Optical Wireless: Theory and Applications

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Mobility, Video and cloud computing are changing communications fundamentally.

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.

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

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!)

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: UNPRECEDEDENT TRAFFIC

Worldwide internet traffic, 1990-2020 PB/month

- +27% CAGR 2008-2020
- +32% Video
- +20% Non-video

Forecast Model

WWW is born

Digital decade

Machine To Machine?

Source: Juniper, Cisco, MINTS
Atmospheric Transmission

- HF
- VHF
- Microwaves
- mm-Waves
- THz
- Infrared
- Vis
- UV

- Ionosphere Opaque
- Radio Window
- Mountain top Transmission Acceptable
- Atmosphere Opaque
- IR & Optical Windows
- Atmosphere Opaque
The Point of Wireless Disconnect

The FCC projects a spectrum deficit for wireless communications by 2013

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 to link with devices fitted with plug-in cards that can both receive and transmit the coded infrared light. 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. Engineers are working on similar systems that use white LED lamps, flickering in code faster than the human eye can detect.
## Classification by Optical Frontend

<table>
<thead>
<tr>
<th>Transmitter</th>
<th>Receiver</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very low speed, dominated by the transmitter</td>
<td>Low speed, dominated by the receiver</td>
</tr>
<tr>
<td>Medium speed</td>
<td>High speed</td>
</tr>
<tr>
<td>Very high speed</td>
<td></td>
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</table>

- **Transmitter**: Bulb, Beam, LED, Laser
- **Receiver**: Camera, Fiber Optic, Photodiode
Technology and Economic Impact

Bandwidth Available

Deployed units Number

1.4 Million

~2 GHz

14 Billion

~300THz
US $2000 Cost of ridding a room of the mercury from a broken CFL
SMART LIGHTING

Smart LED bulbs control from mobile device anywhere

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

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

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

Smartphone control
multi-color, energy efficient LED bulbs

- Stay connected
  Receive lighting notifications during the day

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

Commercial
Retail
Hospitality
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”


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

Undesirable Radio Frequency Interference
Aircraft LEDs used for illumination and communication to provide media services

Automotive VLC
Street Lights

Intelligent Transport System (ITS)
Enabling visible light communication with cars or roadside equipment

Control Station
Fiber
ONU

Aviation VLC

Portable Device LiFi Access

Medical Database Access
Sensor Data

Patient Information
Location based service

Smart LED Lighting
Internet Access
Online Shopping

LiFi Access
Mobile Access

Smart Appliances

Hospital VLC
Mall VLC

Medical Database Access
Sensor Data
VLC Applications Areas

- IT Security
- RF-sensitive Areas, e.g. Hospitals
- Private Households
- Mechanical Engineering
- Advertising, Messaging
- Trade shows, Museums
- In-flight Entertainment
- Underwater Communications
Experimental Video Transmission using Visible Light Communications

TX

Experiment Setup

RX

(a)
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

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)


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.
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

Docking  Spotting  Beaming  Shower
Multi-Gigabit LAN
FEBRUARY 11, 2010

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

Add a Node to the Global Network:  INTERET

The IPv6-Addressable Light Bulb Goes On Sale GreenWave Reality and NXP launch 6LowPAN mesh-networked LED bulbs and home energy control platform.
"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)
Phillips pilots new system that uses intelligent LED in-store lighting to communicate with shoppers' smartphones to deliver targeted offers and information based on their location.

David has decided to cook a Mexican meal for his friends this evening.

1. He chooses guacamole in the supermarket app he downloaded. It suggests a recipe for fresh guacamole that he accepts.

2. The light fixture above David reveals its location to his smartphone, and the app plots a route to the chilies.

3. Spotted David's location at the fresh vegetables section, the light fixture prompts the app to offer him 50% off on avocados.

4. David then receives a suggestion for a dessert of Mexican "churros." He opts for a smoothie option.

5. The light fixture communicates its location, and the app plots a route to the churros.

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
Indoor Coverage Problem of Global Positioning System (GPS)
RF approaches (UWB, WLAN, Bluetooth) deliver positioning accuracies from tens of centimeters to several meters.

<table>
<thead>
<tr>
<th>Positioning Method</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sapphire Dart (UWB)</td>
<td>0.3 m</td>
</tr>
<tr>
<td>Ekahau (WLAN)</td>
<td>1 m</td>
</tr>
<tr>
<td>TOPAZ (Bluetooth+IR)</td>
<td>2 m</td>
</tr>
<tr>
<td>SnapTrack (AGPS)</td>
<td>5 m-50 m</td>
</tr>
<tr>
<td>LANDMARC (RFID)</td>
<td>2 m</td>
</tr>
</tbody>
</table>

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

Positioning Techniques

Circular Lateration

Hyperbolic Lateration

Angulation
Positioning Techniques

Proximity-based Hybrid Positioning using VLC and Zigbee

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)).

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
"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) Photo of demo system – CES 2014
(b) User interface
Summary of Future Research

- Compliance with High-speed Communications

Nodes on the Ceiling

Wi-Fi Uplink

Report current position

Data Request

VLC/IR Downlink

Positioning

Transmitter Data

Mobile Handsets

CSMA/CA
Summary of Future Research

Sensor Fusion

- Accelerometer
- Gyroscope
- E-Compass
- Optical Positioning
- Wi-Fi
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.

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

USRP X310

<table>
<thead>
<tr>
<th>Conversion Performance and Clocks</th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>ADC Sample Rate (max)</td>
<td>200</td>
<td>M5/s</td>
</tr>
<tr>
<td>ADC Resolution</td>
<td>14</td>
<td>bits</td>
</tr>
<tr>
<td>DAC Sample Rate (max)</td>
<td>800</td>
<td>M5/s</td>
</tr>
<tr>
<td>DAC Resolution</td>
<td>16</td>
<td>bits</td>
</tr>
<tr>
<td>Host Sample Rate (16b)</td>
<td>200</td>
<td>M5/s</td>
</tr>
<tr>
<td>Internal Reference Accuracy</td>
<td>2.5</td>
<td>ppm</td>
</tr>
<tr>
<td>Accuracy w/ GPSDO Option (not locked to GPS)</td>
<td>20</td>
<td>ppb</td>
</tr>
</tbody>
</table>
Waveforms and IQ symbols for 64-QAM Spatial Diversity MIMO VLC
Constellation Diagrams of 64-QAM Spatial Diversity MIMO VLC

RMS EVM =1.73%

BER=0
EVM vs Signal Power  64-QAM Spatial Diversity MIMO VLC

EVM=4.59 @ -12.1 dBm

EVM=2.15 @ -3 dBm
BER vs Signal Power  64-QAM Spatial Diversity MIMO VLC

BER=1.2E-3 @ -12.7 dBm

BER=0 @ -1 dBm
Waveforms and IQ symbols for 64-QAM Spatial Multiplexing MIMO VLC
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

128-QAM BER = 0
RMS EVM = 1.82%
Data Rate = 140 Mbps

256-QAM BER = 2E-5
RMS EVM = 1.81%
Data Rate = 160 Mbps
EVM vs Signal Power Spatial Multiplexing MIMO VLC

- EVM = 5.81 @ -12 dBm
- EVM = 2.14 @ 0.6 dBm

120 Mbps
BER vs Signal Power Spatial Multiplex MIMO VLC

BER = 8.2E-4 @ -10 dBm

BER = 0 @ -1 dBm

120 Mbps
Error Performance for Spatial Diversity/Multiplexing MIMO VLC
Bandwidth Efficiency of Spatial Multiplexing/Diversity MIMO VLC

BER = 0, EVM = 1.64%

BER = 0, EVM = 2.31%

BER = 0, EVM = 1.89%

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, 2x10^{-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

- Inter-satellite space optical cross-links
- Down-links
- Mobile and stationary terrestrial links
- Up-links
- Space station
- Spacecraft
- Airplane
- Satellite
- UAV
- Base station
- Building
- Ship
- Ground station

- Mobile aerial and maritime links

- Long distance
- High capacity
- Flexibility
- Security

Atmospheric turbulence
LAN to LAN
PHYSICAL-LAYER SECURITY

Alice

Secret Message

Bob

Eve (Eavesdropper)
Quantum Communications

Quantum Key Distribution

Secret key exchange by quantum cryptography
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