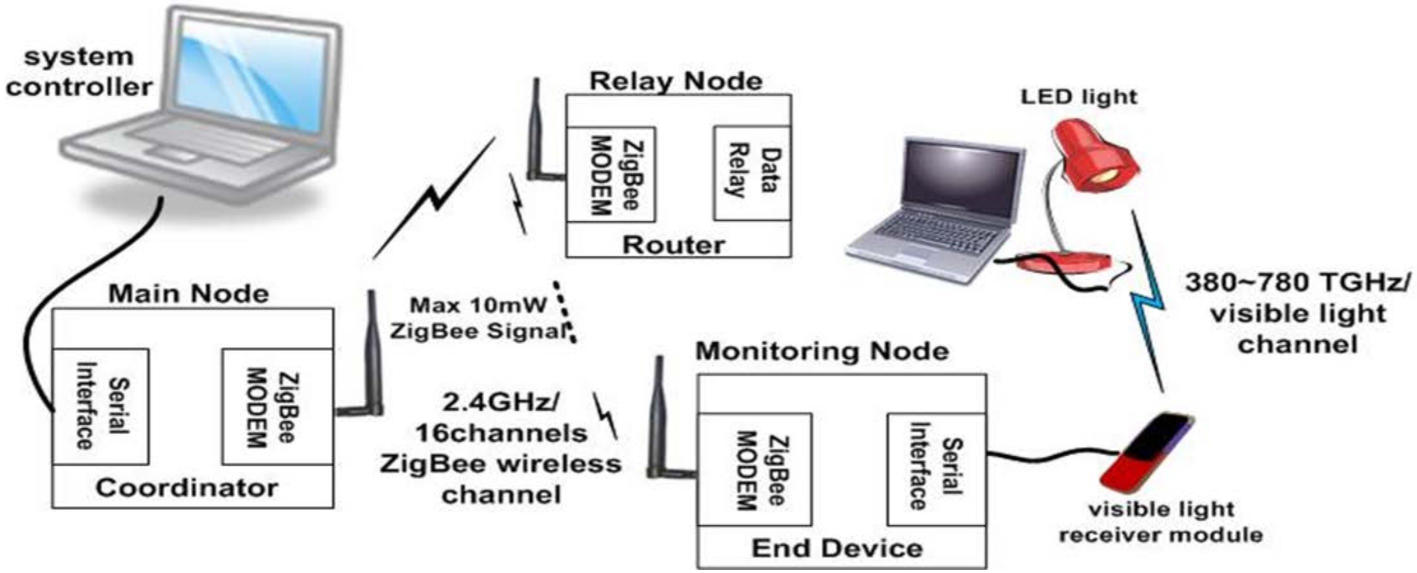
VL reception distance from transmitter depending on the transceiver circuits

Hybrid Positioning with Lighting LEDs and Zigbee Multihop Wireless Network

ScienceDaily®
Your source for the latest research news

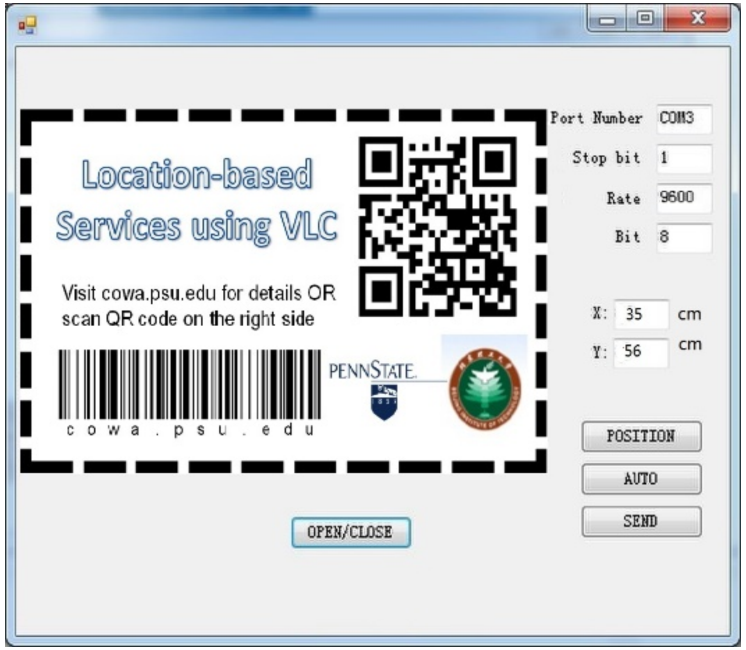
"LED lights are becoming the norm," said M. Kavehrad, W.L. Weiss Chair Professor of Electrical Eng. and director of the NSF COWA at Penn State. "The same lights that brighten a room can also provide location information.“

January 2012



Summary of Work

Experimental realization of location based services

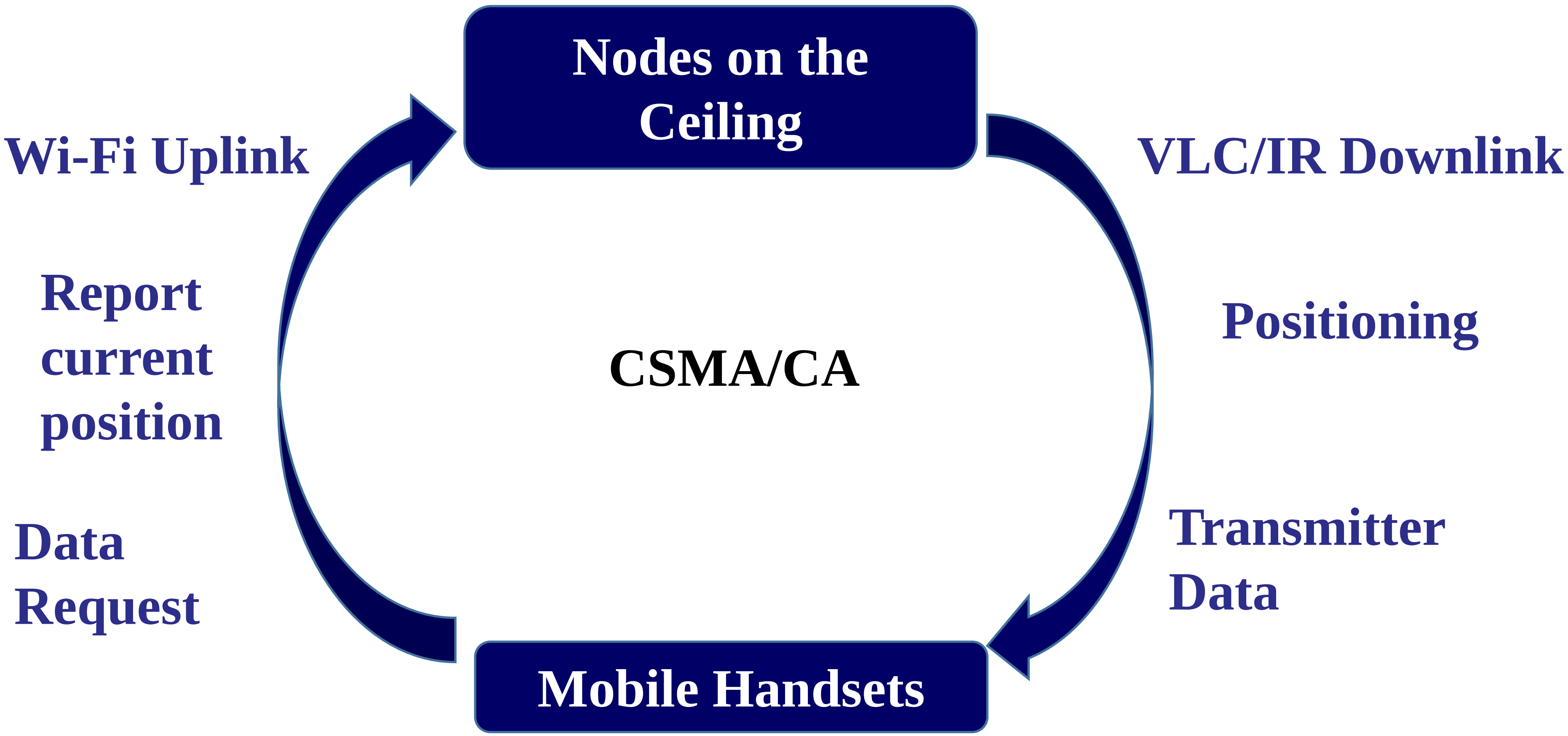


(a) (b)

(a) Photo of demo system – CES 2014 (b) User interface

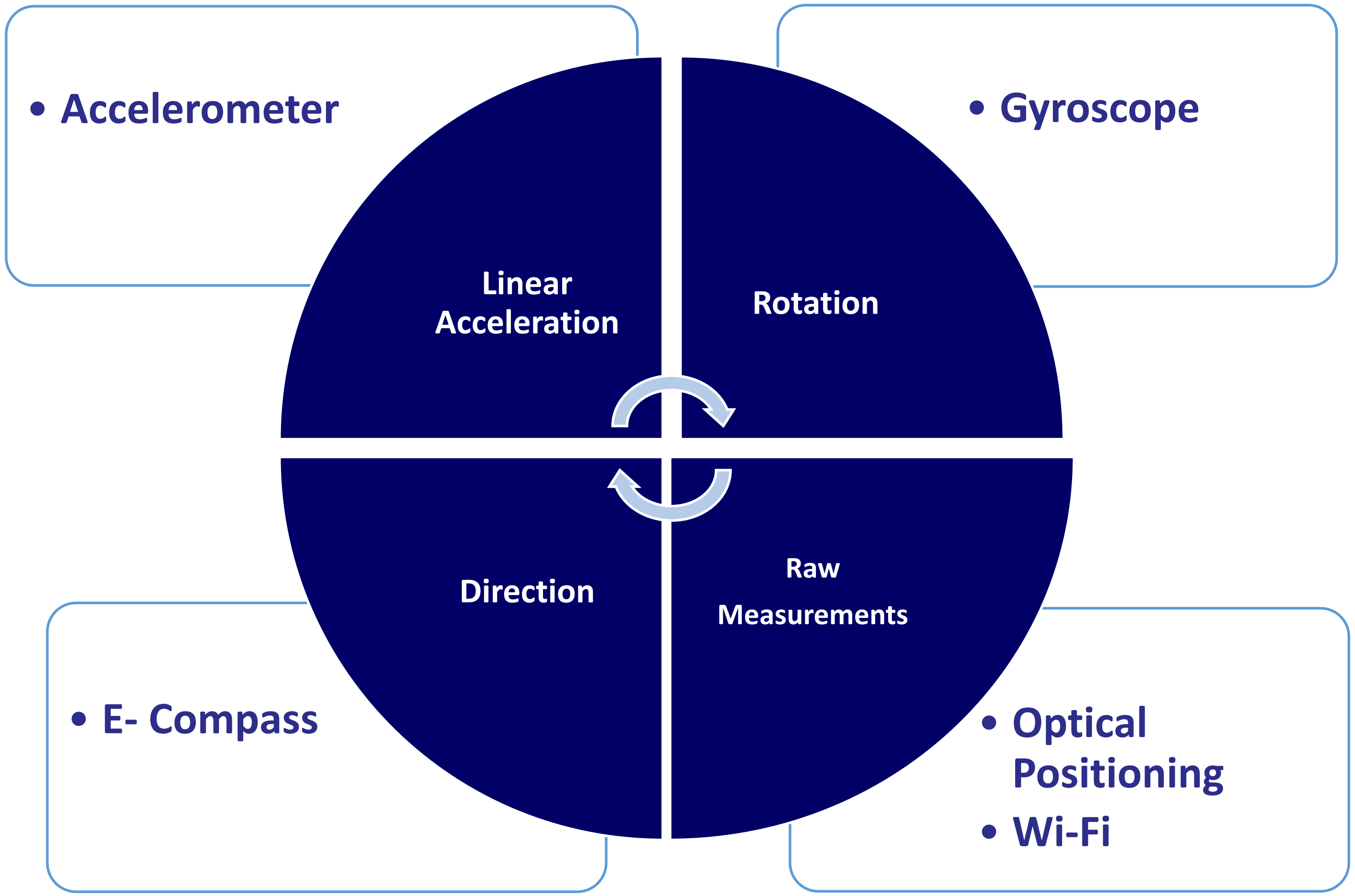
Summary of Future Research

❖ **Compliance with High-speed Communications**



Summary of Future Research

❖ Sensor Fusion



Summary of Future Research

❖ Sensor Fusion

Realization of Sensor Fusion by Kalman Filter

- ✓ Though a good initialization may lead to excellent performance, inertial navigation cannot yield satisfactory performance by itself.
- ✓ Develop a Kalman filter structure for realization of sensor fusion to combine the measurements from the light positioning system (LPS) and inertial navigation system (INS).
- ✓ Sensor fusion technology further improves the positioning accuracy and neutralize the effects of outlier and light blockage by taking advantages of both LPS and our proposed INS.

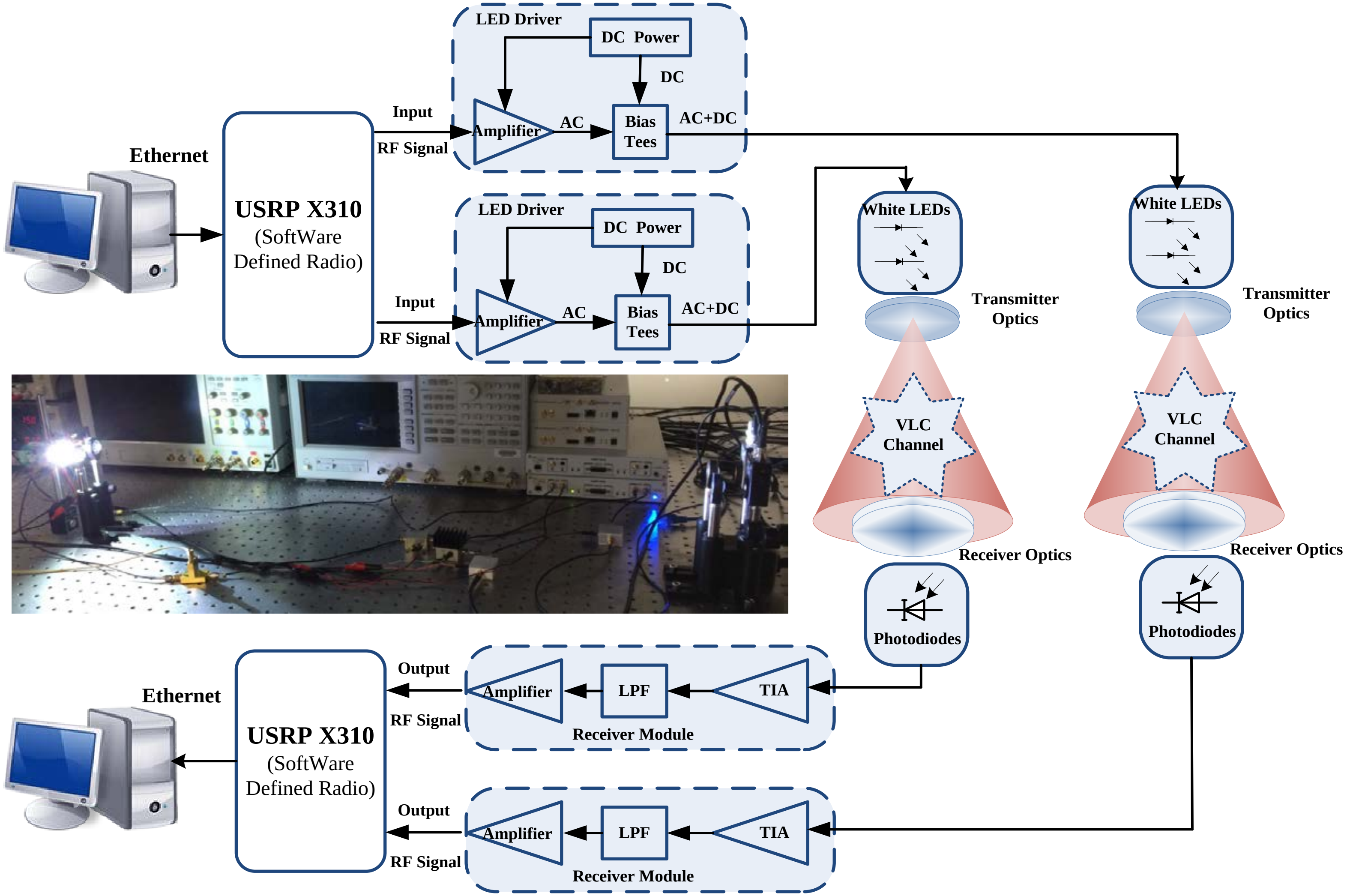
REAL-TIME SOFTWARE-DEFINED 2x2 MIMO VLC

- Design and implement a software-defined real-time SC-QAM MIMO VLC transceiver system using FPGA based USRP-X310.

- Measure and compare constellation diagram, EVM and BER performance for single-carried M-QAM MIMO VLC using spatial diversity and spatial multiplexing.

P. Deng, and M. Kavehrad, "Real-Time Software-Defined Single-Carrier QAM MIMO Visible Light Communications System, "Proceedings of IEEE Integrated Communications Navigation and Surveillance (ICNS), Herndon, VA. , April 2016.

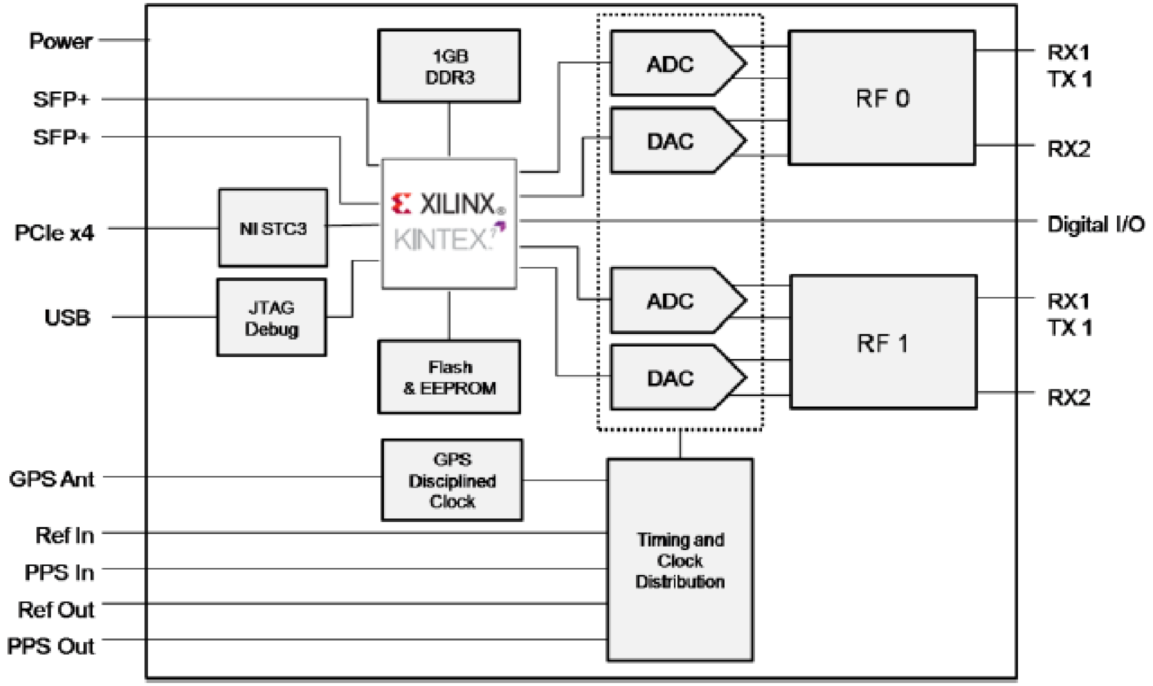
REAL-TIME SOFTWARE-DEFINED 2x2 MIMO VLC - Experiment Setup



Experiment Setup

USRP X310

Conversion Performance and Clocks		
ADC Sample Rate (max)	200	MS/s
ADC Resolution	14	bits
DAC Sample Rate (max)	800	MS/s
DAC Resolution	16	bits
Host Sample Rate (16b) **	200	MS/s
Internal Reference Accuracy	2.5	ppm
Accuracy w/ GPSDO Option (not locked to GPS)	20	ppb



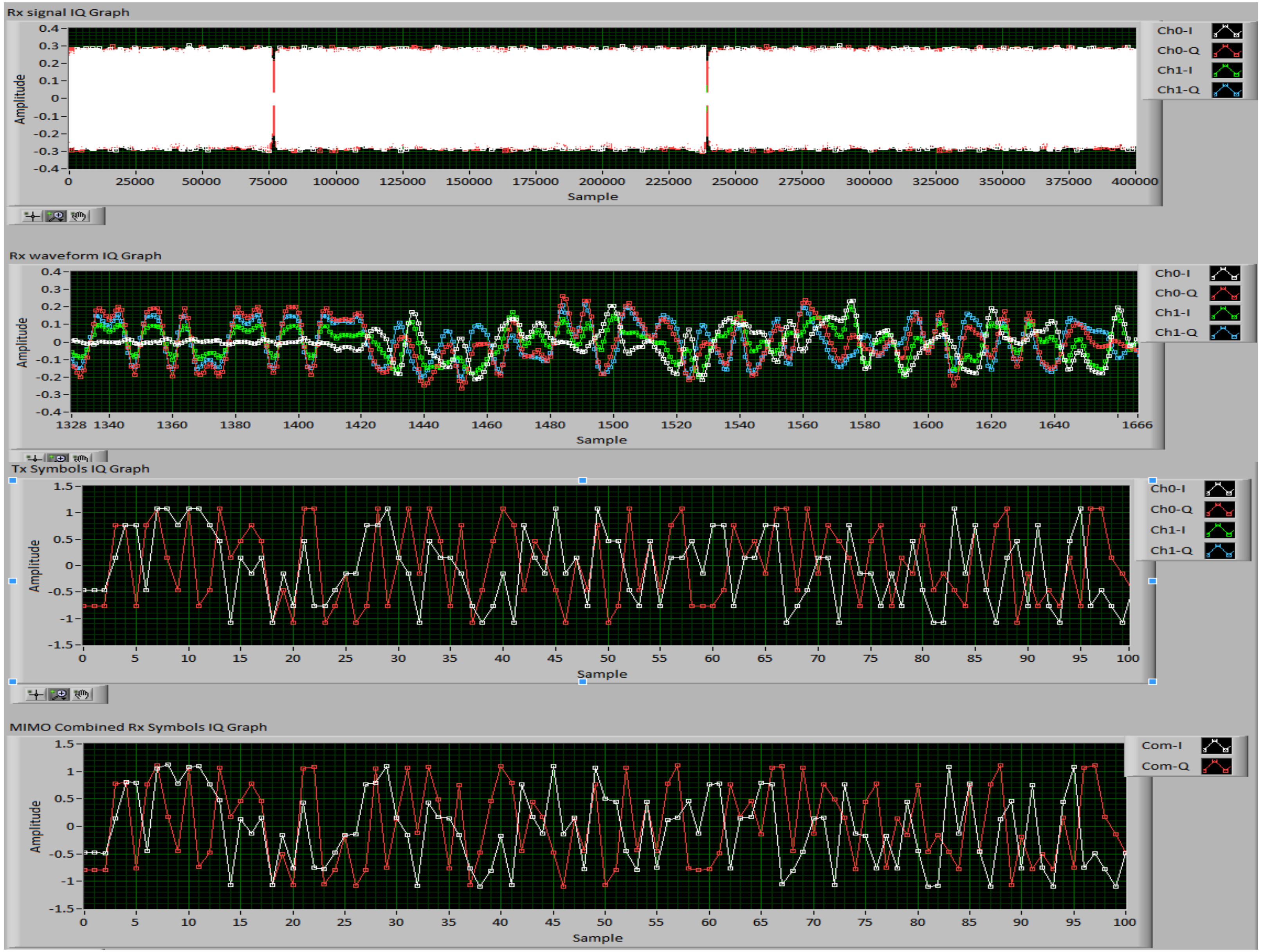
Waveforms and IQ symbols for 64-QAM Spatial Diversity MIMO VLC

Rx Signal IQ Graph

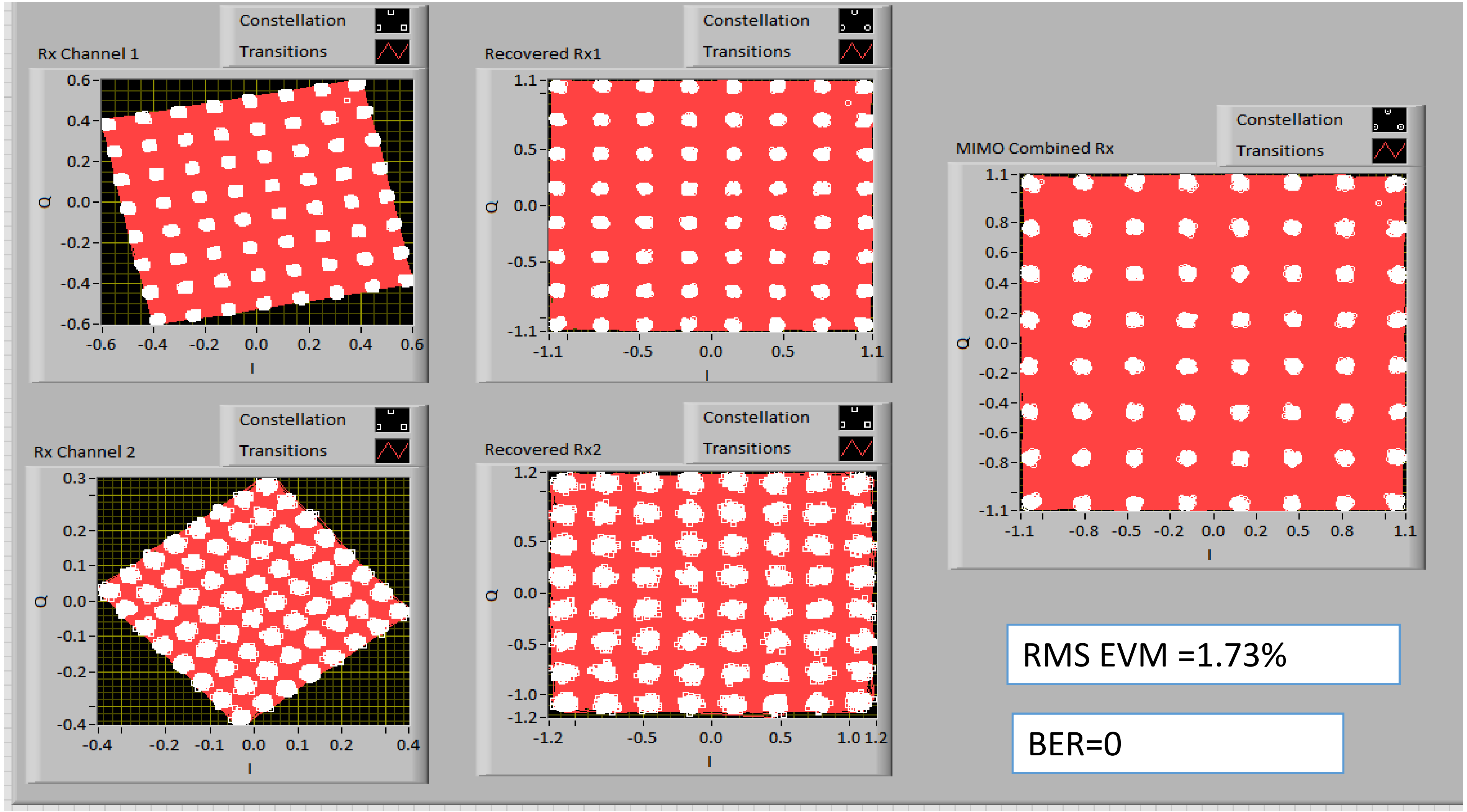
Rx Waveform IQ Graph

CH 0-1 Tx Symbols IQ Graph

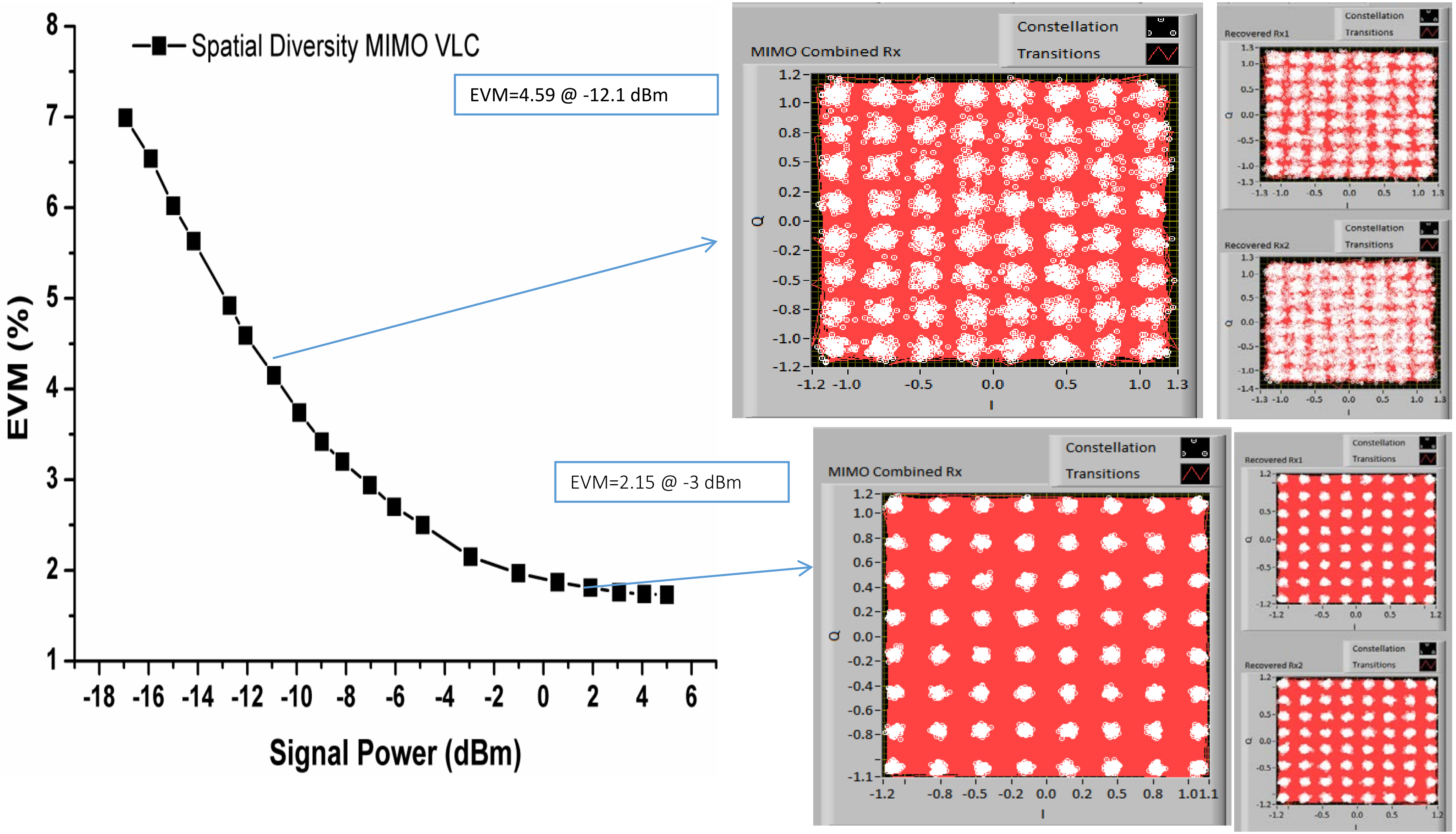
MIMO Combined RX Symbol IQ Graph



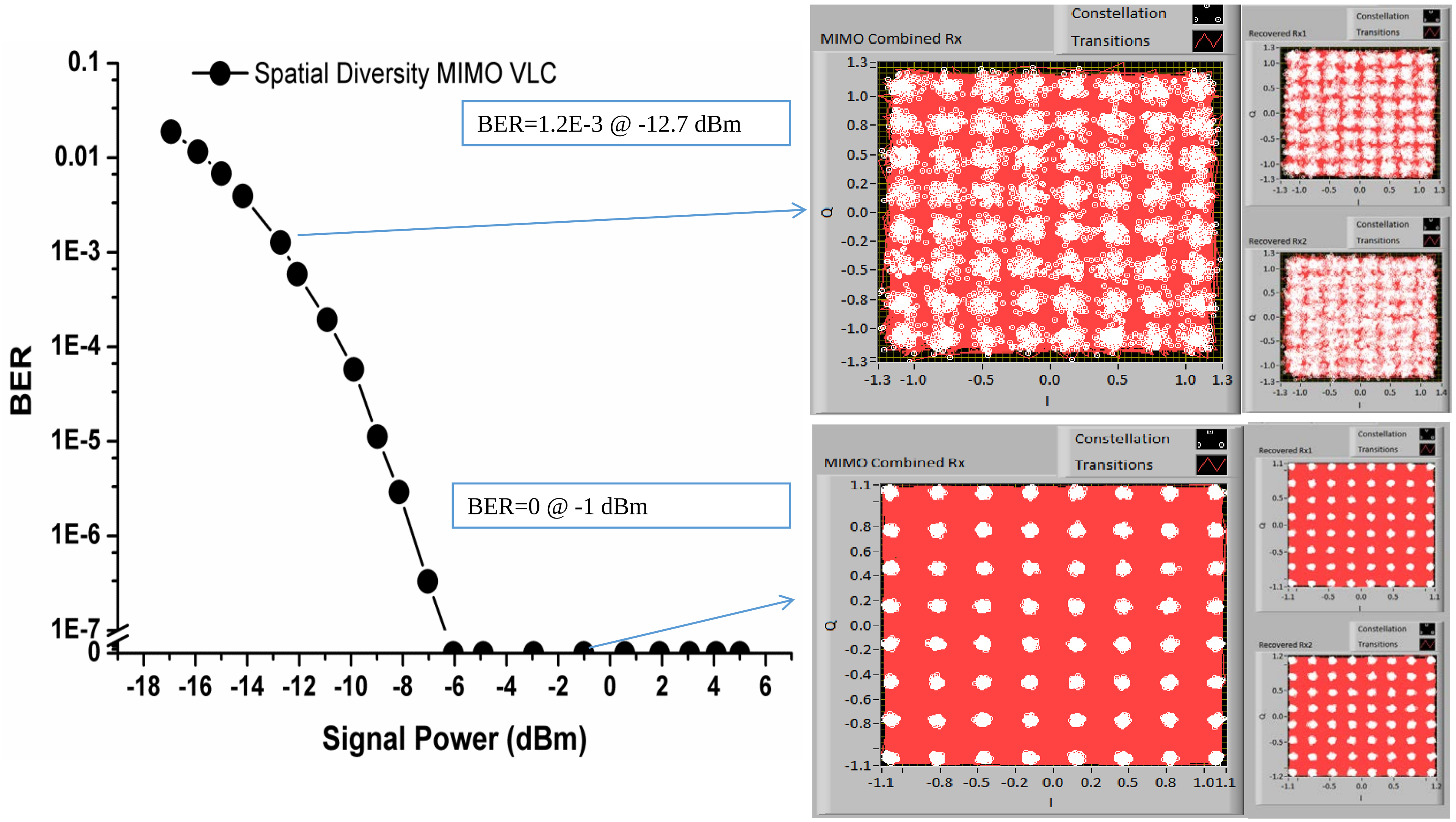
Constellation Diagrams of 64-QAM Spatial Diversity MIMO VLC



EVM vs Signal Power 64-QAM Spatial Diversity MIMO VLC

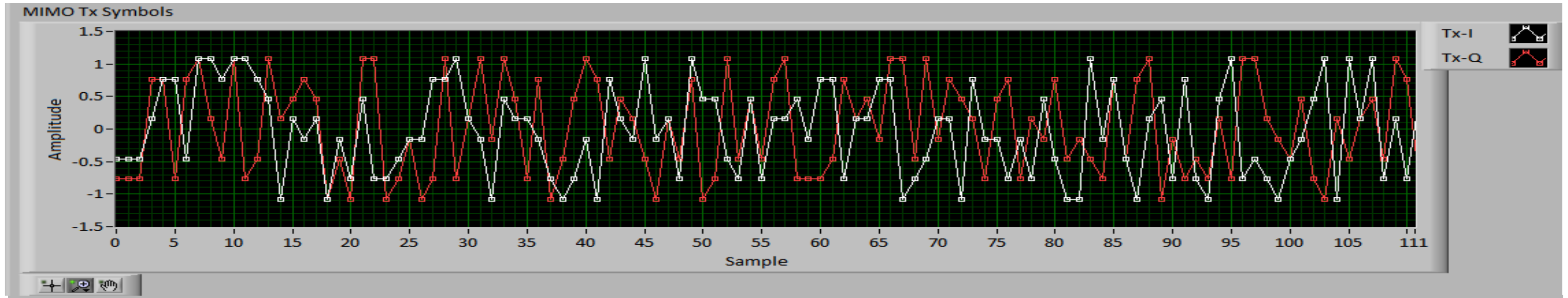


BER vs Signal Power 64-QAM Spatial Diversity MIMO VLC

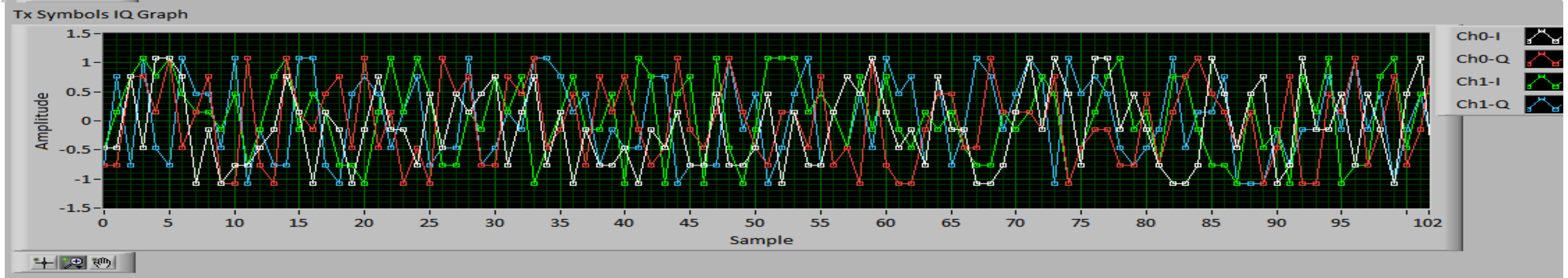


Waveforms and IQ symbols for 64-QAM Spatial Multiplexing MIMO VLC

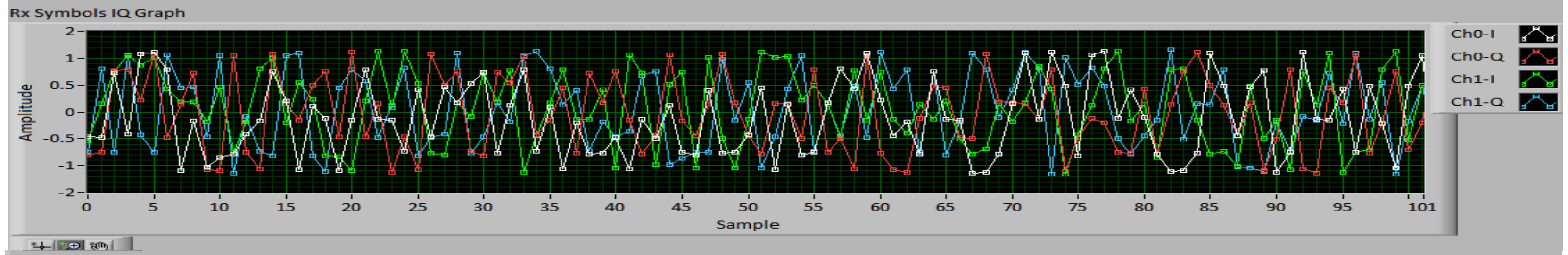
MIMO TX Symbols IQ Graph



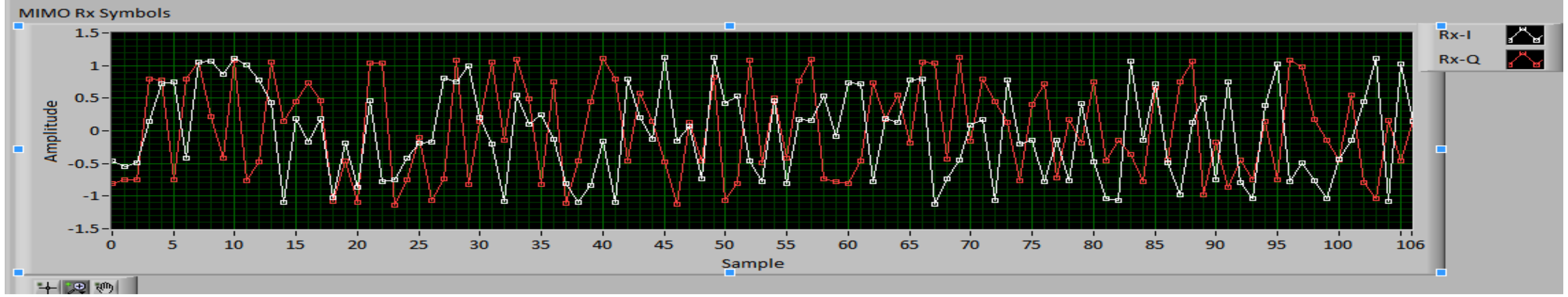
CH 0-1 TX Symbols IQ Graph



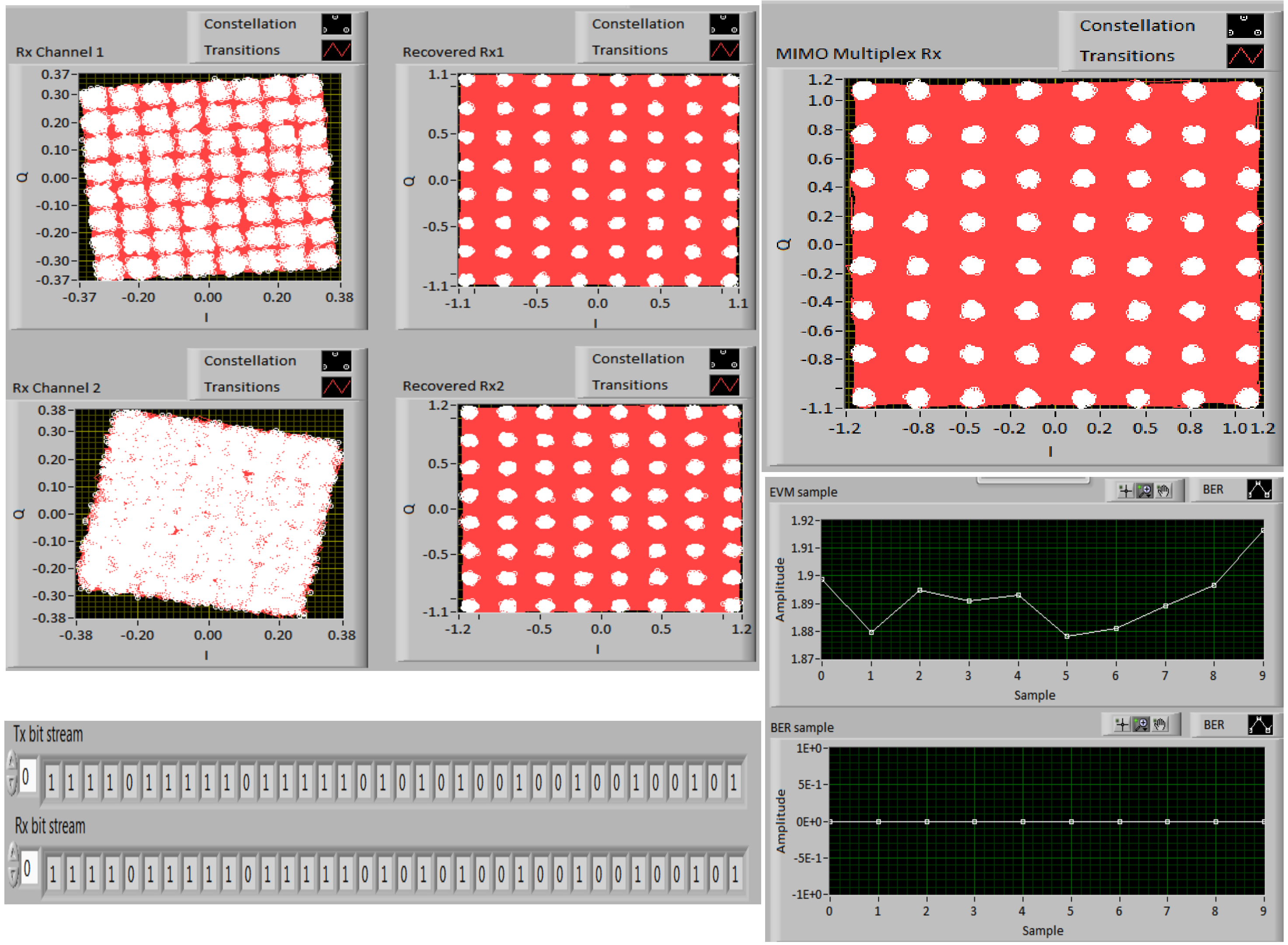
CH 0-1 RX Symbols IQ Graph



Multiplex MIMO RX Symbols IQ Graph



Constellation BER EVM for 64-QAM Spatial Multiplexing MIMO VLC



64-QAM Spatial Multiplexed 2x2 MIMO VLC

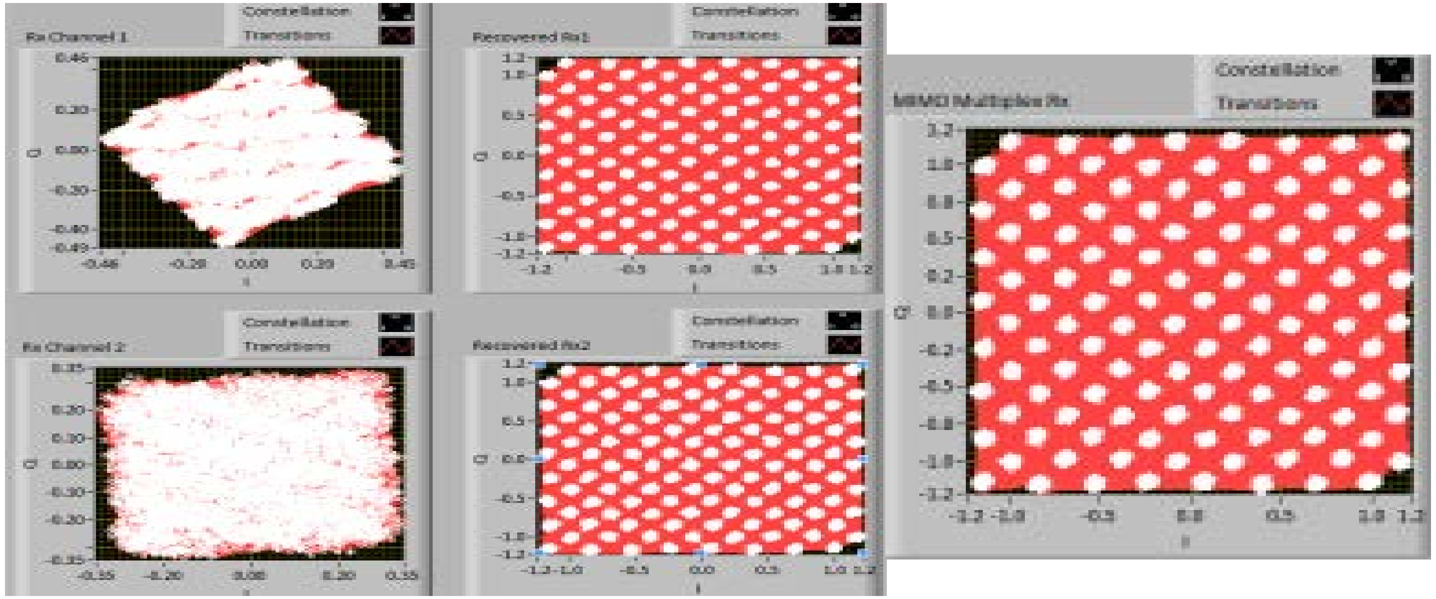
Data rate = 120 Mbps

Distance = 2 meters

RMS EVM =1.89%

Mean BER = 0

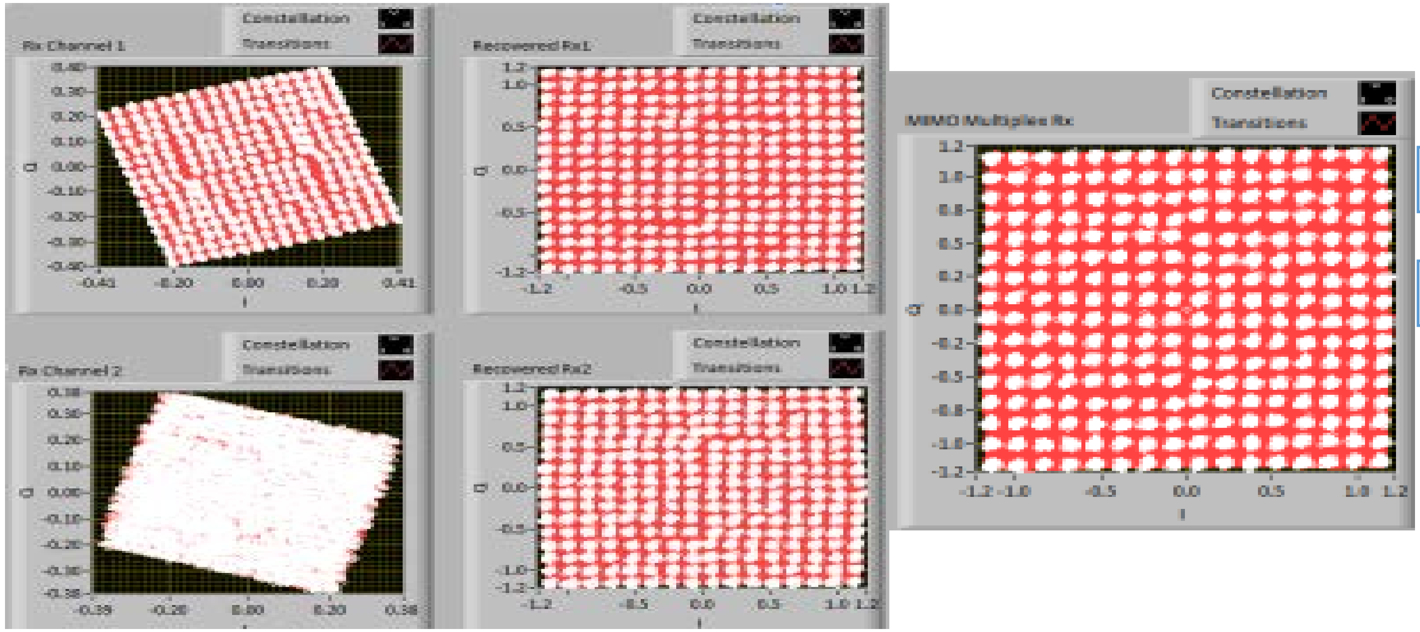
Constellation BER EVM for 128-256-QAM Spatial Multiplex MIMO VLC



RMS EVM =1.82%

128-QAM BER=0

Data Rate = 140 Mbps

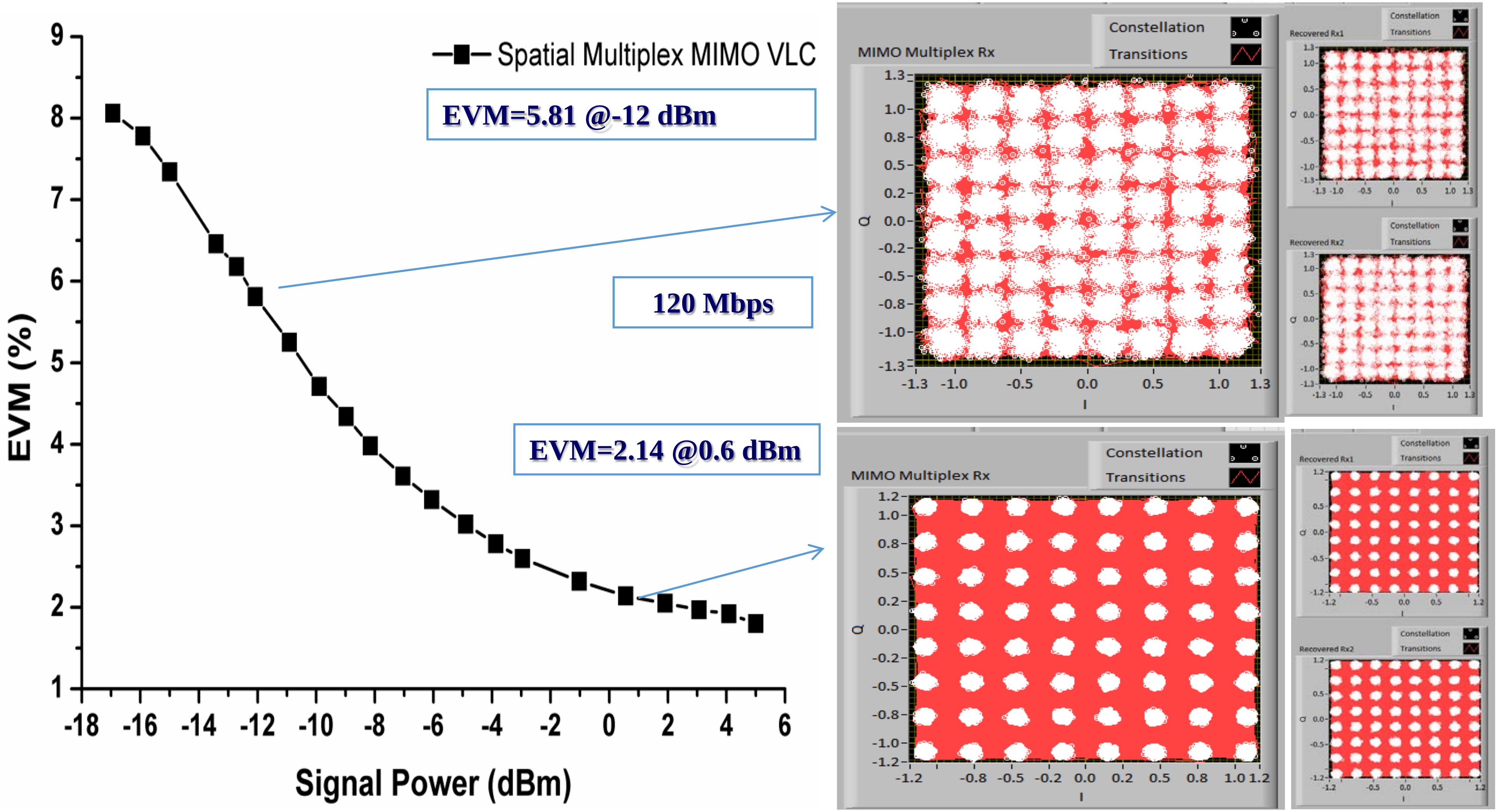


RMS EVM =1.81%

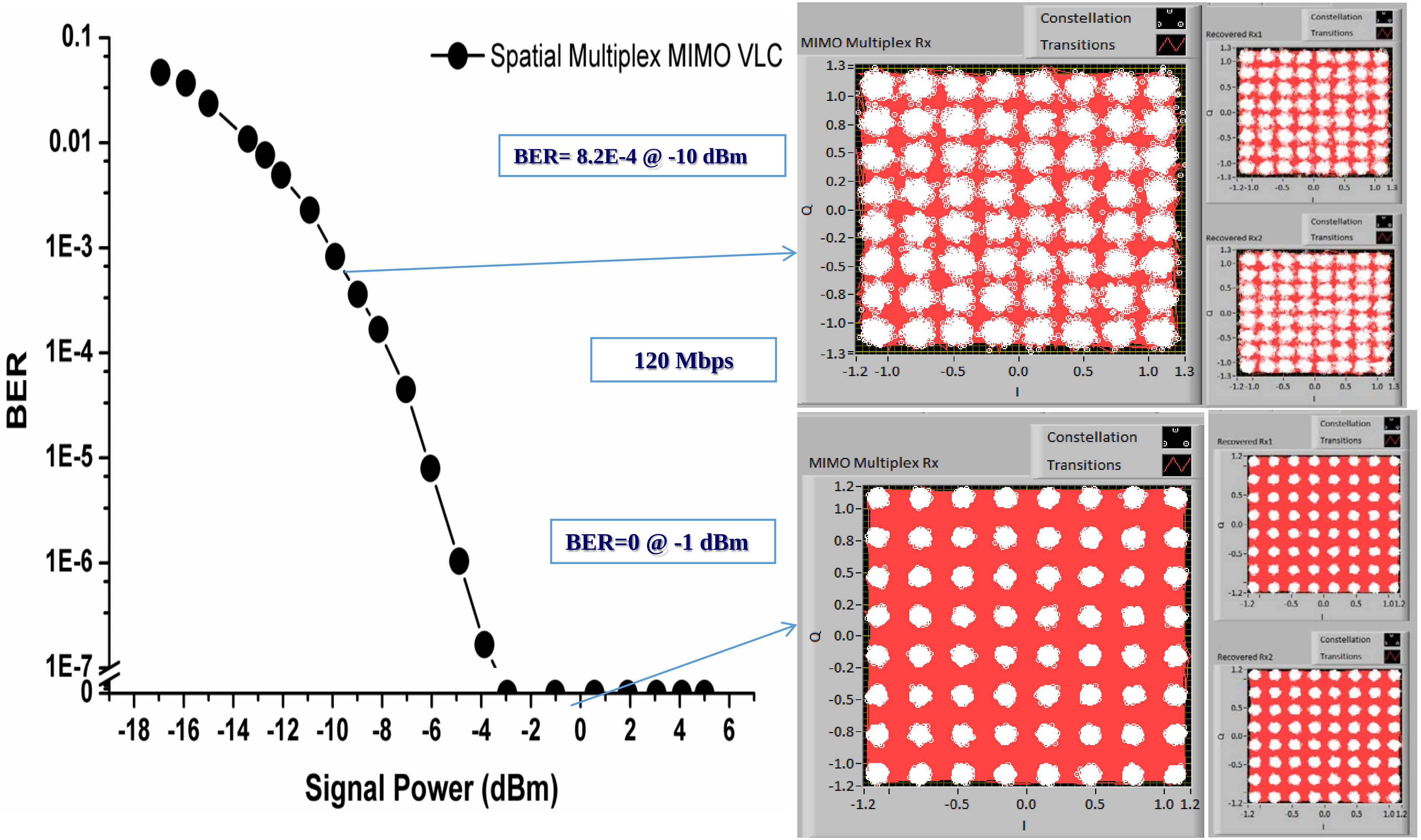
256-QAM BER=2E-5

Data rate = 160 Mbps

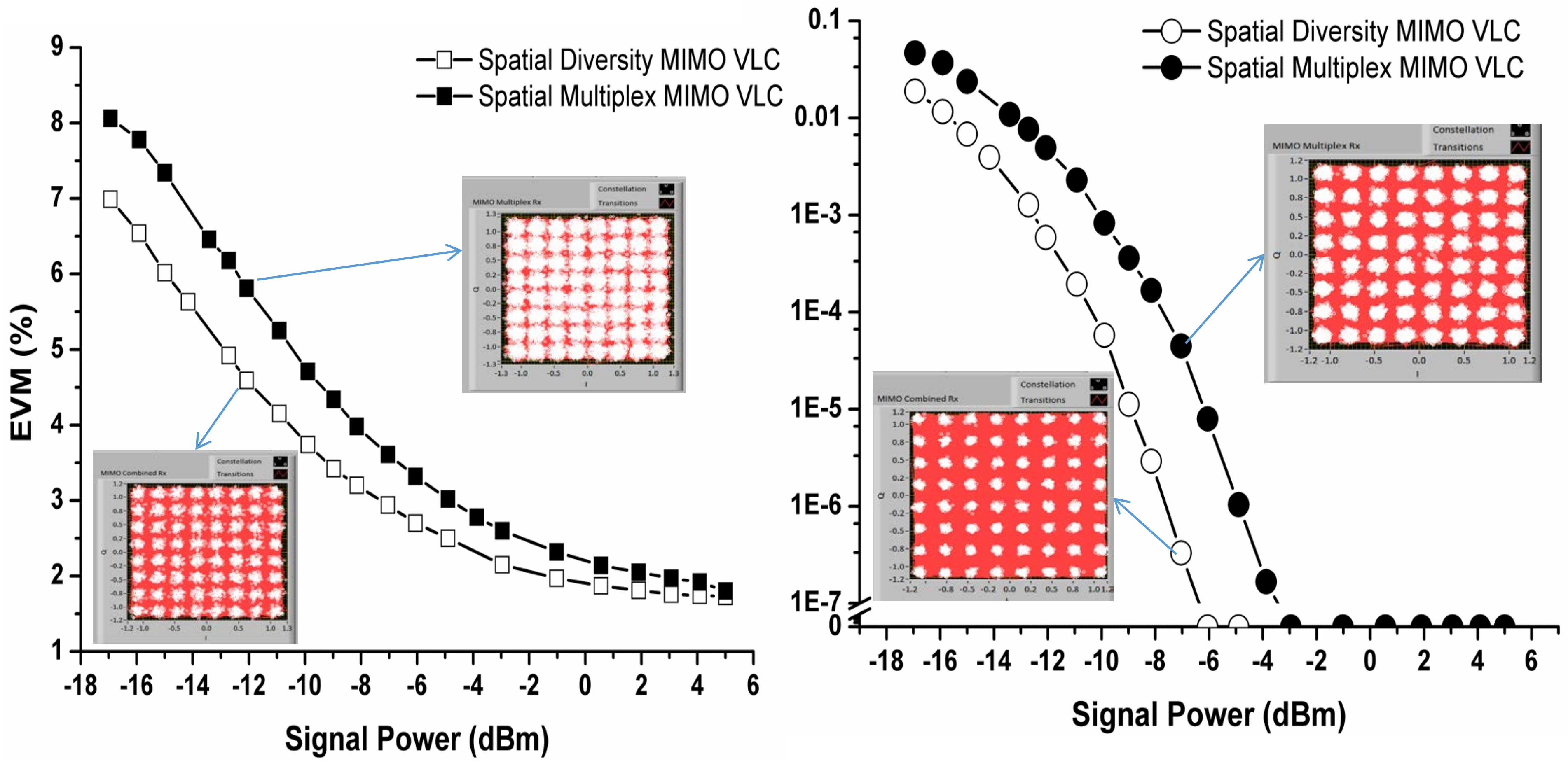
EVM vs Signal Power Spatial Multiplexing MIMO VLC



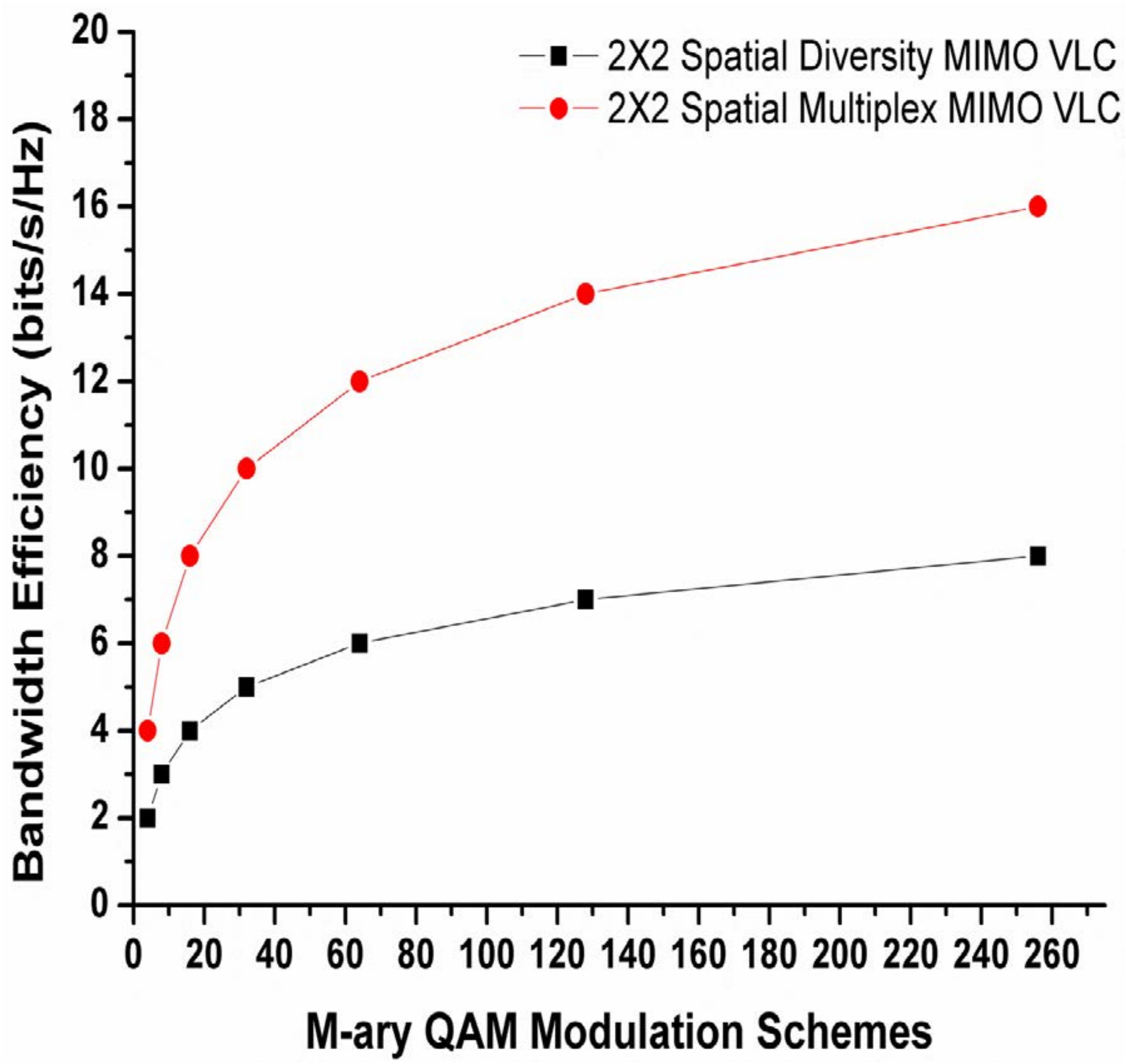
BER vs Signal Power Spatial Multiplex MIMO VLC



Error Performance for Spatial Diversity/Multiplexing MIMO VLC

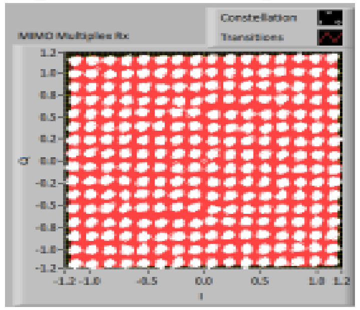


Bandwidth Efficiency of Spatial Multiplexing/Diversity MIMO VLC

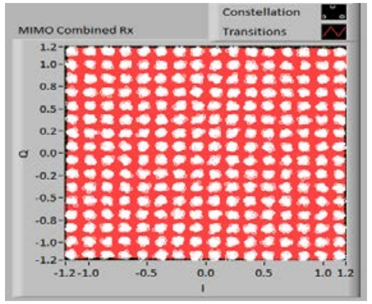


Spatial Multiplex

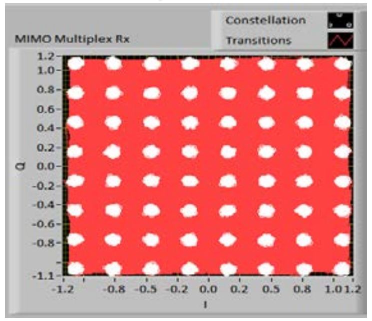
Spatial Diversity



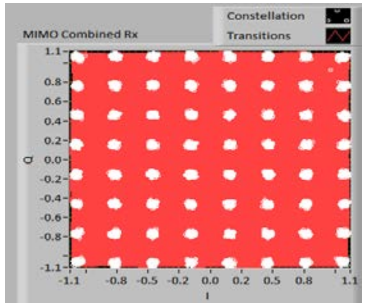
BER=2E-5, EVM =1.81%



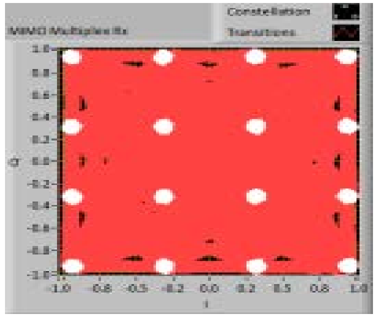
BER=0, EVM =1.64%



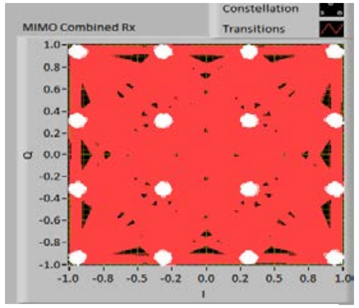
BER=0, EVM =1.89%



BER=0, EVM =1.73%



BER=0, EVM =2.37%



BER=0, EVM =2.31%

Observations

- Demonstrated a real-time Single-Carrier 256-QAM 2x2 spatial multiplexing MIMO VLC link and achieved 1.81% EVM, 2×10^{-5} BER and 12.3 b/s/Hz spectral efficiency over a 2 meters distance.

- Spatial diversity MIMO VLC improves error performance, while spatial multiplexing MIMO VLC enhances bandwidth efficiency.

Challenges

- Further topics
  - Uplink transmission using retro-reflecting elements
  - Dynamic data rate adaptation → to adapt to LOS & NLOS scenarios
  - Driver / modulator bandwidth & efficiency
  - Indoor lighting → LED arrays → parallel transmission by MIMO
  - Various novel applications such as indoor navigation & positioning

- Challenges
  - Data rates up to 10 Gb/s using LEDs and WDM
  - Receiver technology

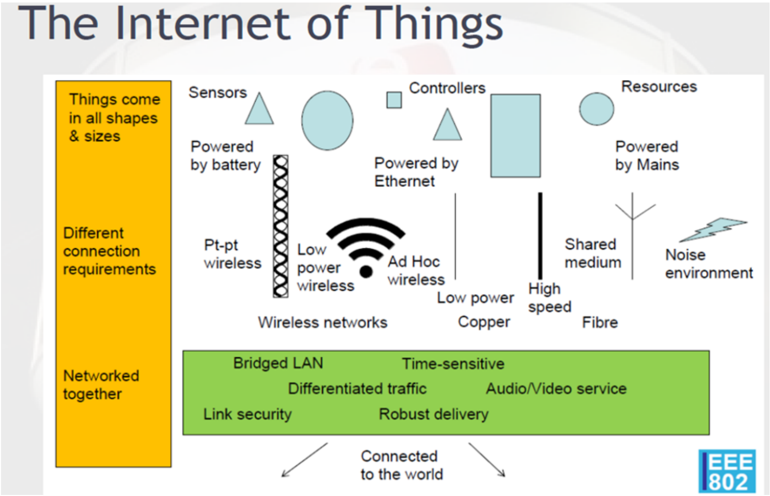
Integration of OWC into a more general wireless infrastructure
→ cooperative wireless (VLC + IR, or VLC + radio)

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.

An Eye on the Future - Information Superiority

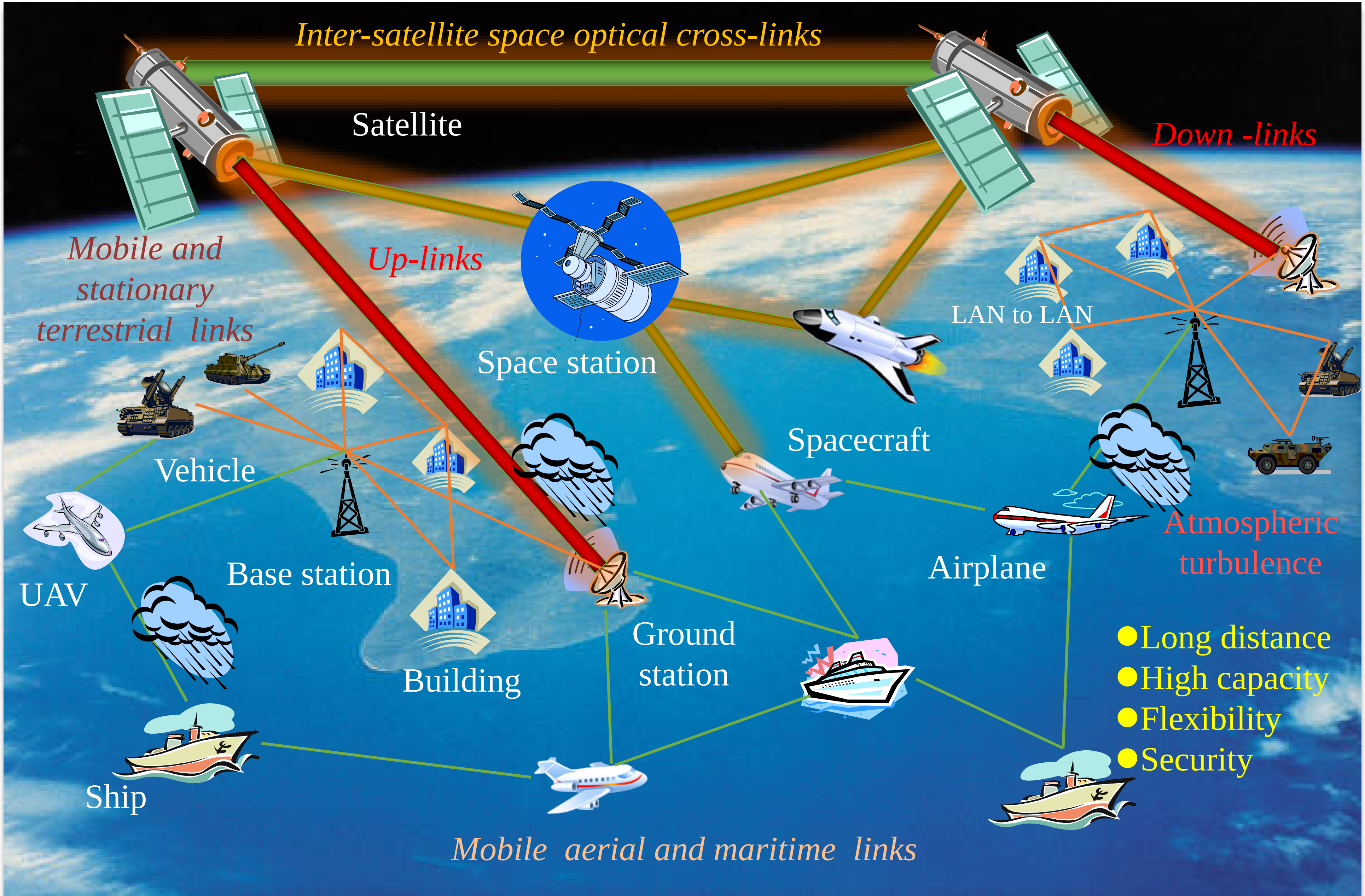
- The “Internet-of-Things” and “Big Data” are here.



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

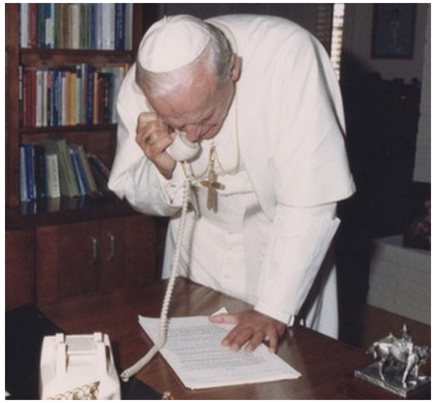
- Information superiority through global-connectivity will re-define the “**Have’s**” and the “**Have not’s**”.

Free Space Optical Communications



PHYSICAL-LAYER SECURITY

Secret Message



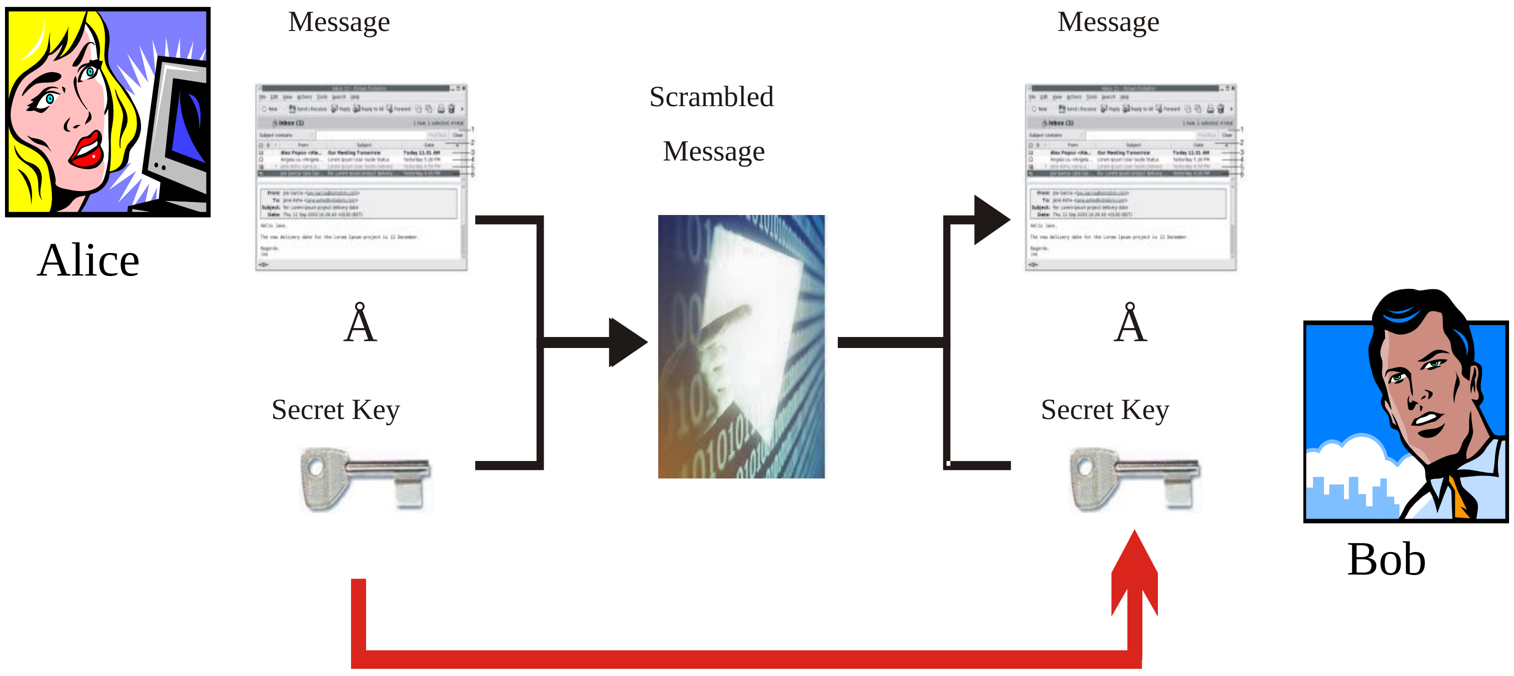
Alice

Bob

Eve (Eavesdropper)

Quantum Communications

Quantum Key Distribution



Secret key exchange by quantum cryptography

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**