Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: [Visible Light Communication : Tutorial]

Date Submitted: [9 March 2008]

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Re: []

Abstract: [The overview of the visible light communication (VLC), application scenarios and demonstrations in the various are presented in this document. The research issues, which should be discussed in the near future, also are presented.]

Purpose: [Tutorial to IEEE 802.15]

Visible Light Communication

- Tutorial -

2008. 03. 17

Samsung Electronics

ETRI

VLCC

University of Oxford

Outline

- Part 1 (Samsung, ETRI)
  - VLC introduction
  - LED introduction
  - VLC potential application
- Part 2 (VLCC)
  - Introduction of VLCC members
  - A characteristic of the visible light communications
  - Field experiments and demonstrations using visible light communications
  - Approach to Commercialization
- Part 3 (University of Oxford)
  - VLC components
  - Technical challenges

VLC introduction

- **VLC (Visible Light Communication)**

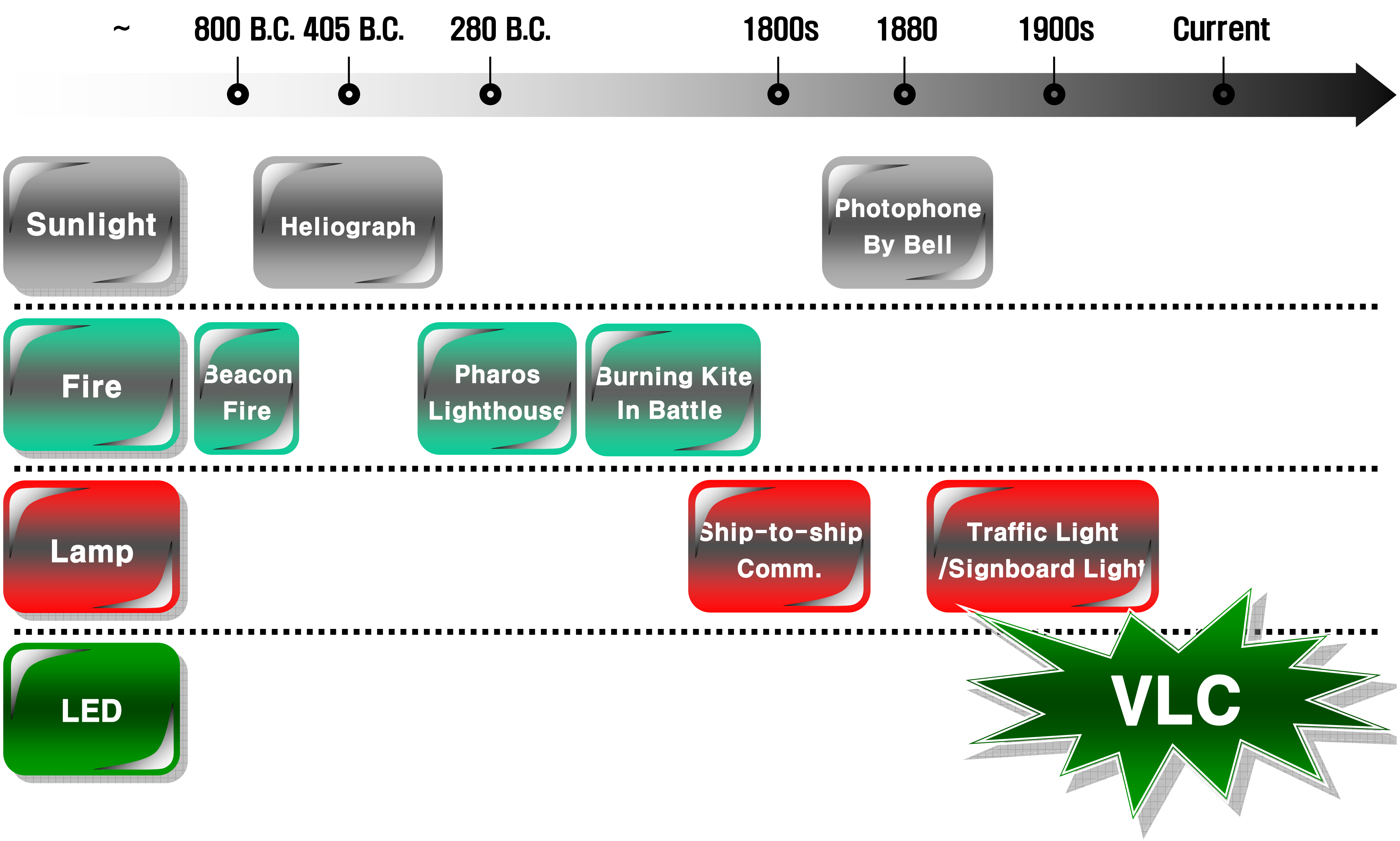
  : **New communication technology using "Visible Light".**

- **Visible Light**

  : **Wavelength between ~400nm (750THz) and ~700nm (428THz)**

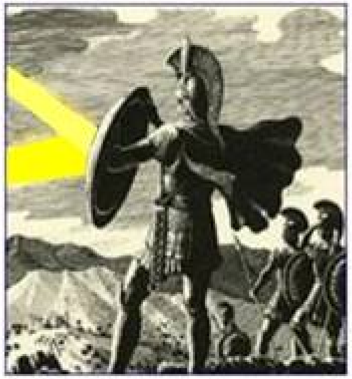
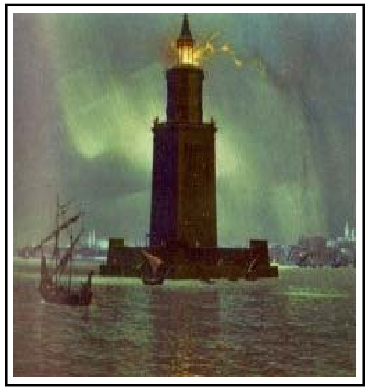
- **General Characteristic**
  - Visibility : Aesthetically pleasing
  - Security : What You See Is What You Send.
  - Health : Harmless for human body
  - Unregulated : no regulation in optical frequency
  - Using in the restricted area : aircraft, spaceship, hospital
  - Eye safety

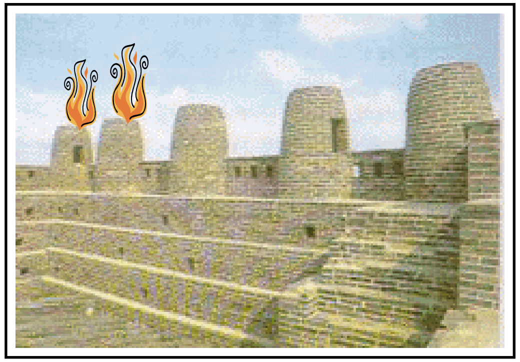
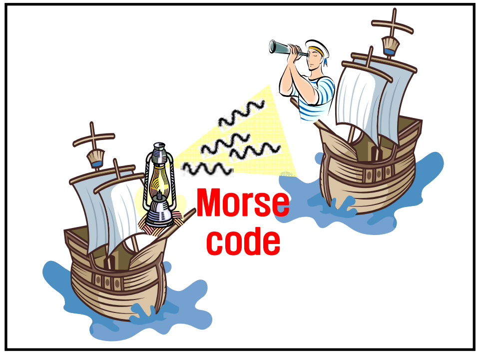
VLC history


~
800 B.C.
405 B.C.
280 B.C.
1800s
1880
1900s
Current
Sunlight
Heliograph
Photophone By Bell
Fire
Beacon Fire
Pharos Lighthouse
Burning Kite In Battle
Lamp
Ship-to-ship Comm.
Traffic Light /Signboard Light
LED
VLC

VLC history – Low speed

- ❖ Information delivery using mirror reflection (Heliograph)
- ❖ The use of fire or lamp
  - Beacon fire, lighthouse, ship-to-ship comm. by Morse code
- ❖ Traffic light : R/G/B color multiplexing (Walk/Stop)

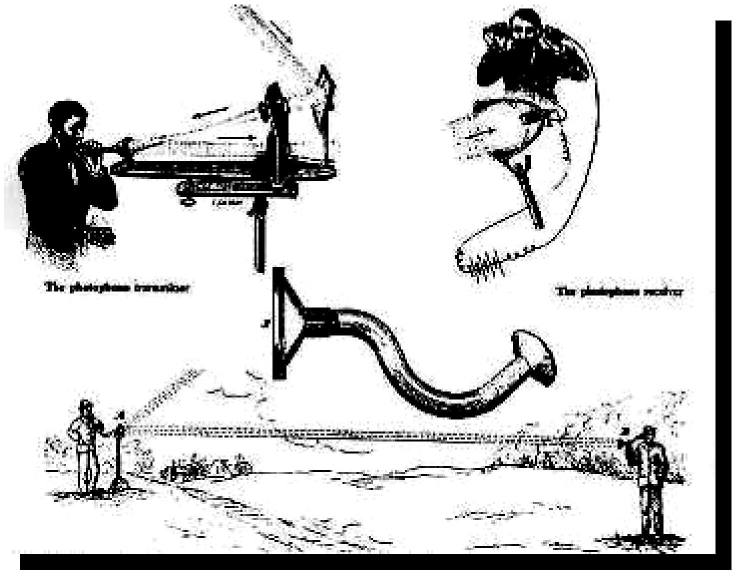



VLC history – Photophone

❖ Bell's Photophone (1880)

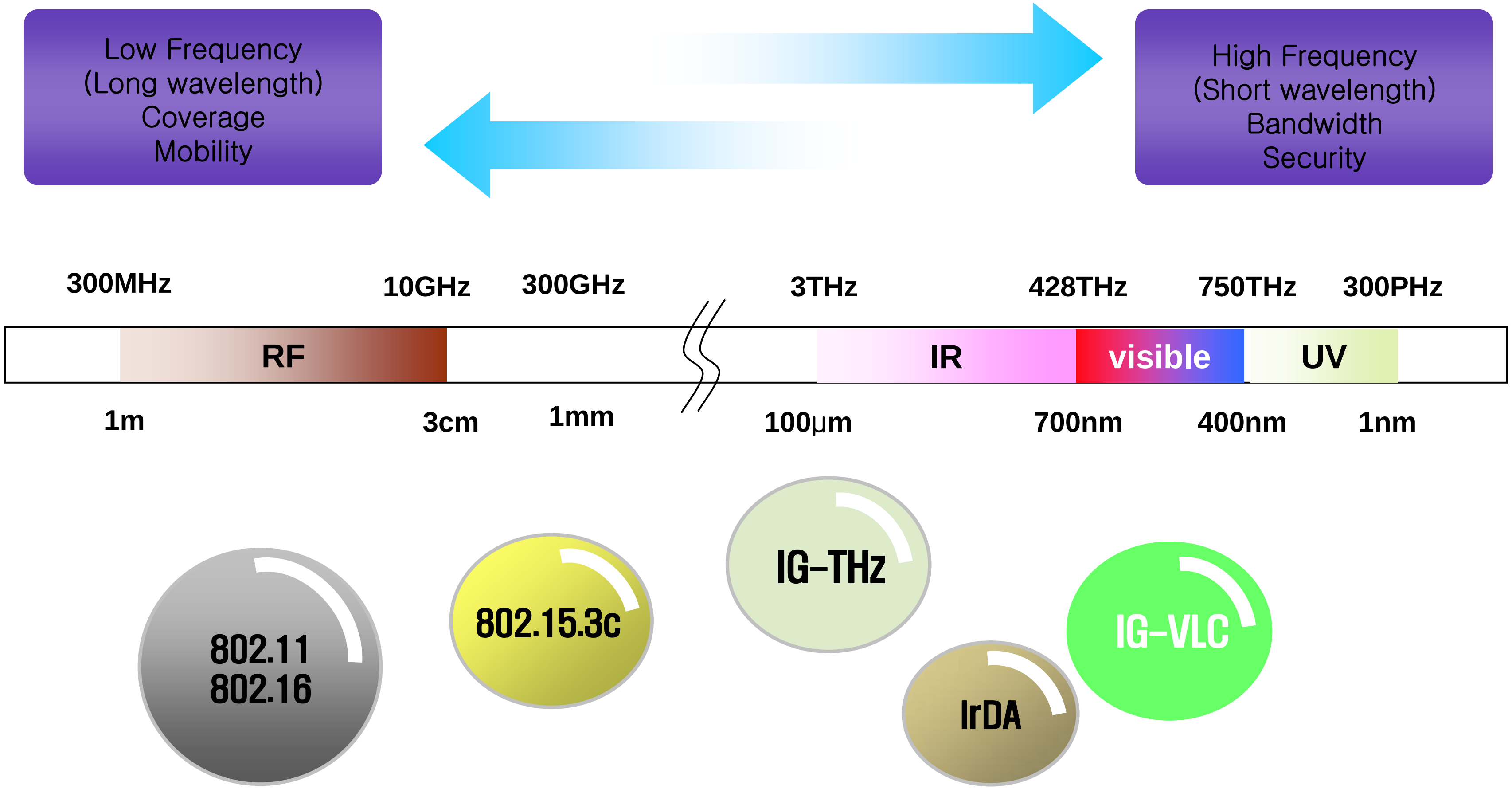
- Optical source : sunlight
- Modulation : vibrating mirror
- Receiver : parabolic mirror
- Distance : 700 ft (213m)

http://www.freespaceoptic.com/



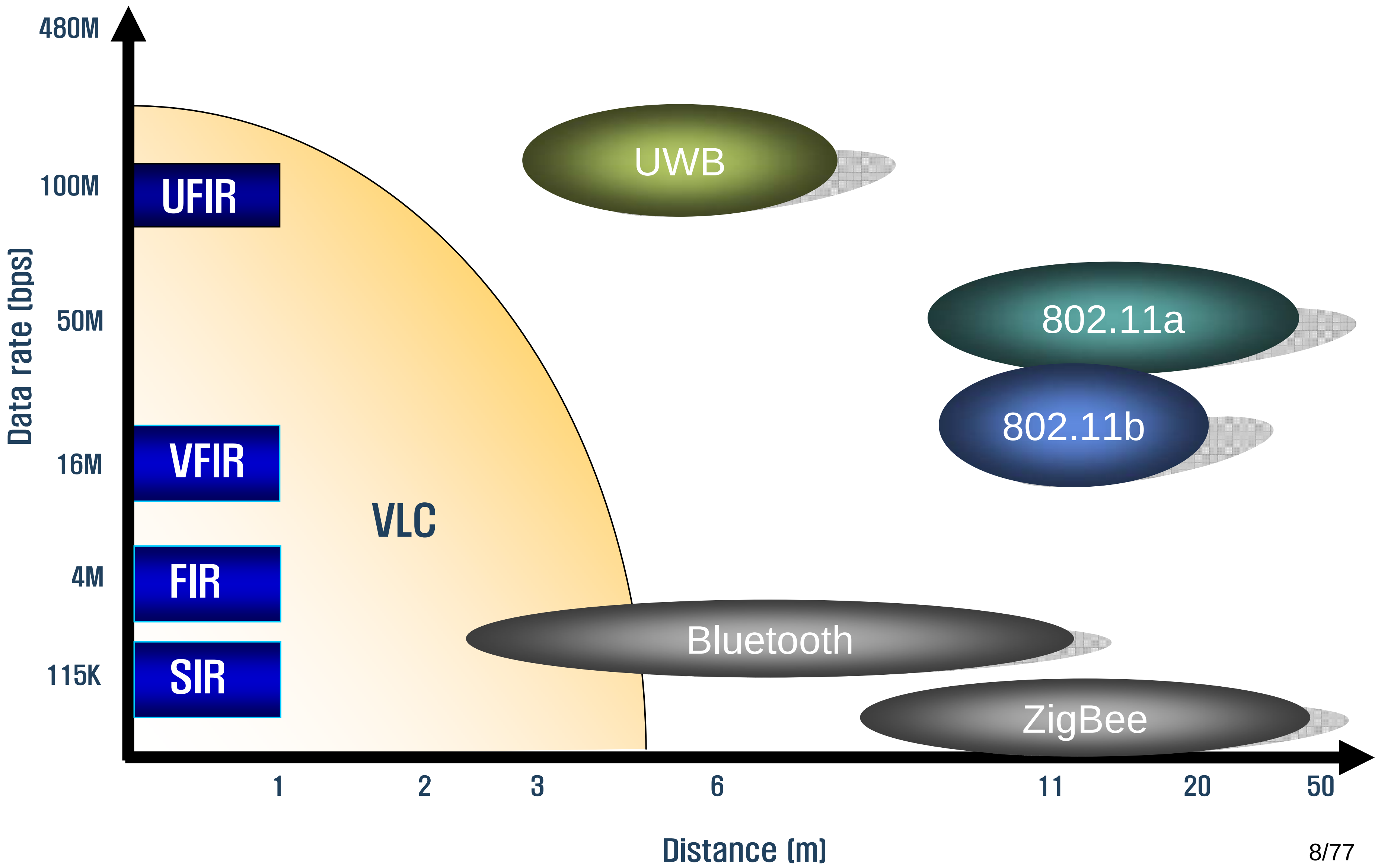
Excerpted from: The New Idea Self-Instructor edited by Ferdinand Ellsworth Cary, A. M. (Monarch Book Company, Chicago & Philadelphia, 1904)

Frequency band for VLC



- IG-THz : 300 GHz to 10 THz (contribution 15-07-0623-01)
- 802.15.3c : 57 GHz to 64 GHz
- IrDA : 334THz(900nm) to 353THz (850nm)

VLC Characteristics



VLC vs. RF Characteristics

Property		VLC	RF
Bandwidth		Unlimited, 400nm~700nm	Regulatory, BW Limited
EMI		No	High
Line of Sight		Yes	No
Standard		Beginning (IG-VLC)	Matured
Hazard		No	Yes
Mobile To Mobile	Visibility (Security)	Yes	No
	Power Consumption	Relatively low	Medium
	Distance	Short	Medium
Infra to Mobile	Visibility (Security)	Yes	No
	Infra	LED Illumination	Access Point
	Mobility	Limited	Yes
	Coverage	Narrow	Wide

VLC motivation

- **Communication community trend**
  - Ubiquitous (Connected anywhere, anytime)
  - Security
- **LED trend**
  - LED technical evolution (efficiency, brightness)
  - LED illumination infra
- **Environmental trend**
  - Energy saving
  - No E-smog
- **Intrinsic characteristic of VLC**
  - Visibility
  - No interference / No regulation

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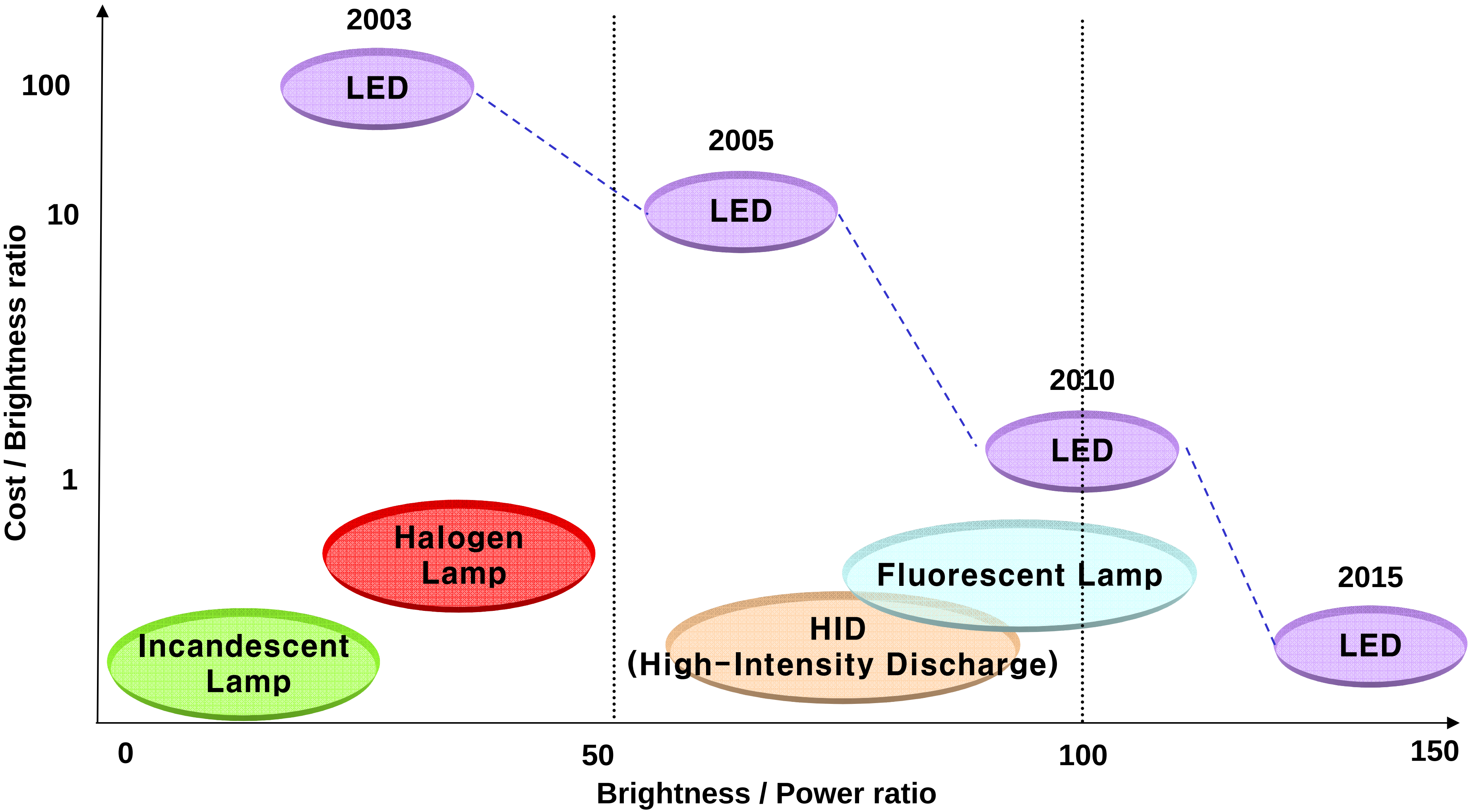
LED technical evolution

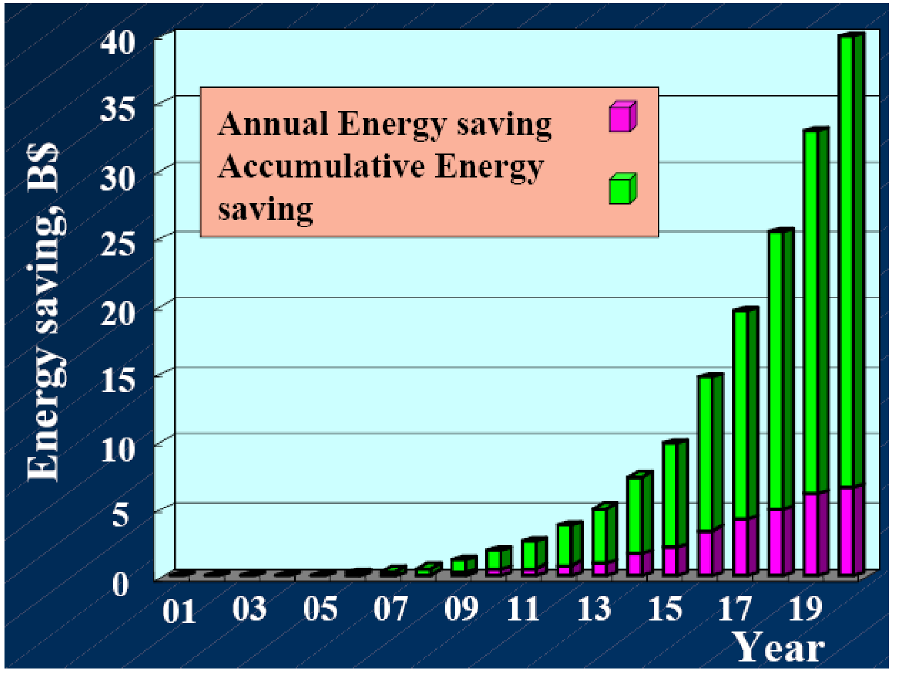
❖ Performance and Price comparison



Source: Credit Suisse, 2006.11.2

LED driver (environmental perspective)

- Environment protection
  - Kyoto Protocol : CO_2 emission regulation
  - RoHS : Hg-free bulb
  - WEEE : Producer responsibility
- Energy saving
  - Electricity in Korea
    - 278 TWh(2002), 7.2 % of USA
  - 20% for Lighting : 55.6 TWh
  - 50% saving by LED : 27.8TWh
  - Energy Saving Effect:
    - 3 Nuclear Stations (1GW/day)
    - 2 B$/year

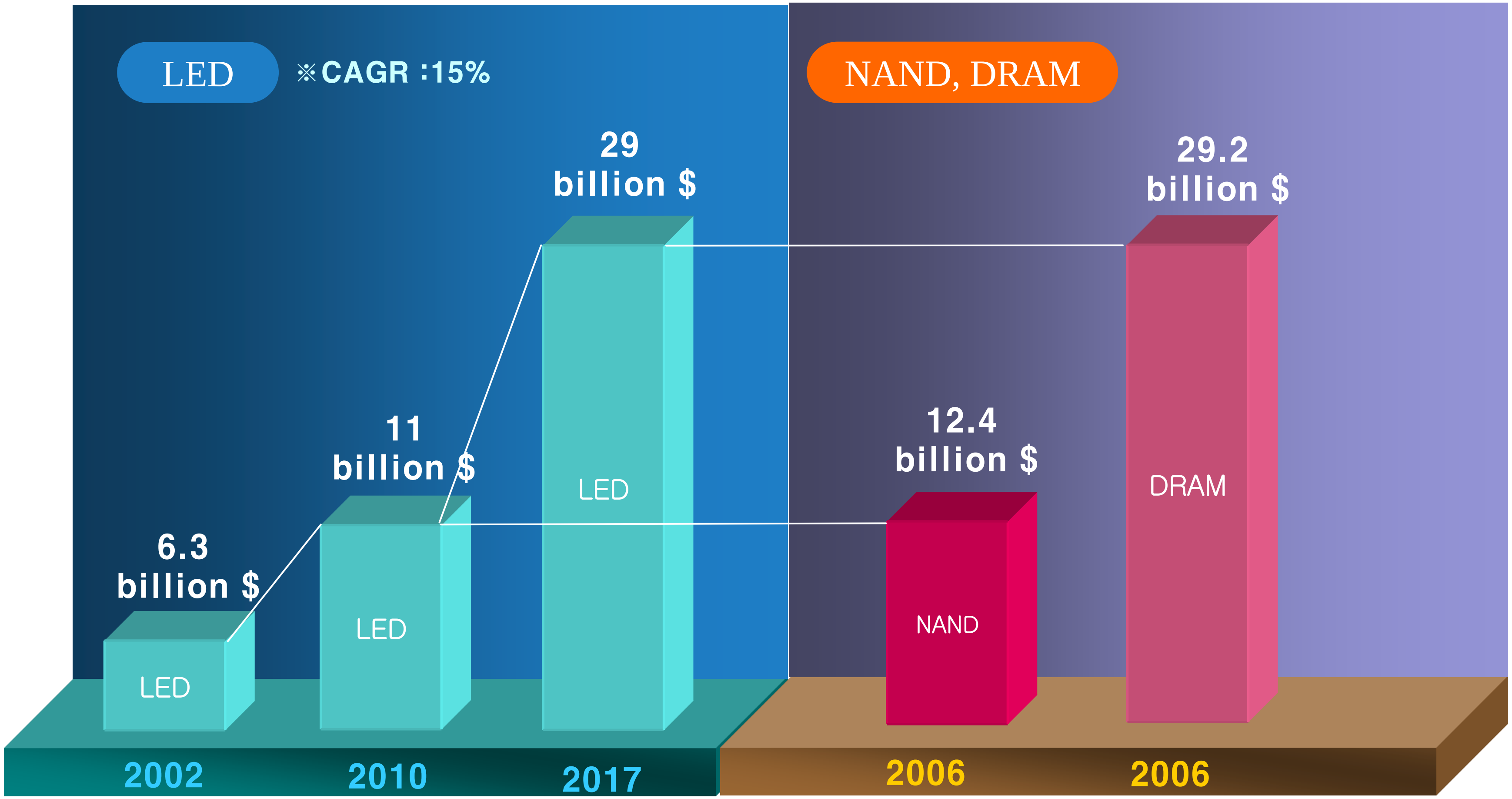


Source: KOPTI (The Korea Photonics Technology Institute)

RoHS : Restriction of the use of Certain Hazardous Substance
WEEE : Waste Electrical and Electronic Equipment

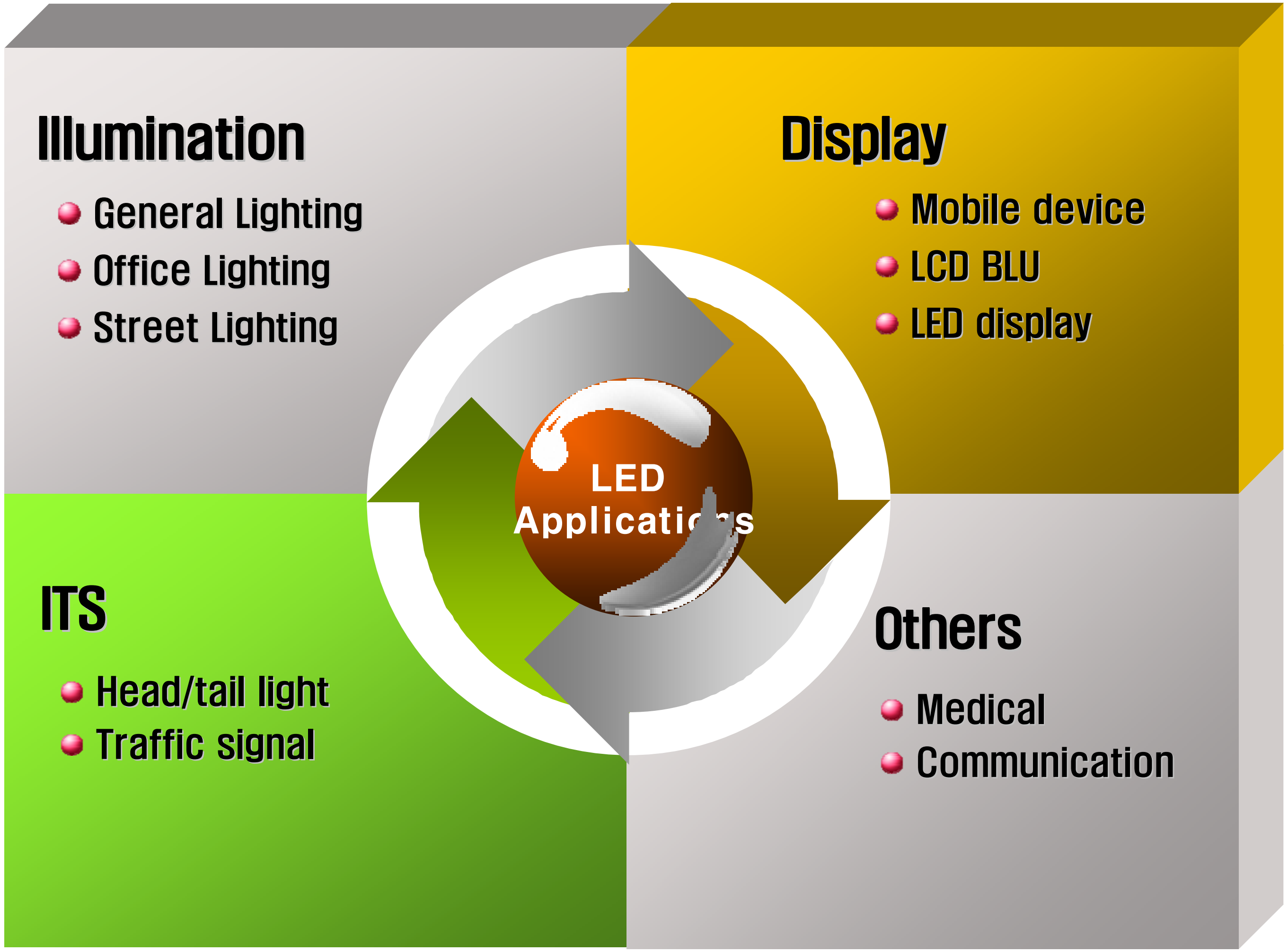
LED Market Forecast

❖ LED market comparison with NAND, DRAM

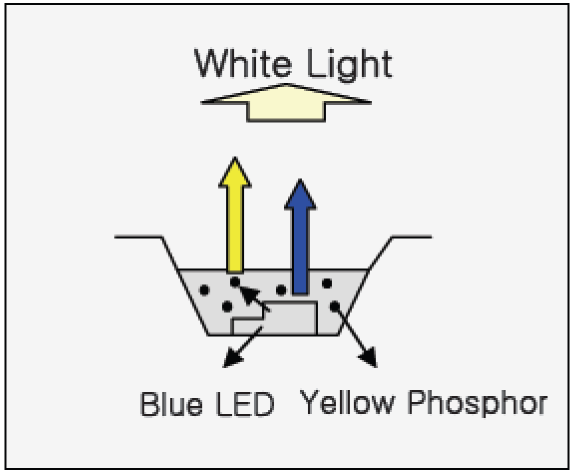


Source: Deutsche Bank, 2007. 2

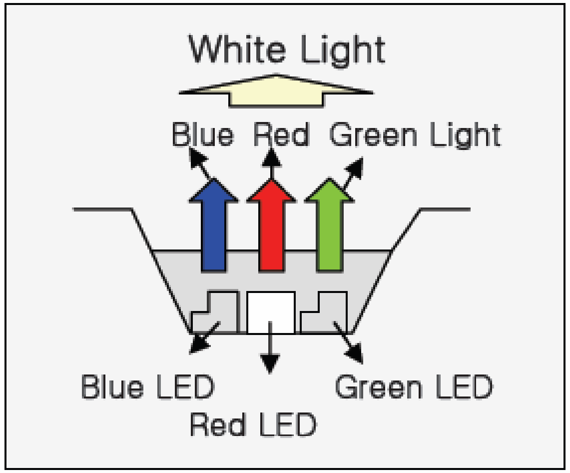
LED application



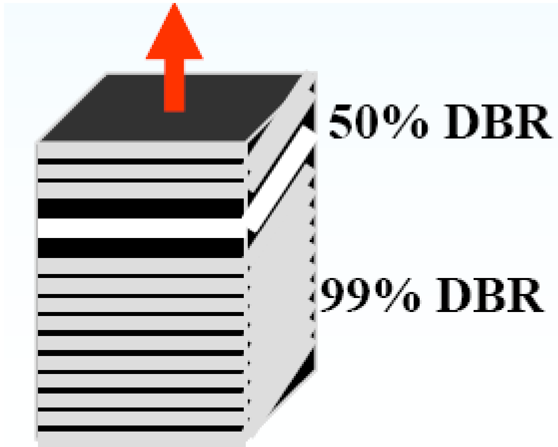
LED modulation characteristics



B + Phosphor LED



R+G+B LED



RCLED

~40 Mbps

~100 Mbps

~500 Mbps

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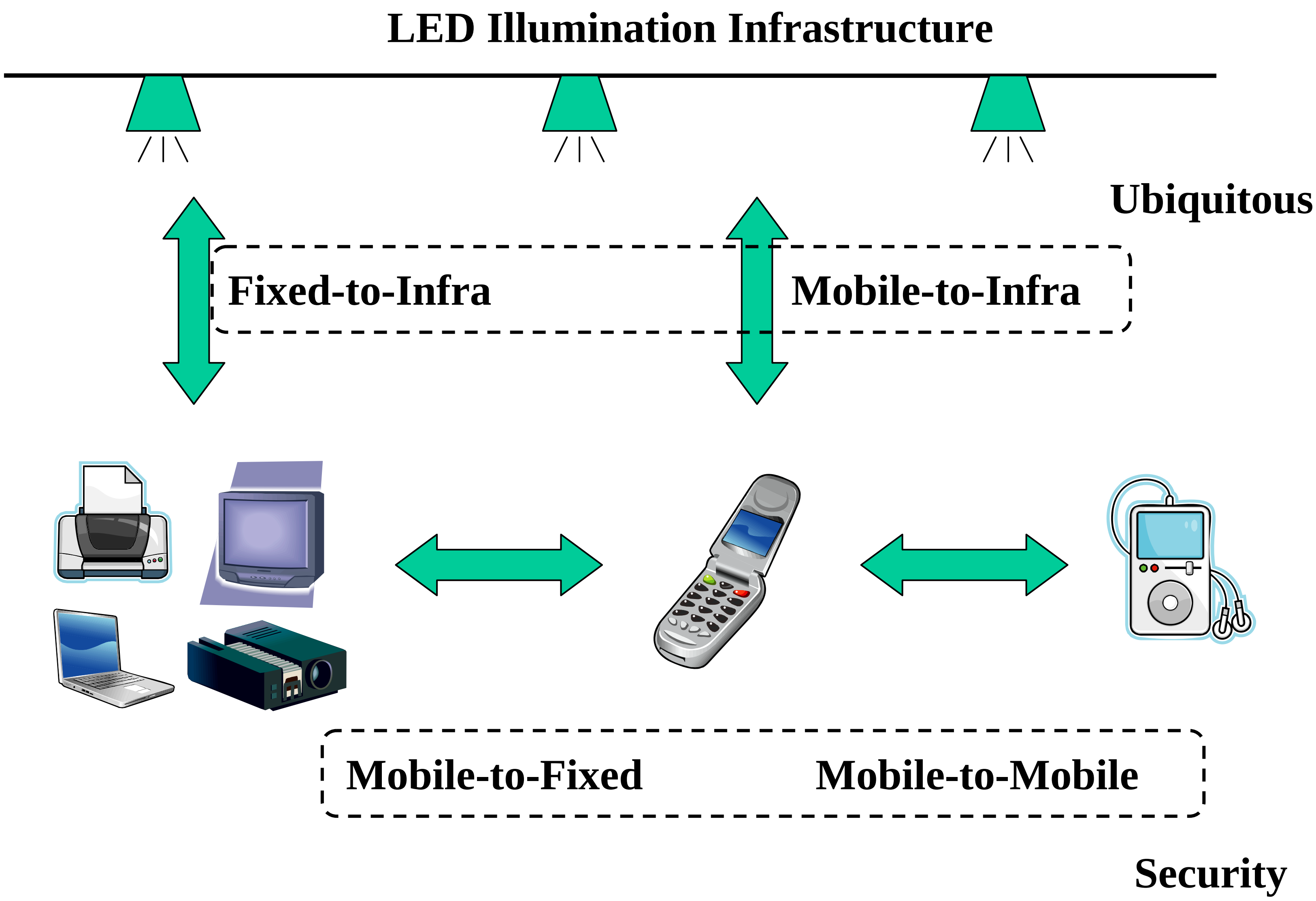
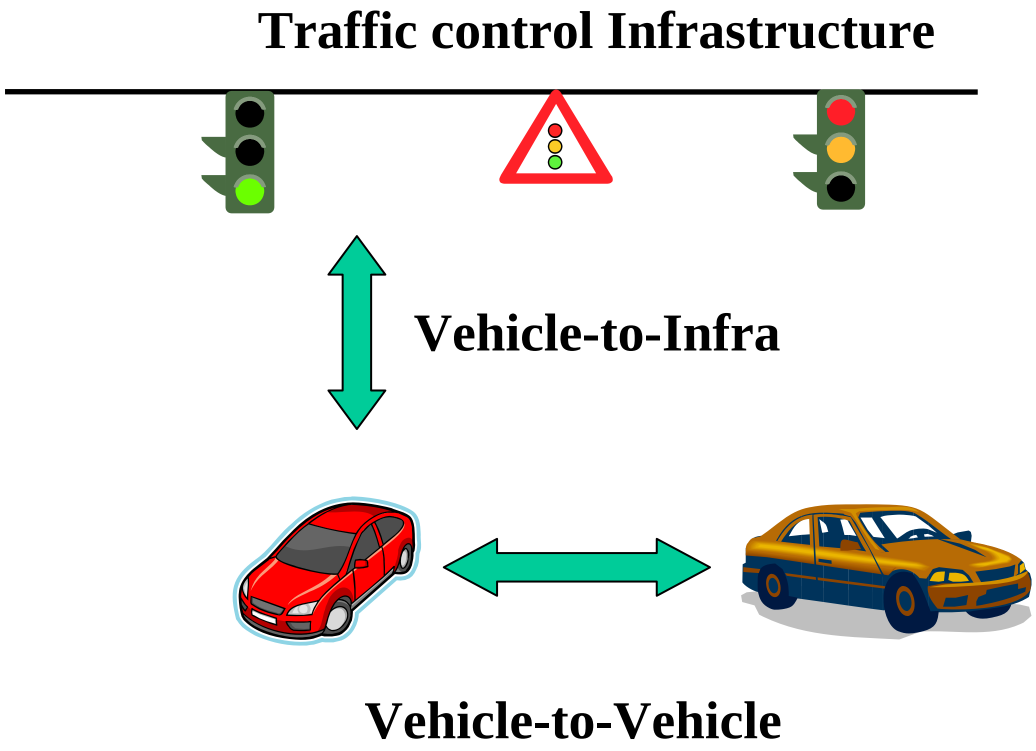
Indoor application



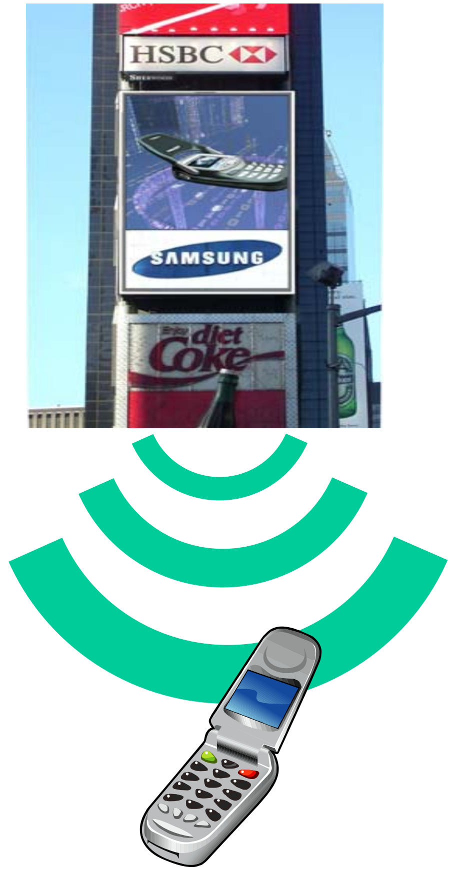
Requirements (Indoor application)

	Mobile to Mobile	Mobile to Fixed	Mobile to Infra	Fixed to Infra
Link	Bi-direction	Bi-direction	Bi or Uni	Bi or Uni
Reach	~1m	~1m	~3m	~3m
Rate	~100Mbps	~100Mbps	~10Mbps	~10Mbps
Application	Contents sharing	File transfer Video streaming M-commerce	Indoor navigation LBS Networked robot	Data broadcast
Alternative	IrDA, Bluetooth, UWB	IrDA, Bluetooth, UWB		WLAN

Outdoor application

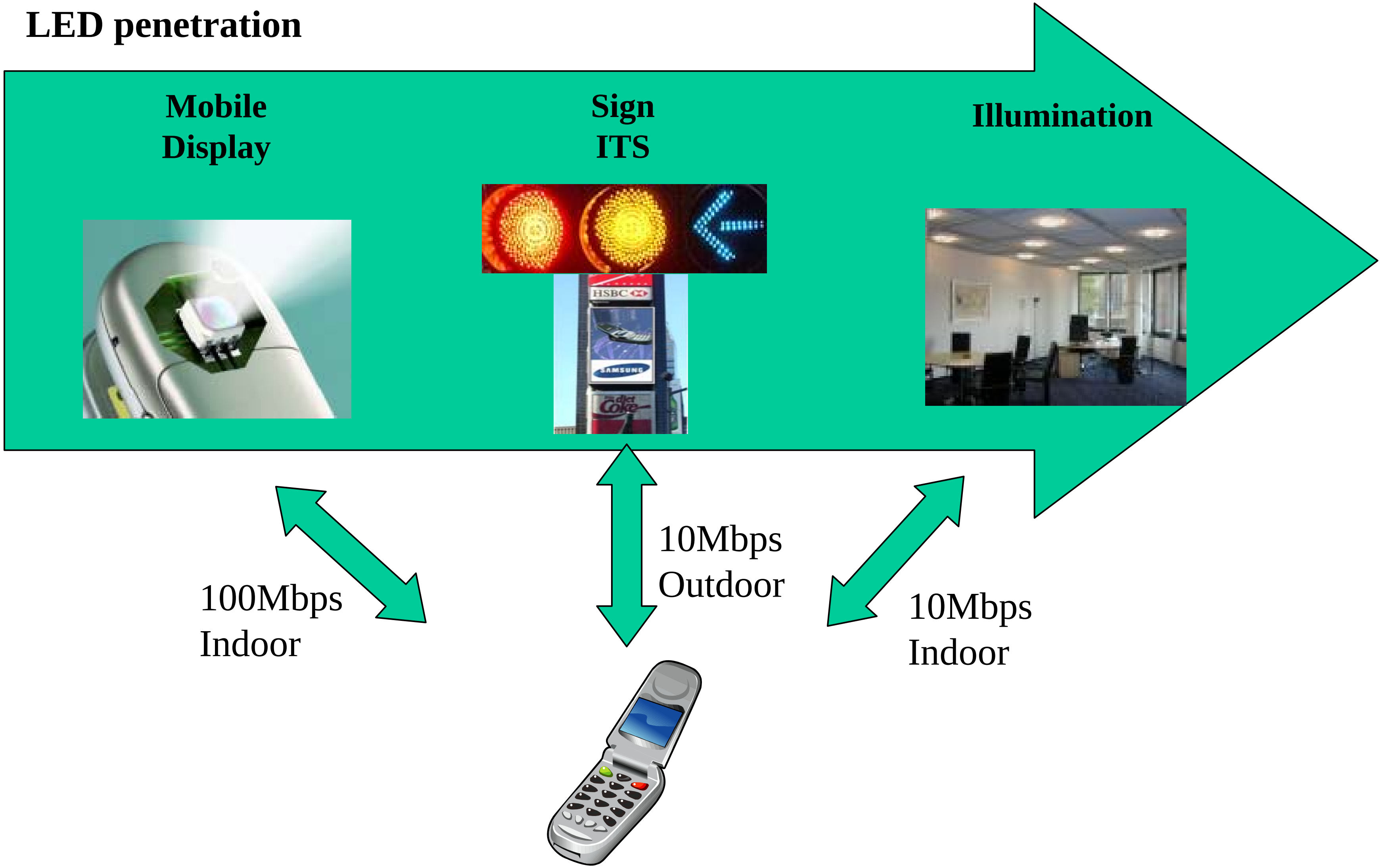


Outdoor advertising

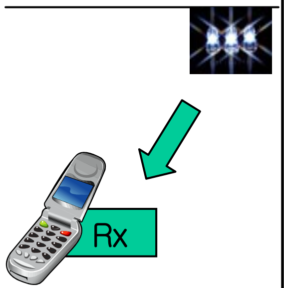
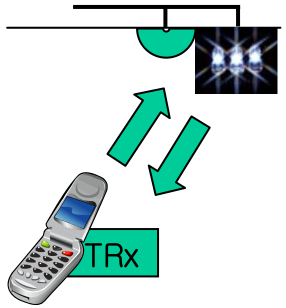
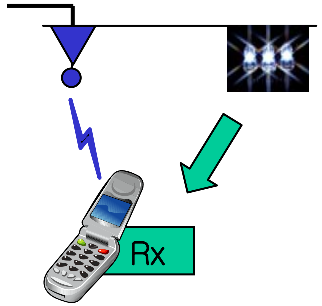
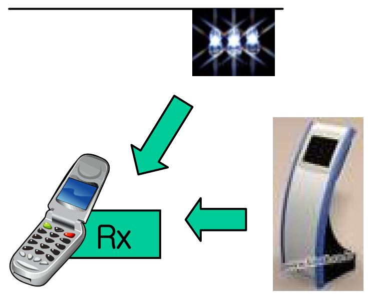


VLC application evolution

LED penetration



Indoor navigation scheme

	Uni-direction	Bi-direction	Hybrid	Hot spot
Link				
Rate	▪ Down : ~10kbps	▪ Down : ~10Mbps ▪ Up : ~100Mbps	▪ Down : ~10kbps ▪ Up : ~10Mbps	▪ Down(light) : ~10kbps ▪ Down(HS) : ~100Mbps
Infra	▪ Lighting with optical ID	▪ Lighting with optical ID ▪ Receiver ▪ In-building network ▪ Routing server	▪ Lighting with optical ID ▪ RF access point ▪ In-building network ▪ Routing server	▪ Lighting with optical ID ▪ Hot spot
Mobile	▪ Receiver ▪ Large storage ▪ Map info ▪ Routing software	▪ Receiver ▪ Transmitter	▪ Receiver ▪ RF connectivity	▪ Receiver ▪ Large storage ▪ Routing software
Other service		LBS Ad-hoc connection	LBS	

Demonstrations

High speed

Mobile to Mobile
(100Mbps,Samsung)

Tx, Rx
(~30Mbps, Univ.of Oxford)

LED array
(~1Gbps, Keio Univ.)

Music broadcasting
(6Mbps, Univ. of Oxford)

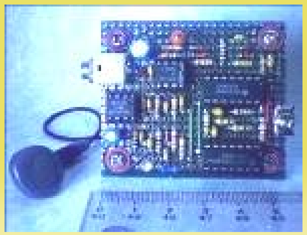
Infra to Mobile
(10Mbps, Tamura Inc.)

Sign board
(10Mbps, Samsung)

Infra to Mobile (LAN)
(4Mbps, Samsung)

Low speed

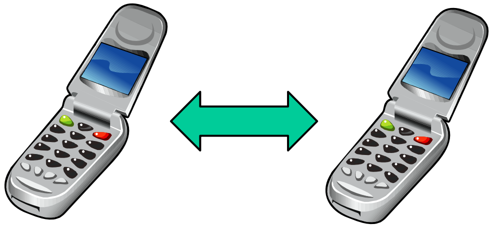
Audio transmission
(100kbps, Hongkong Univ.)

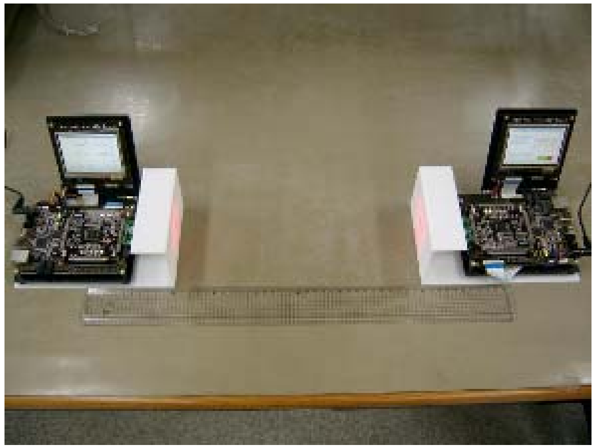


Infra to Mobile, VLCC (Keio Univ., NEC, Toshiba, Sony, Matsushita, Casio etc.)
(4.8kbps, illuminations, visible light ID, sign board, applications based on JEITA)

VLC Demonstrations

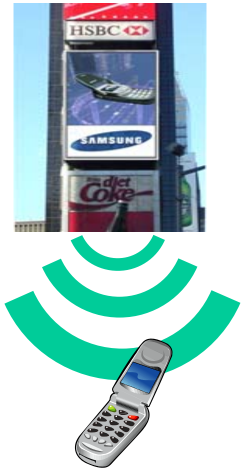
Mobile to mobile





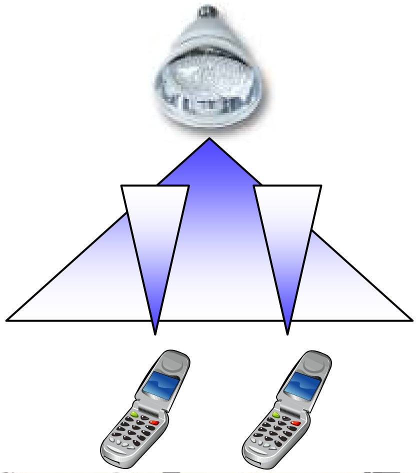
100 Mbps, 1m
Bidirection

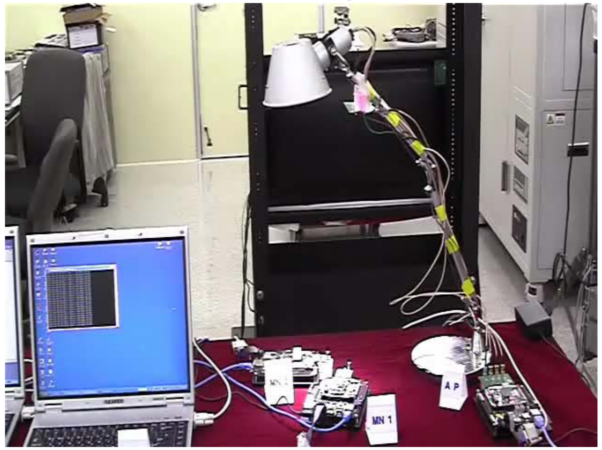
Infra to mobile



20 Mbps, 3m
Unidirection

Infra to mobile

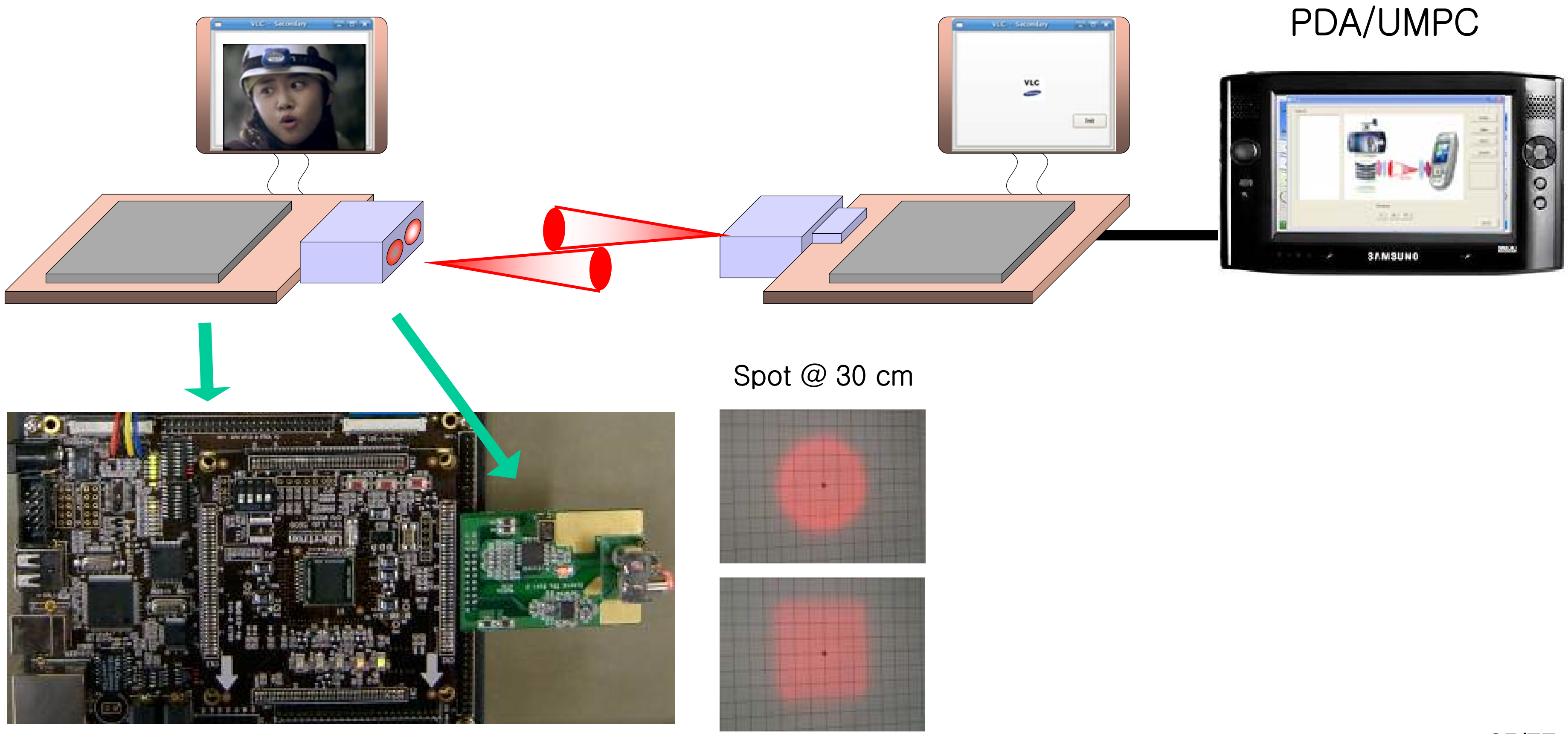




4 Mbps, 3m
Bidirection

Mobile-to-mobile demo

- What You See Is What You Send (WYSIWYS)
- 120 Mbps, 1m, Full duplex
- File transfer and video streaming

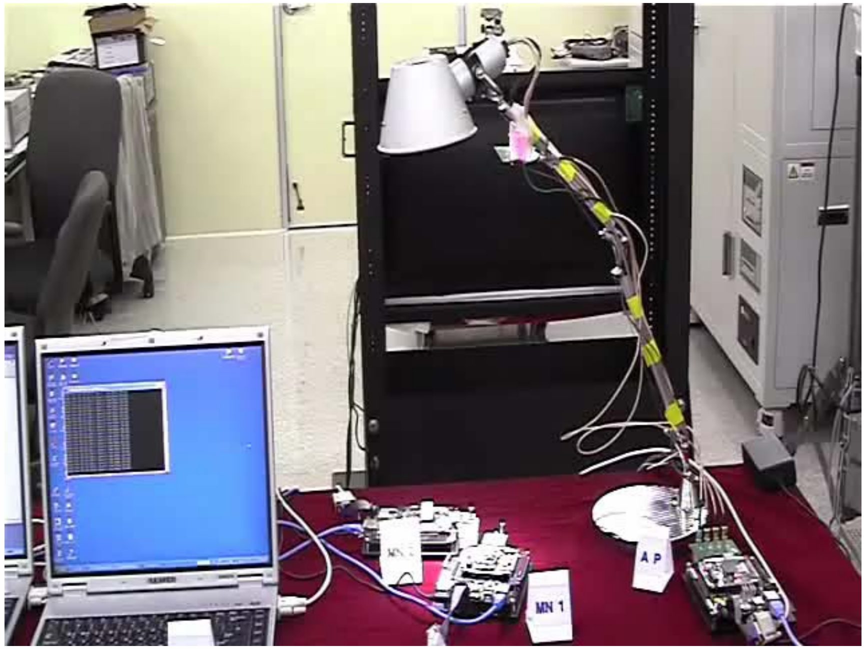


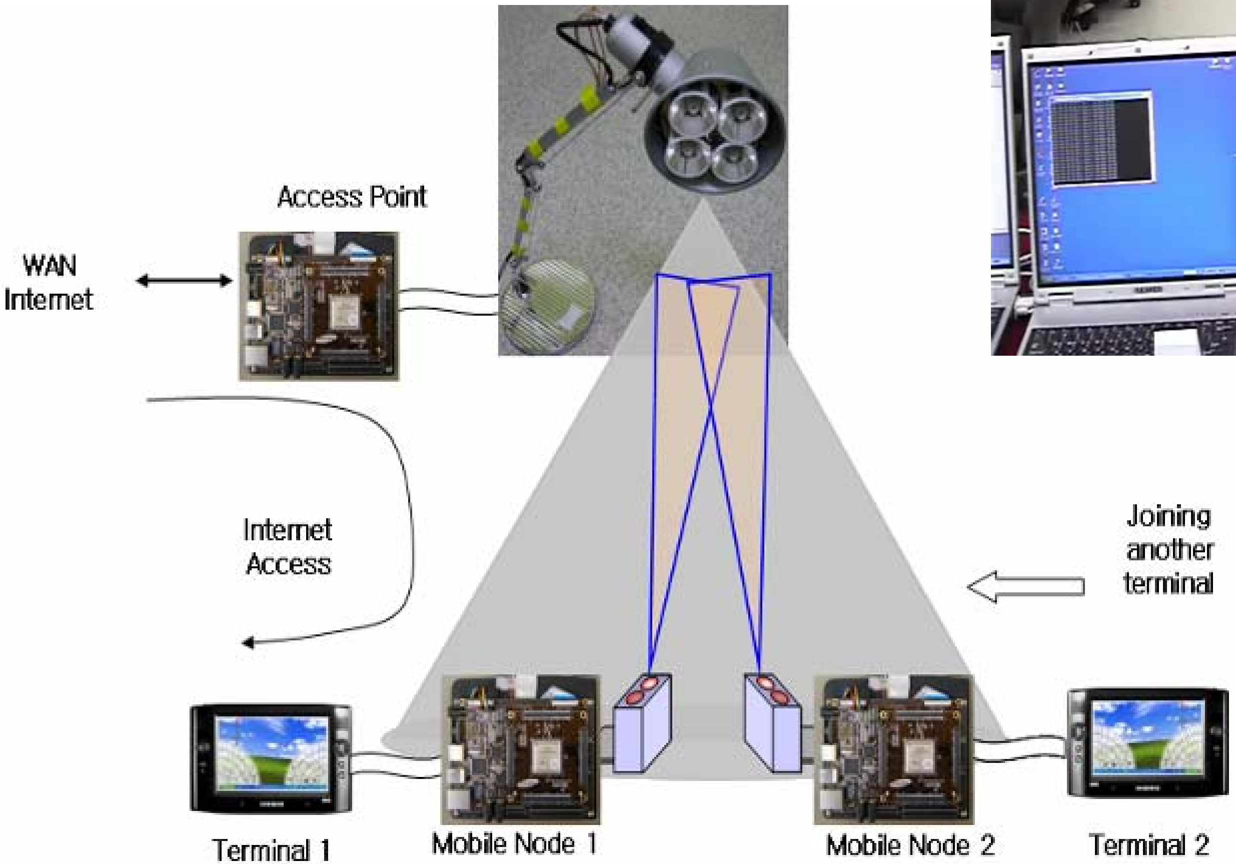
Infra-to-mobile (uni-direction)

- RGB WDM transmission
- 20 Mbps, 3m, Uni-direction
- Information broadcast from sign board

Infra-to-mobile (bi-direction)

- TDMA-based P2MP
- 4 Mbps, 3 m, bi-direction
- Secure indoor LAN





Summary (Part 1)

- VLC introduction
  - VLC history
  - Motivation
- LED introduction
  - LED technical evolution
  - LED market forecast
  - LED application
  - LED modulation characteristics
- VLC potential application
  - Application category
  - Indoor : Navigation, High-speed connectivity
  - Outdoor : ITS, Advertising
  - Demonstration
    - Demonstration overview
    - Mobile-to-mobile
    - Infra-to-mobile

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Visible Light Communications Activities

Tom Matsumura

Secretary General

VLCC (Visible Light Communications Consortium)

President

Nakagawa Laboratories, Inc.

Contents

- Introduction of VLCC members
- A characteristic of the visible light communic ations
- Field experiments and demonstrations using visible light communications
- Approach to Commercialization

VLCC Member Companies

Participation from various industries such as telecommunications companies, lighting companies, LED makers, electric power companies, electronics makers, etc.

- The Tokyo Electric Power Co., Inc.
- KDDI R&D Laboratories
- NEC Corporation
- Matsushita Electric Works, Ltd.
- The Nippon Signal Co., Ltd.
- Information System Research Institute
- Toshiba Corporation
- Samsung Electronics Co., Ltd.
- Avago Technologies Japan, Ltd.
- Toyoda Gosei Co., Ltd.
- Sony Corporation
- NTT DoCoMo, Inc.
- Casio Computer Co., Ltd.
- NEC Communication Systems, Ltd.
- NEC Lighting, Ltd.
- Nakagawa Laboratories, Inc.
- Fuji Television
- Oi Electric Co., Ltd.
- Sumitomo Mitsui Construction Co., Ltd.
- Wasshoi Co., Ltd.
- MoMoAlliance Co., Ltd.
- Tamura Corporation
- Nitto Denko Corporation
- Sharp Corporation
- Coast Guard Research Center
- Comtech 2000
- Outstanding Technology
- Rise Corporation

Characteristic of the Visible Light Communications

- A lighting is used as a communication facility.
- VLC is harmless for our health as well as our daily circumstances. And, it's ecological-conscious !
- A friendly user interface
- The visible light communications do not have any regulations such as the radio communication system.
- VLC has an affinity to the power line communication.

Field experiments and demonstrations for the visible light communications system

- A sound communication system
  (analog system)
- A sound communication system
  (digital system)
- Visible light ID system
  (digital system)
- High-speed data transmission system
  (digital system)

A sound communication system (analog system)

Photo by Yoshio Miyairi

Amusement Use

Exhibition in Yokohama National Gallery
Illumination are synchronized with music sounds, which are transmitted through the lights(bottom) by VLC to the audience.

The state of the daytime art object

A sound communication system (analog system)

RGB Music Sound System

▪Music sounds are transmitted through visible lights (RGB) independently.
(i.e. R:Drum, G:Bass, B:Piano)

▪Music sounds can be controlled through their combination.
(i.e. B:Piano only, R&G: Drum and Bass, White(RGB):Drum, Bass, Piano altogether)

A sound communication system (digital system)

Music sounds are transmitted through RGB lights (Each RGB light has a different sound; guittar, keyboard, etc.

Prototype presented by SONY and Agilent Technologies

Visible light ID system

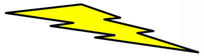
Merchandise information distribution system

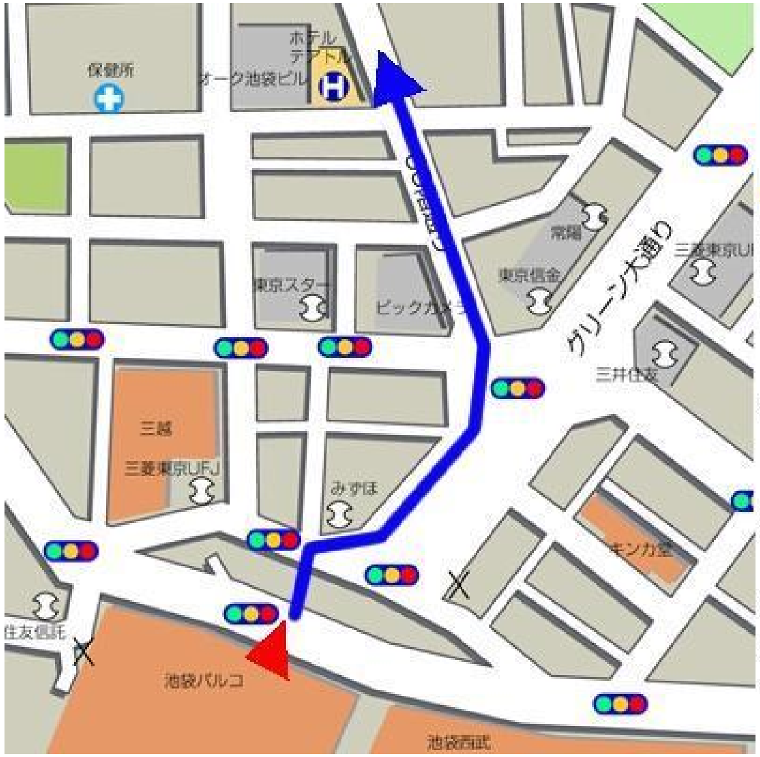
The product information is acquired by the visible light receiver on the shopping cart.

Prototype presented by NEC and Matsushita Electric Works

Visible light ID system

The neighbor information distribution system from a traffic light





A signal is red.

Please cross a street and turn to the right, which leads to "Sunshine 60" Building.

Visible Light Communications Consortium

日本信号
THE NIPPON SIGNAL CO., LTD.

Visible light ID system

Indoor Navigation System

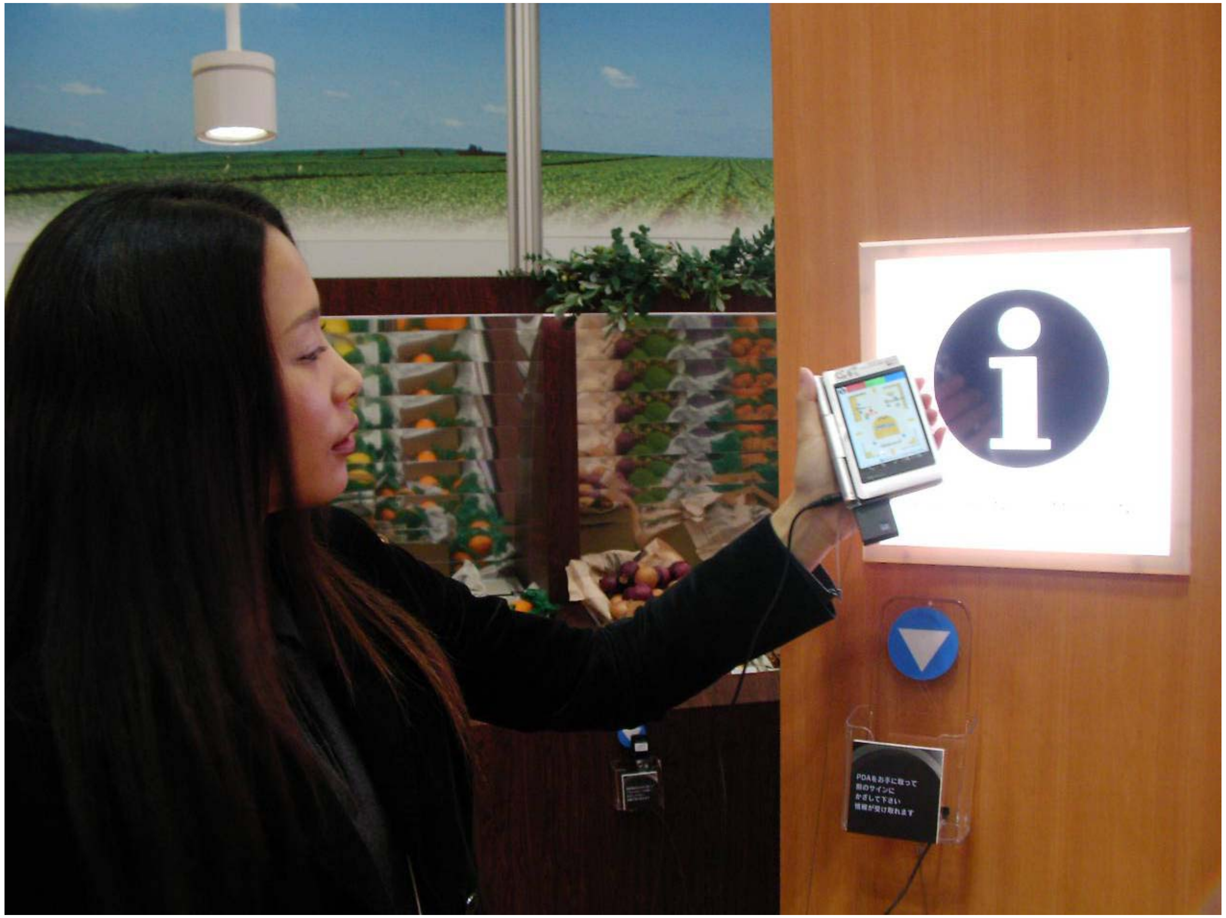
The lighting can be used as a visible light ID system, which informs an exact location (for example, A corner of Room Number 123, ABC Building, etc). The each light has a different ID, which shows a different exact location. This positioning system can be used even in the underground subway station, shopping mall etc, where GPS is not accurately used. The system is also very convenient for the emergency use. (Indoor Navigation System). This is used inside hospitals, too.

Other data are also obtained using the Internet access by a cellular phone based on ID.

Prototype presented by NEC and Matsushita Electric Works

Visible light ID system

The guidance system using sign light



Prototype presented by Shimizu Corporation , NEC and NEC Lighting, Ltd.

Information is received from LED sign light.

10Mbps VLC Wireless LAN System

Presentation at IT Pro Expo 2008

Poster Display

Approach to Commercialization

At Nakagawa Laboratories Inc., VLC ID system products are developed for commercialization.

The traffic-diagram-research system for stores

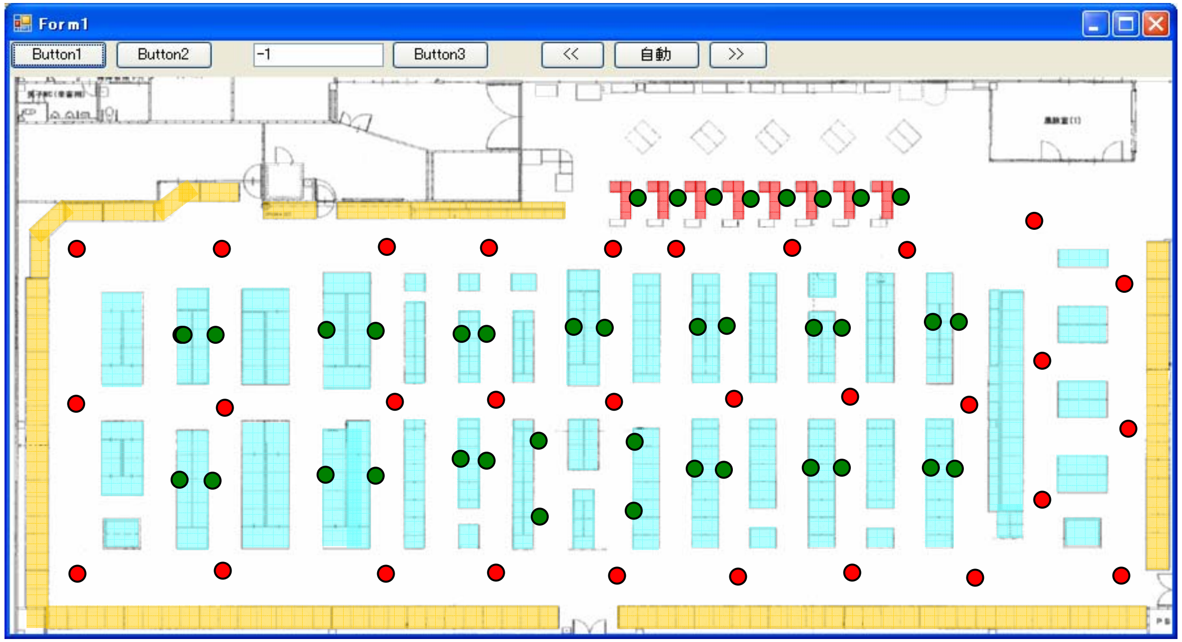
In a supermarket, many visible light ID lamps are set in the passages, and a visible light ID receiver is attached to a shopping cart.

The outline of traffic diagram research

The store , where the field experiments are made.

Store space :1,711㎡
(“Fujiya Store” in Shizuoka, Japan)

ID lamp allocation



Shelf space allocation

- Surrounding shelf
- Inside shelf
- Cash register

ID lamp allocation

- Ceiling lamp
- Floor lamp

Visible Light Communications Consortium

Visible light ID transmitter

A ceiling lamp type

A floor lamp type

A floor lamp type on freezer

A floor lamp type on cash register

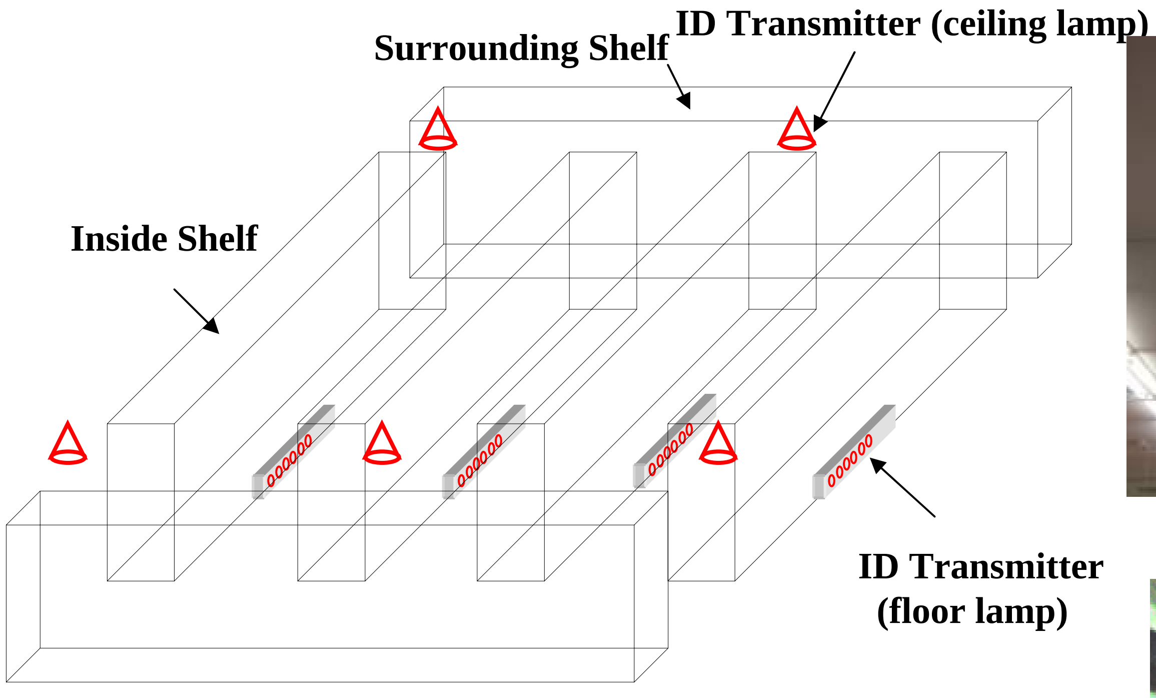
Visible light ID receiver

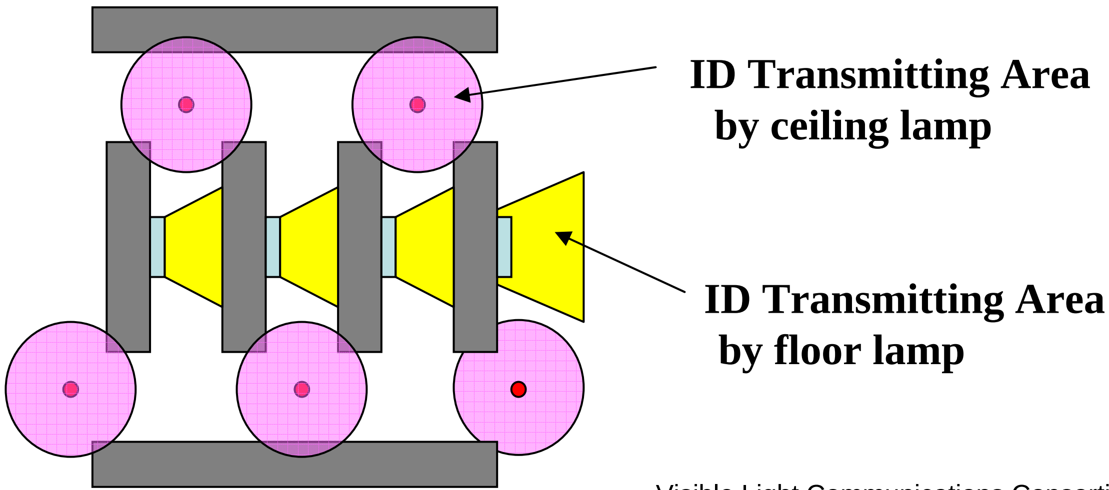
Attached to the bottom of a shopping cart

The state that reversed a shopping cart

IDs (Exact Position and Time) are accumulated in a memory card when the shopping cart goes through the passages.

ID Transmitting Area



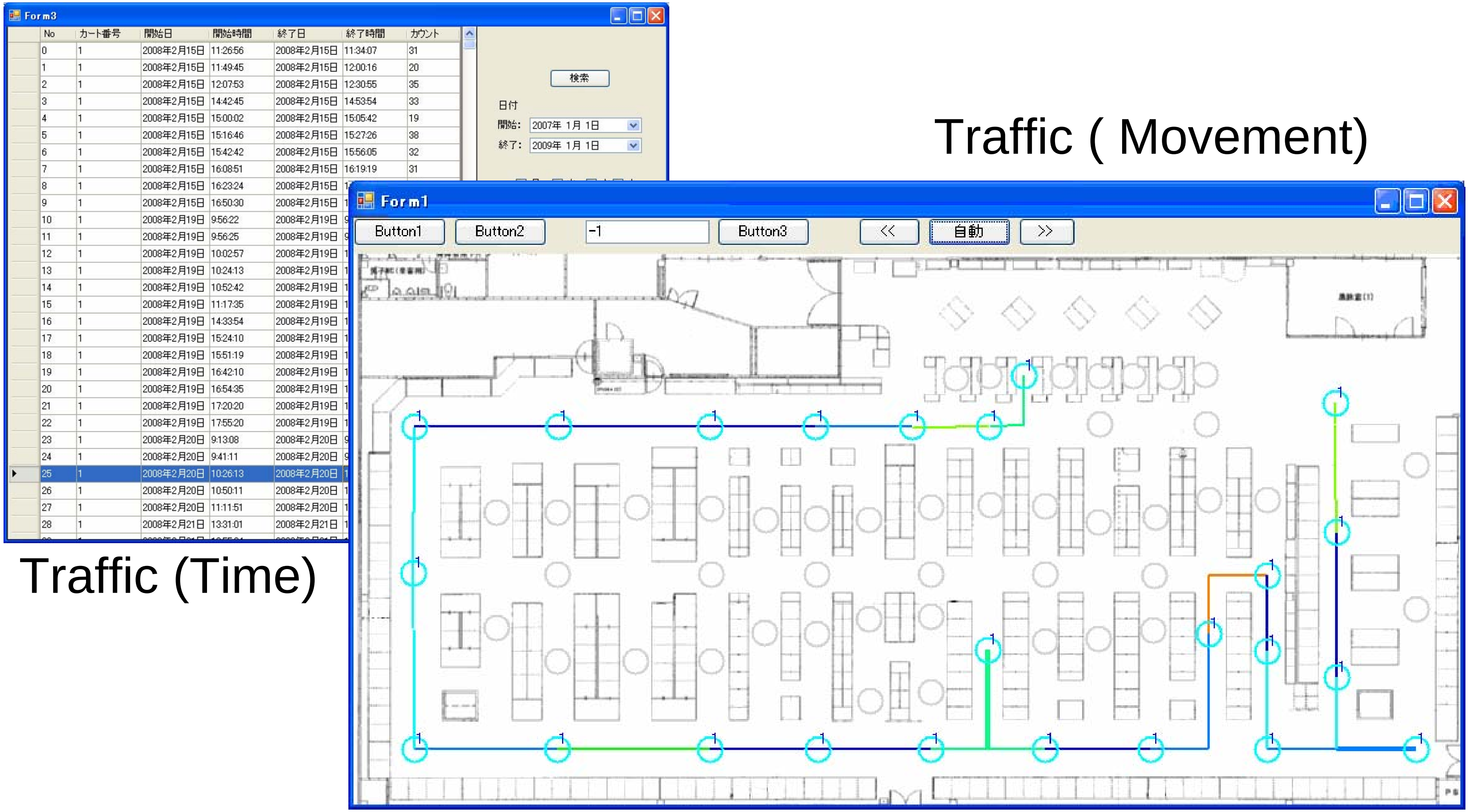


Ceiling Lamp Allocation

Lighting by Ceiling Lamp

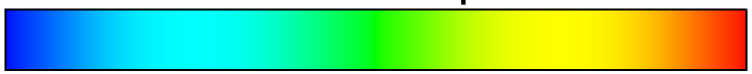
Traffic Data （Single)

Traffic (Movement)

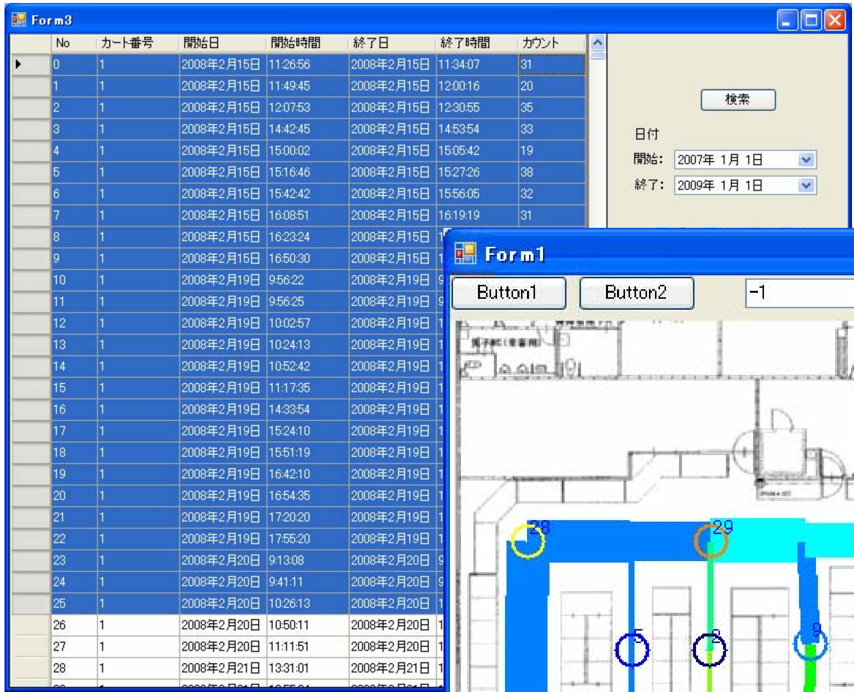


Traffic (Time)

Traffic Speed

Slow  Fast

Traffic Data (Plural)


Form3

	No	カート番号	開始日	開始時間	終了日	終了時間	カウント
▶	0	1	2008年2月15日	11:26:56	2008年2月15日	11:34:07	31
	1	1	2008年2月15日	11:49:45	2008年2月15日	12:00:16	20
	2	1	2008年2月15日	12:07:53	2008年2月15日	12:30:55	35
	3	1	2008年2月15日	14:42:45	2008年2月15日	14:53:54	33
	4	1	2008年2月15日	15:00:02	2008年2月15日	15:05:42	19
	5	1	2008年2月15日	15:16:46	2008年2月15日	15:27:26	38
	6	1	2008年2月15日	15:42:42	2008年2月15日	15:56:05	32
	7	1	2008年2月15日	16:08:51	2008年2月15日	16:19:19	31
	8	1	2008年2月15日	16:23:24	2008年2月15日		
	9	1	2008年2月15日	16:50:30	2008年2月15日		
	10	1	2008年2月19日	9:56:22	2008年2月19日		
	11	1	2008年2月19日	9:56:25	2008年2月19日		
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	13	1	2008年2月19日	10:24:13	2008年2月19日		
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	18	1	2008年2月19日	15:51:19	2008年2月19日		
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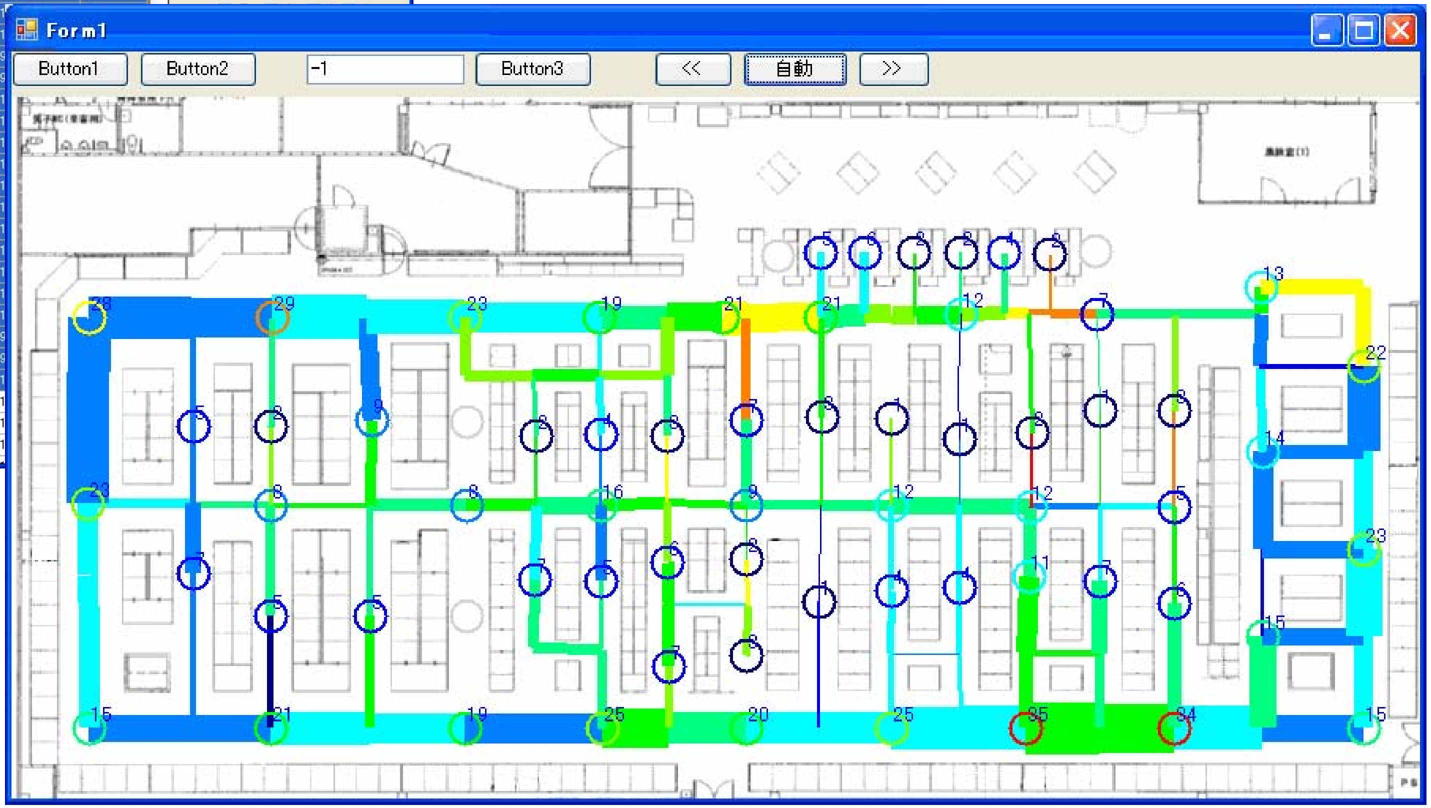
	20	1	2008年2月19日	16:54:35	2008年2月19日		
	21	1	2008年2月19日	17:20:20	2008年2月19日		
	22	1	2008年2月19日	17:55:20	2008年2月19日		
	23	1	2008年2月20日	9:13:08	2008年2月20日		
	24	1	2008年2月20日	9:41:11	2008年2月20日		
	25	1	2008年2月20日	10:26:13	2008年2月20日		
	26	1	2008年2月20日	10:50:11	2008年2月20日		
	27	1	2008年2月20日	11:11:51	2008年2月20日		
	28	1	2008年2月21日	13:31:01	2008年2月21日		

検索
日付
開始: 2007年 1月 1日
終了: 2009年 1月 1日

Traffic (Time)

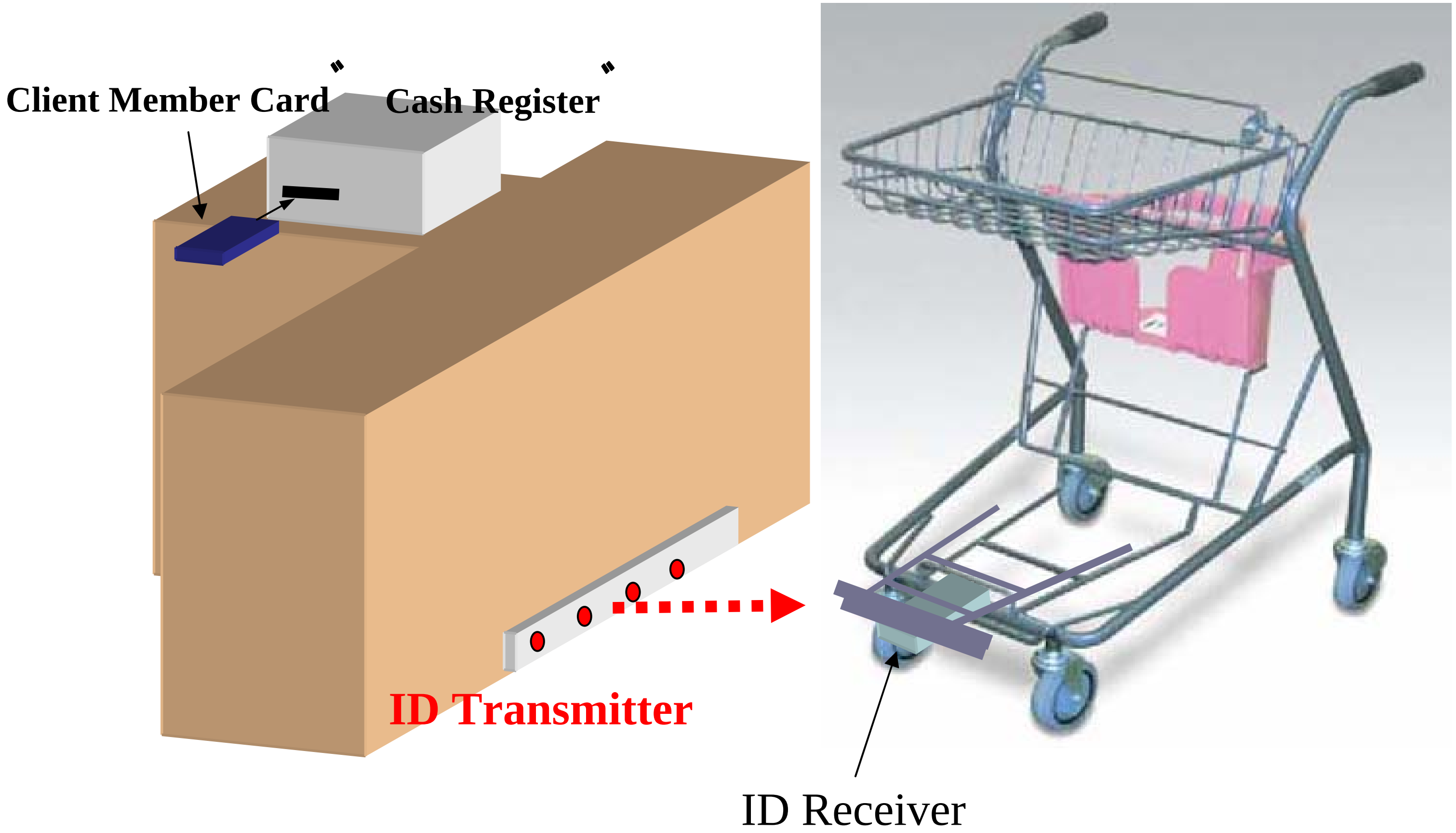
Traffic (Movement)



Average Speed

Slow — Fast

Client/POS Data linked with Traffic Data



Client data can be linked with the traffic data.
POS data can be also linked with the traffic data.

Summary

Visible Light Communications is the best system for an ecological and human health, and can use the established retro-system including the lighting facility as well as power line system. This system is also free from the current radio regulation.

Visible Light ID System (which is already standardized by JEITA: Japan Electronics and Information Technology Industries Association) is good for “Indoor Navigation system” as well as “Indoor Traffic-research system linked with POS/Client data”.

Outline

- Part 1 (Samsung, ETRI)
  - VLC introduction
  - LED introduction
  - VLC potential application
- Part 2 (VLCC)
  - The revolution of the lighting
  - Introduction of VLCC members
  - A characteristic of the visible light communications
  - Field experiments and demonstrations using visible light communications
  - Approach to Commercialization
- Part 3 (University of Oxford)
  - VLC components
  - Technical challenges

Visible Light Communications

Dominic O'Brien, University of Oxford,

dominic.obrien@eng.ox.ac.uk

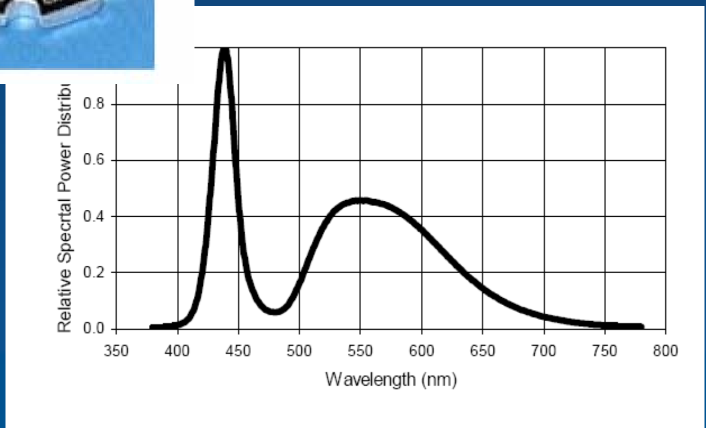
Contributions from Communications Group at Oxford

Overview

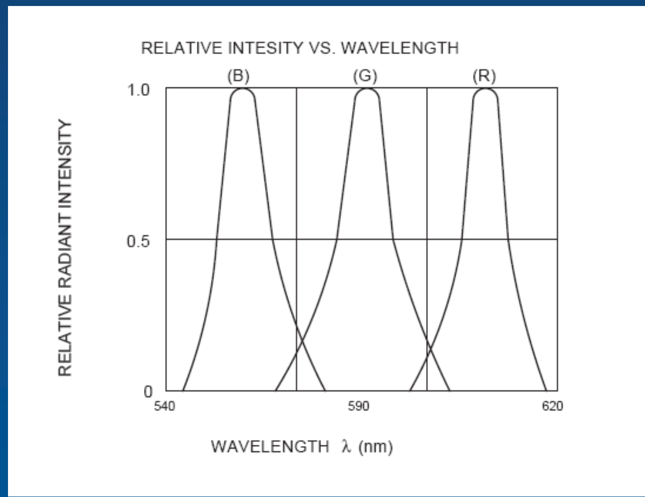
- Visible Light Communications
  - Transmitter
  - Channel
  - Receiver
- Technical challenges
  - Higher bandwidth
  - Enabling mobility and reliability
- Conclusions

VLC Sources

- Blue LED & Phosphor
  - Low cost
  - Phosphor limits bandwidth
  - Modulation can cause colour shift
- RGB triplet
  - Higher cost
  - Potentially higher bandwidth
  - Potential for WDM
  - Modulation without colour shift



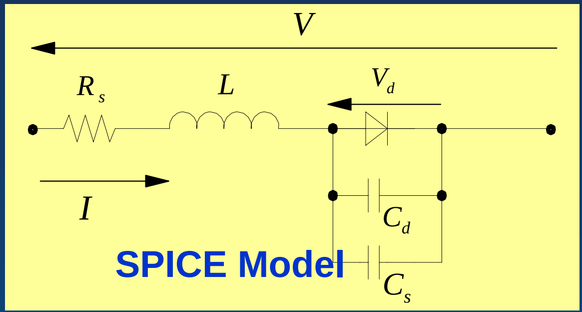
Single chip LED spectrum



RGB LED spectrum

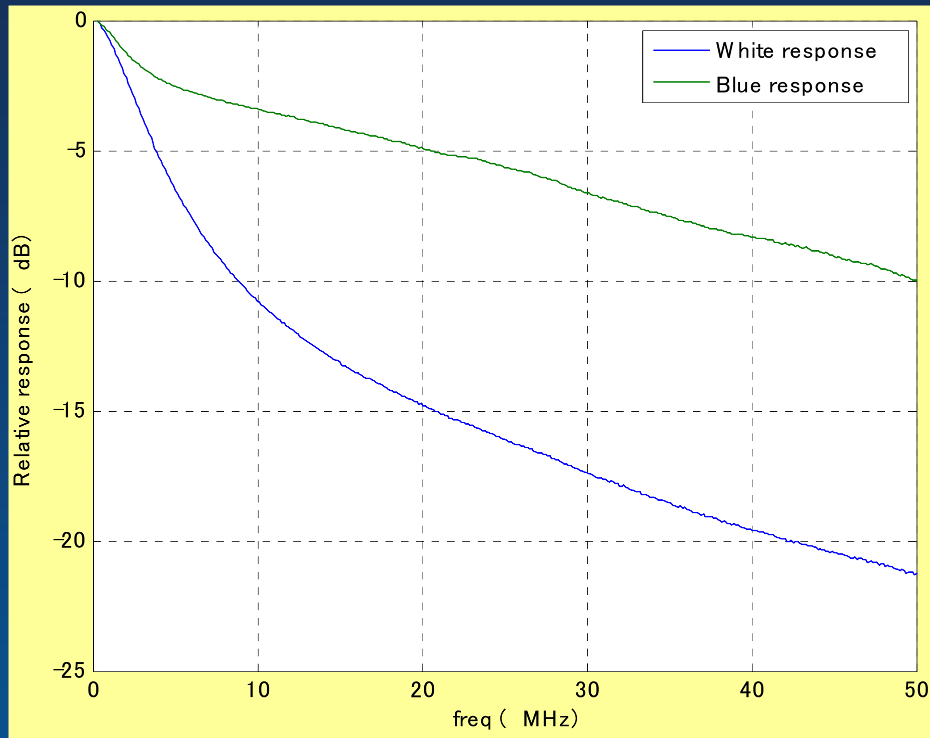
LED Modulation

> **Opto-electronic response**



Luxeon LED

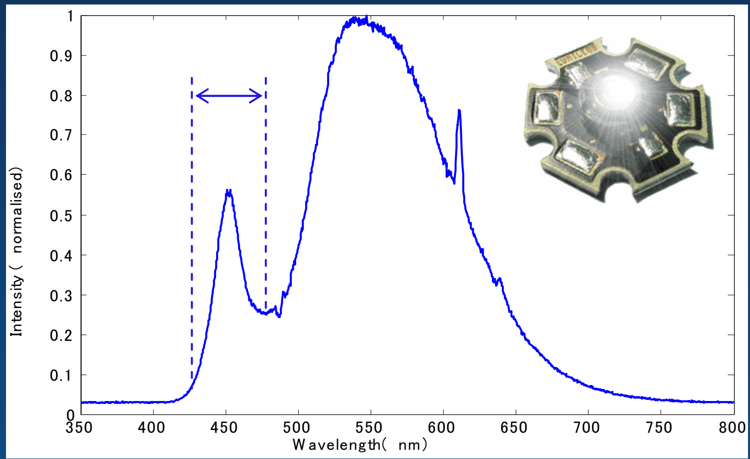
R_s = 0.9727 Ω
L = 33.342 nH
C_s = 2.8 nF
C_d = 2.567 nF
tt = 1.09 ns



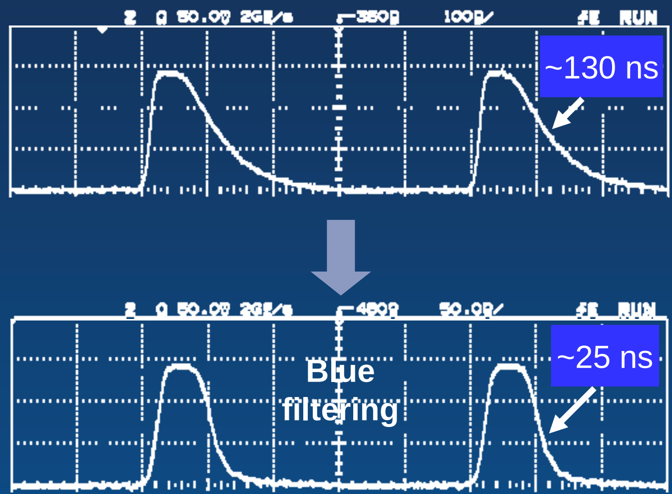
Measured LED small-signal bandwidth

Improvement of LED response

> **Using blue-response only (blue filtering)**



Measured optical spectrum



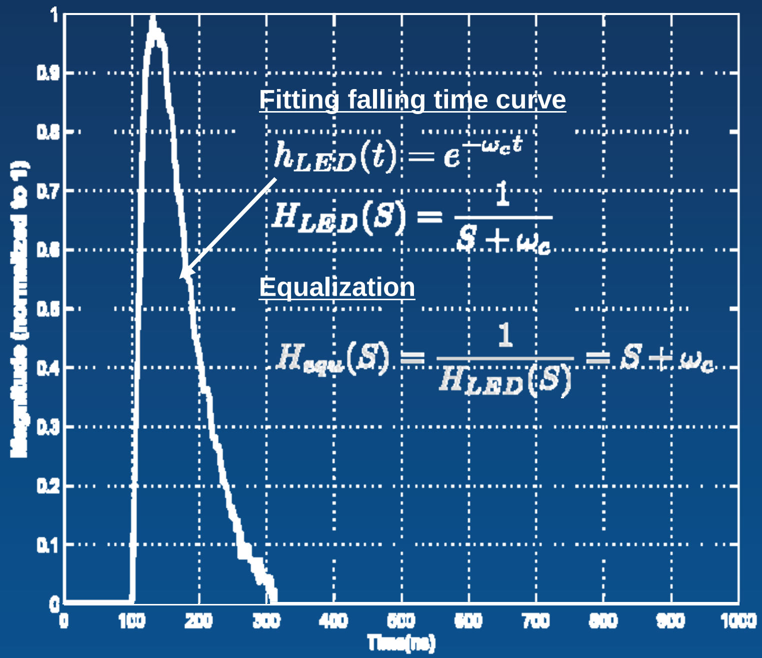
Measured impulse response

- **Issue: Only 10% of signal power is recovered**
  $\Rightarrow$ **Reducing SNR, link distance**
- **LEDs with more blue energy [1] could be used to gain more filtered power, however the balance of white colour is shifted**

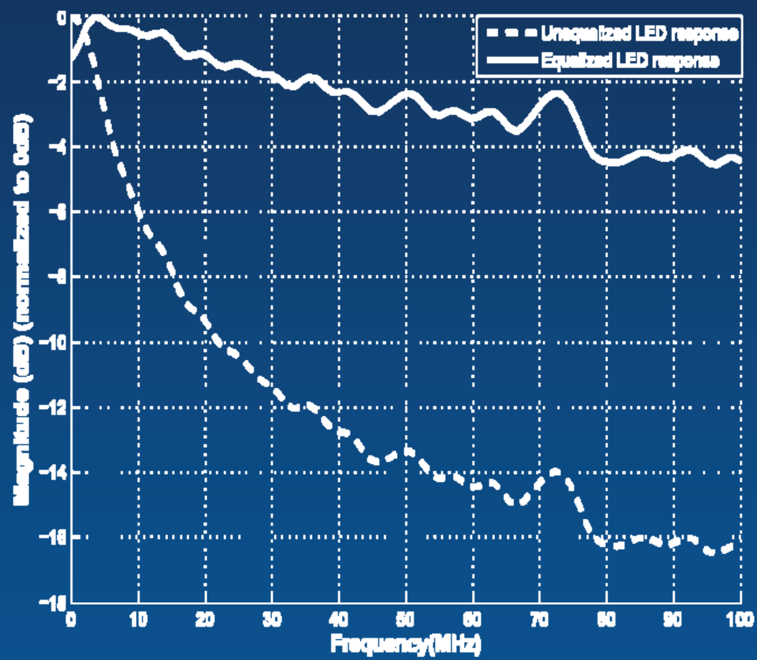
[1] Grubor, J., et al., "Wireless high-speed data transmission with phosphorescent white-light LEDs", Proc. ECOC 07 (PDS 3.6), pp. 1-2. ECO [06.11], 16-20 Sep. 2007, Berlin, Germany

Improvement of channel response

> **Receiver equalisation**



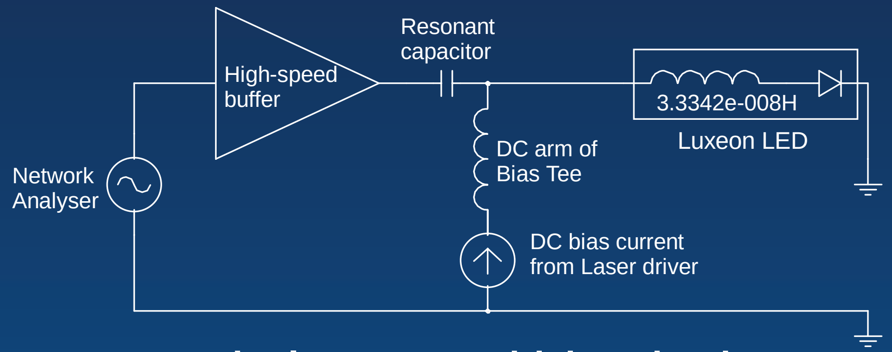
Measured LED impulse response



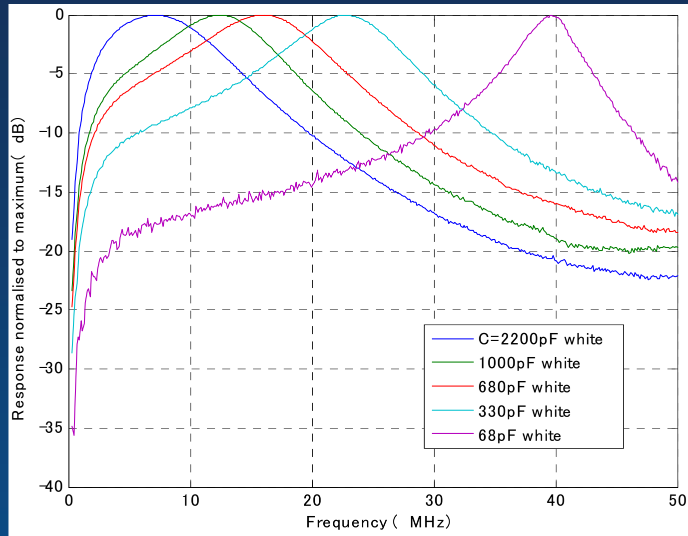
Improved LED transmission BW

Improvement of LED bandwidth

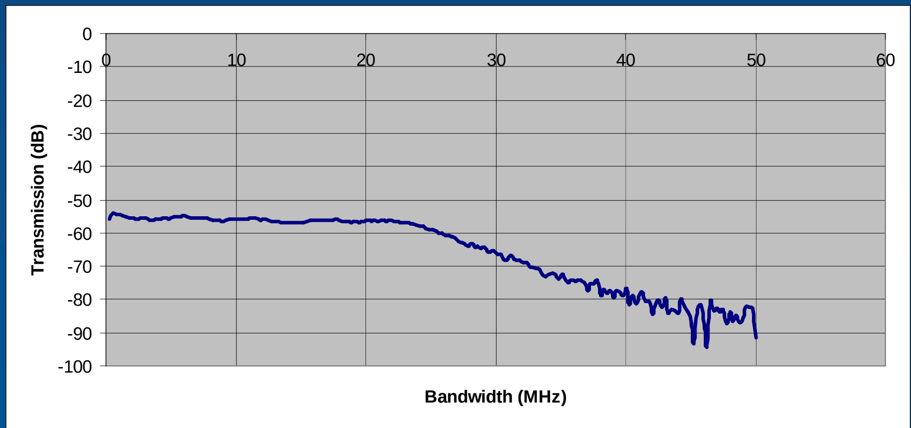
> **Pre-equalization: Resonant driving circuit**



A single resonant driving circuit



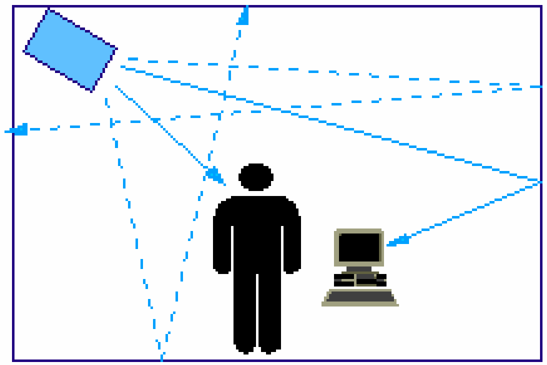
Multiple resonant points (normalized)



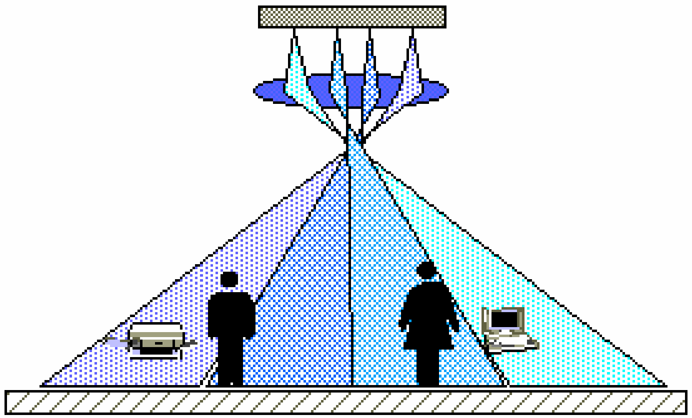
Bandwidth of 16 LED source

Channel modelling

- **Two propagation paths:**
- **Line of sight (LOS): strong paths calculated using the illumination patterns from LED arrays**
- **Diffuse: modelled by assuming the room is equivalent to an integrating sphere**
- **Channel impulse response is calculated for each point in the room**

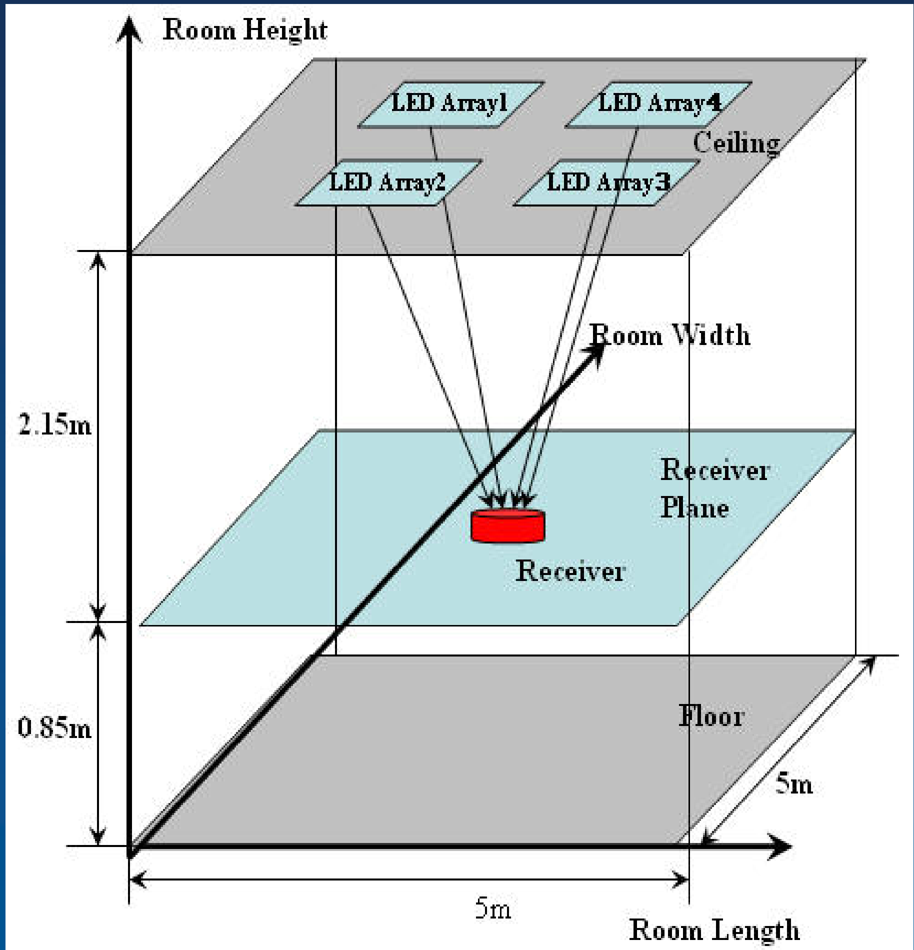


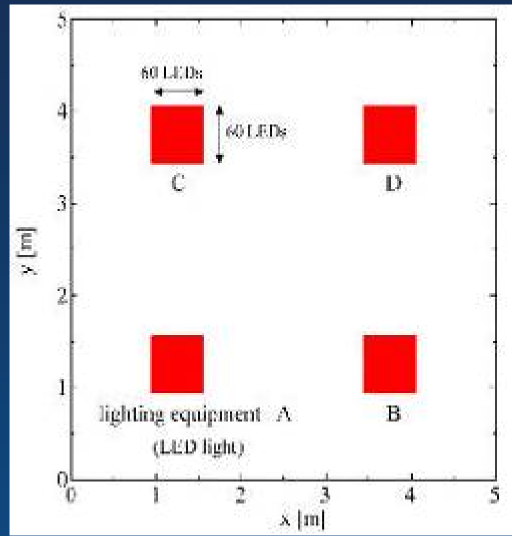
Diffuse channels

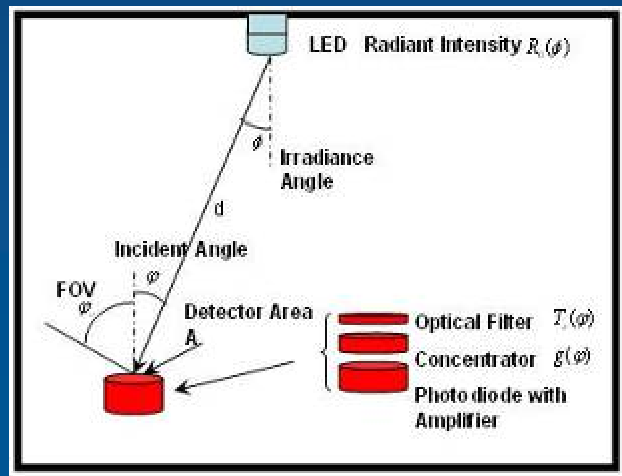


Line of sight channels

VLC modelling

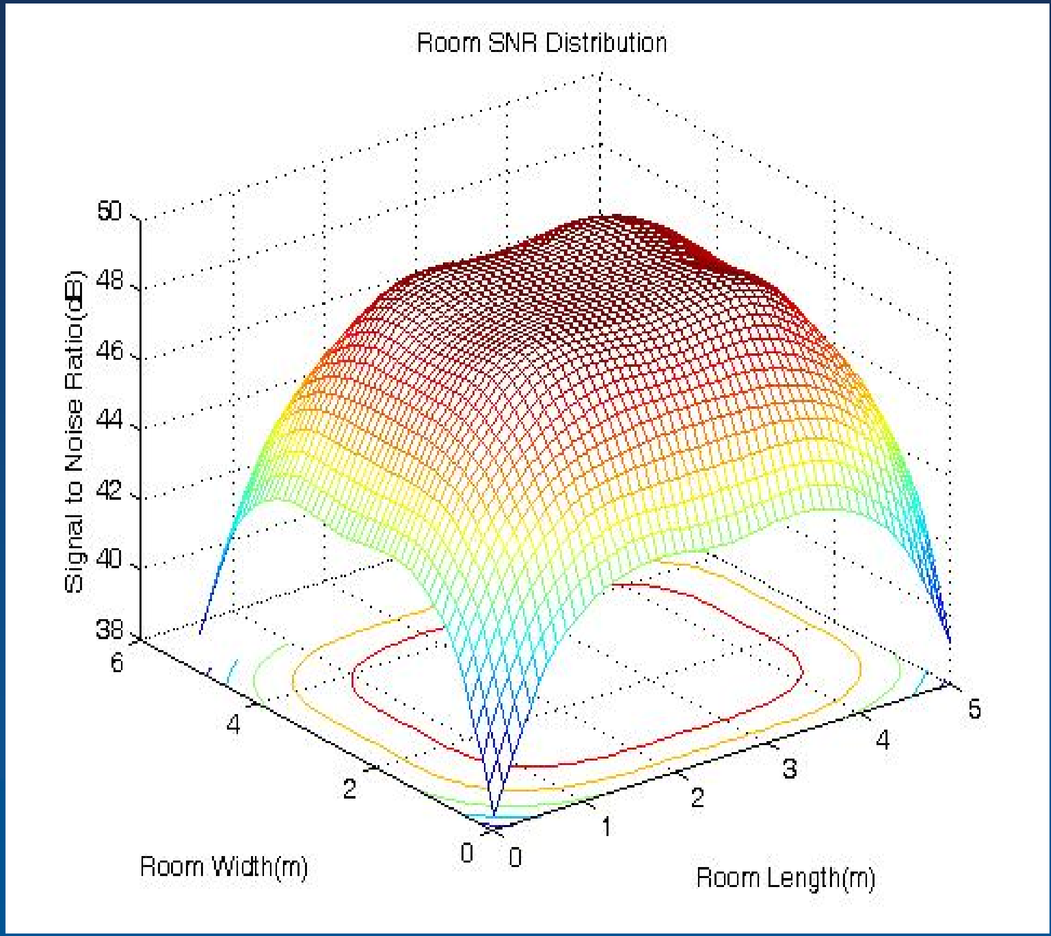






Room Power Distribution

- Assume
  - 1% modulation of typical illumination power
  - Typical receiver performance
- Conclusions
  - Very high SNR available
    - SNRmin = 38.50dB
    - SNRmax = 49.41dB
  - Modulation limited by source bandwidth

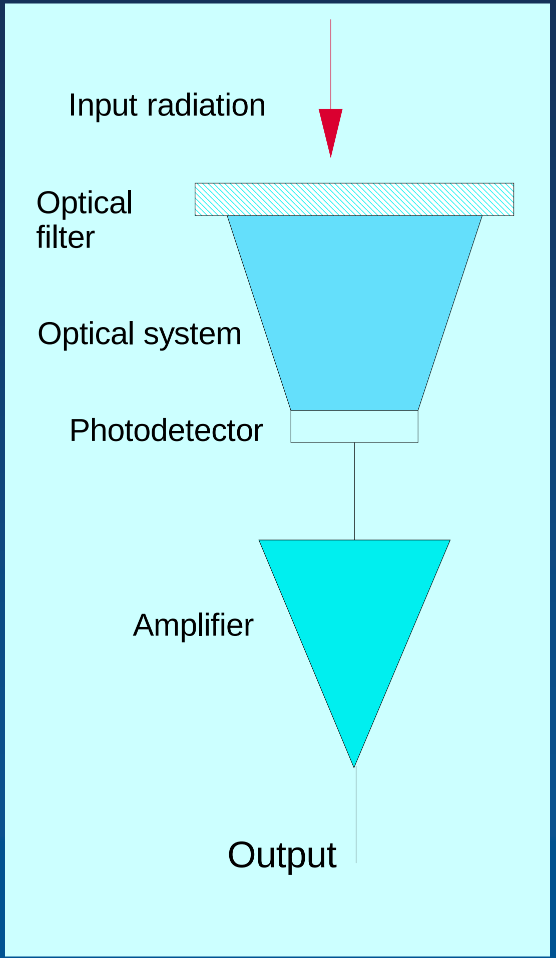


Noise sources

- Optical noise
  - Daylight
    - Generates DC photocurrent
      - Blocked at receiver due to AC coupling
      - Creates shot noise
  - Other optical sources
    - Fluorescent, Incandescent
      - Creates electrical interference photocurrent harmonics
  - Mitigated by
    - Optical filtering
      - Wavelength is in band of desired signal
    - Electrical filtering

Optical receiver

- Receiver consists of
  - Optical filter
    - Rejects ‘out-of-band’ ambient illumination noise
  - Lens system or concentrator
    - Collects and focuses radiation
  - Photodetector (or array of detectors)
    - Converts optical *power* to *photocurrent*
      - Incoherent detection
  - Preamplifier (or number of preamplifiers)
    - Determines system noise performance
  - Post-amplifier and subsequent processing

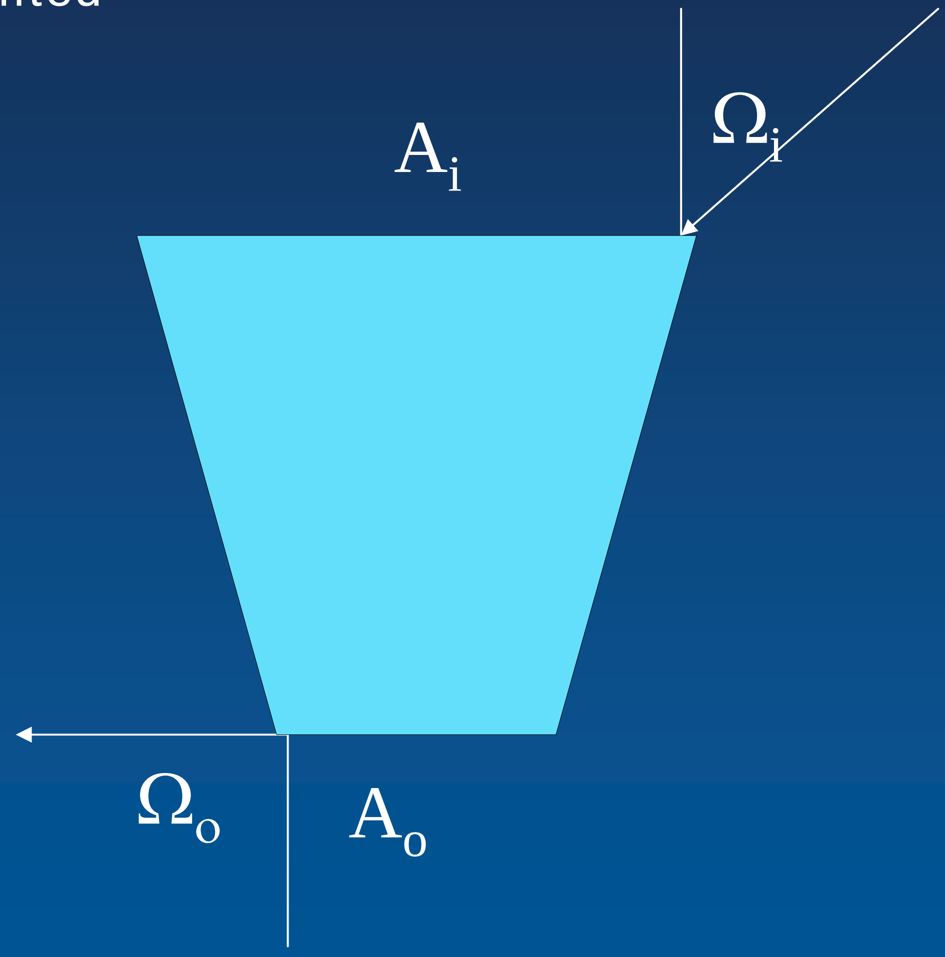


Optical receiver: constant radiance theorem

- Optical ‘gain’ of receiver limited by required field of view

$$A_i\Omega_i <= A_o\Omega_o$$

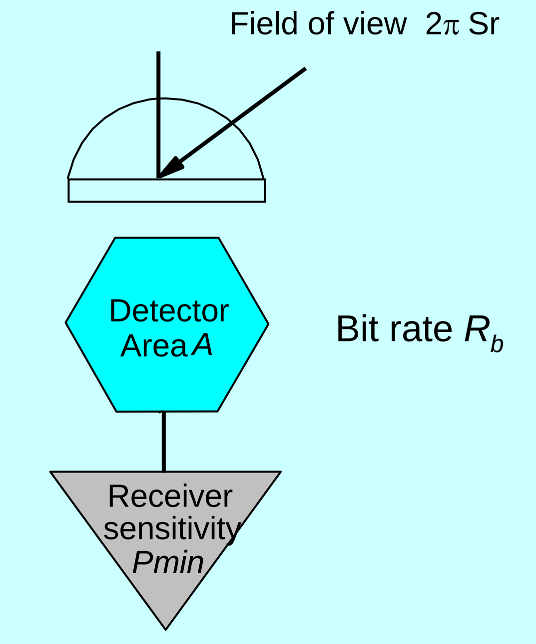
$$A_i\Omega_i <= A_o 2\pi$$



Receiver performance: figure of merit

- Receiver Figure of Merit (FOM)
  - Fibre systems
    - Performance determined by sensitivity (given sufficient detector area)
    - FOV usually not relevant
  - Free space systems
    - Etendue crucial determinant

$$FOM = \frac{2\pi R_b A}{P_{\min}}$$

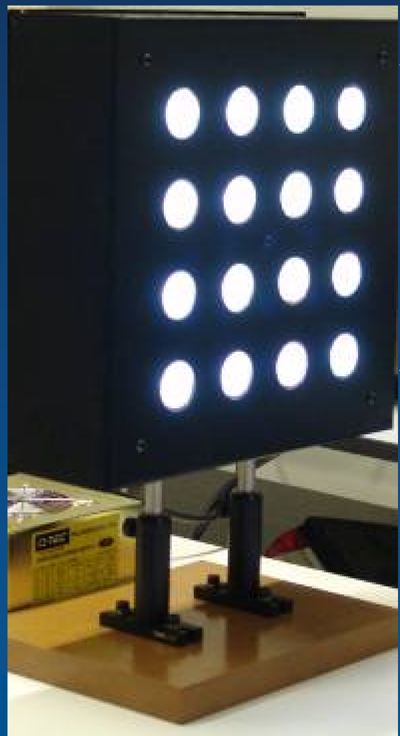


Typical link: components

Transmitter and receiver specifications

Transmitter

- 16 Luxeon LEDs
- P_{ILLUM} = 1.5W
- LED pitch = 60 mm
- I_{DC} = 220 mA
- Mod-index = 0.1
- 45° wide-beam lens
- 7 resonant freq.
- Flat BW of 25 MHz



$2 \times R_{illum}$ = 3 m

L_{LOS} = 2 m

Range

L = 2 m

R_{illum} = 1.5 m

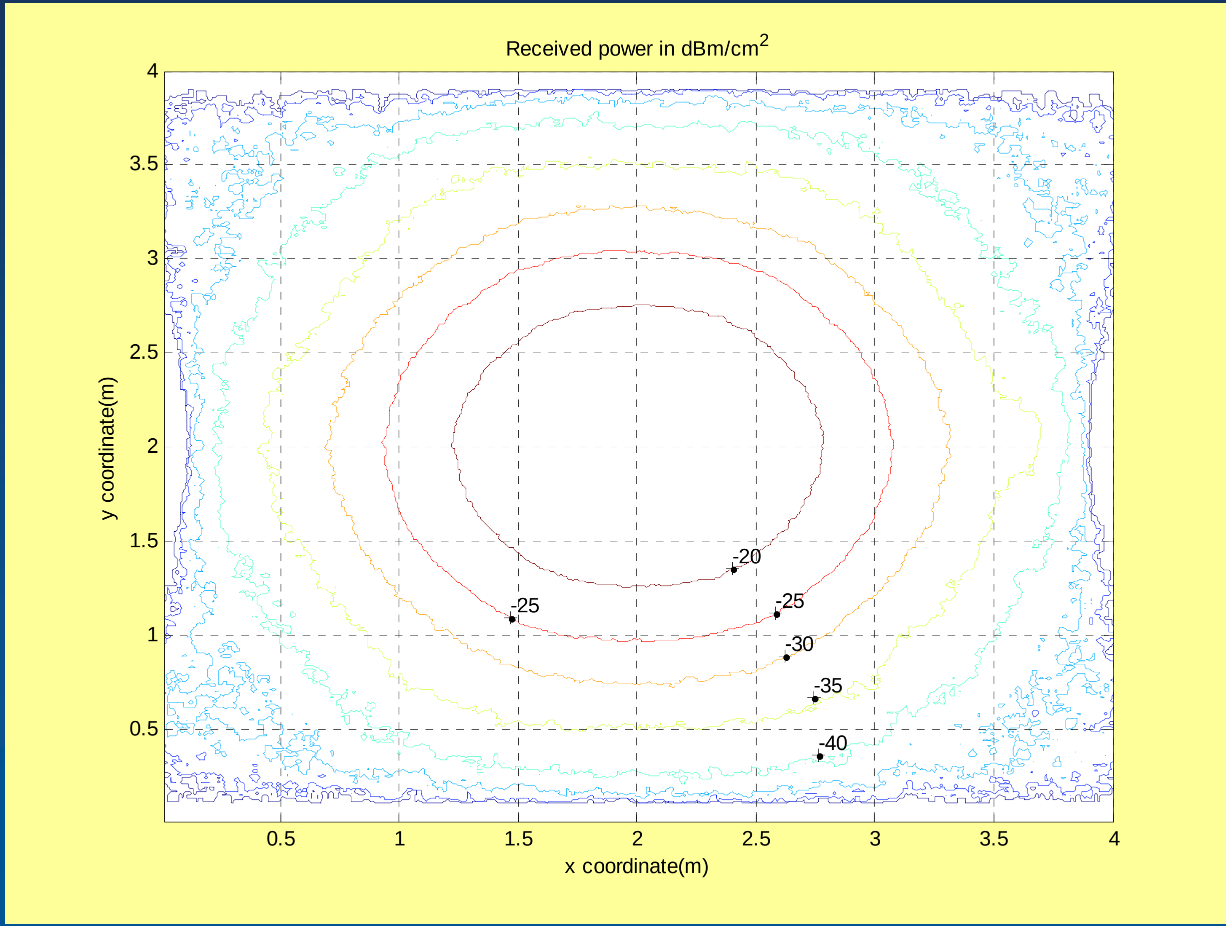
R_{comm} = 0.5 m

Receiver

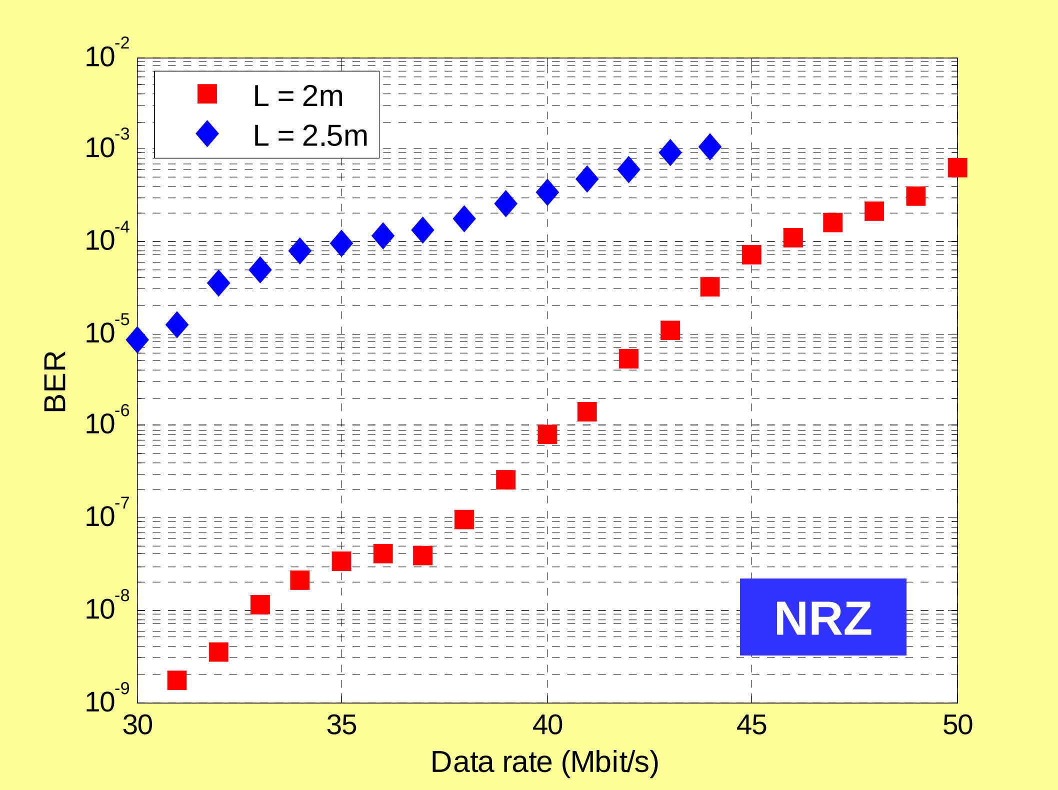
- Concentration lens
  D = 50mm
  F = 60mm
- Detection area
  35 mm^2
- Pre-Amp
- Post-Amp
  (ampl. limiting)

Typical link: illumination

Power distribution in receiving plane

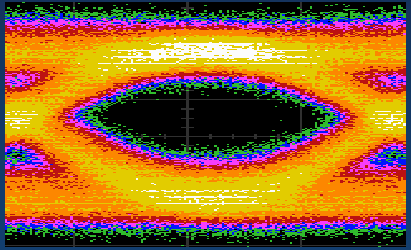


Typical link: BER performance

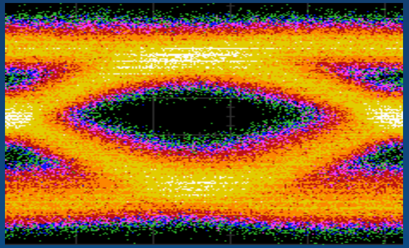


Eye diagram

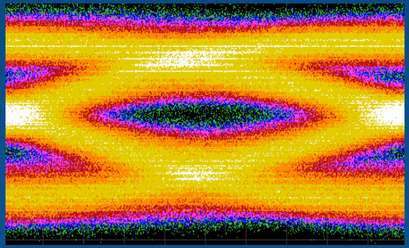
30 Mb/s



40 Mb/s



50 Mb/s

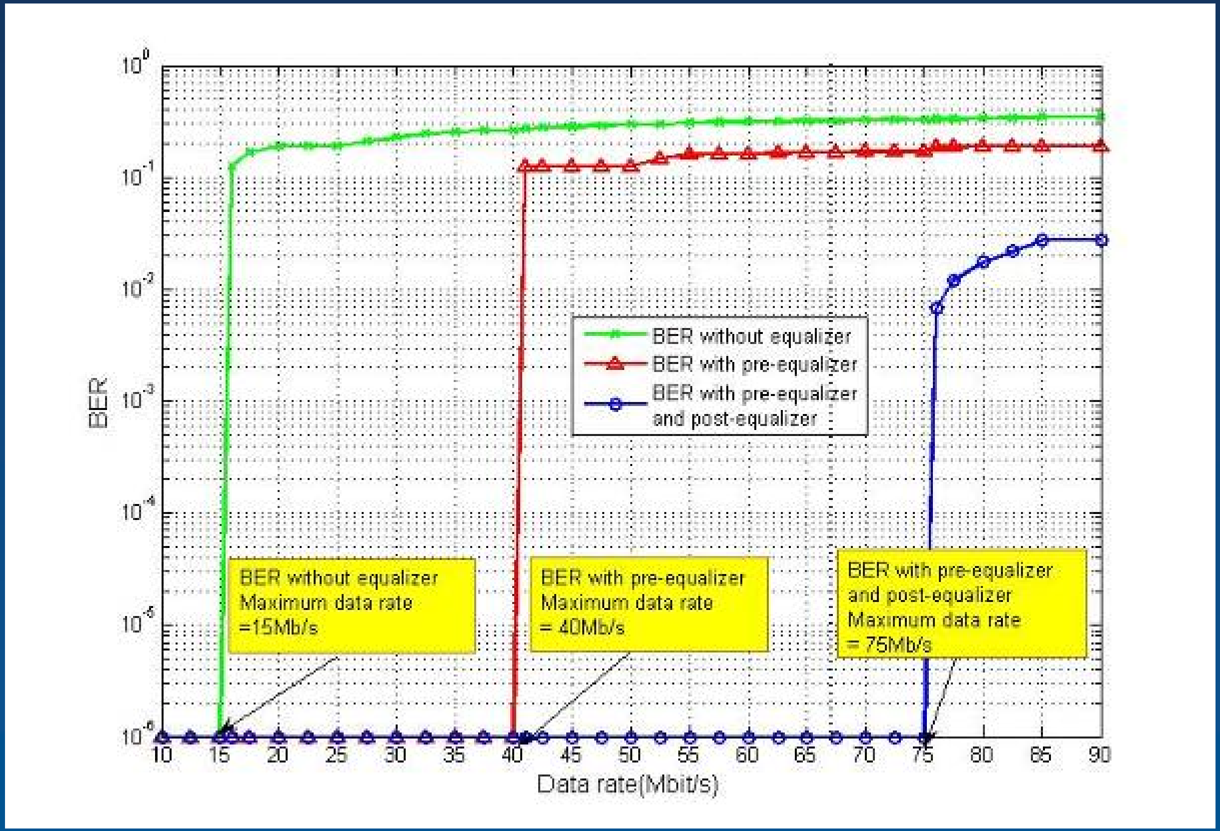


Flat BW ⇒ baseline wandering reduction

- System test in normal lighting condition (room filled with other high-power white light sources)
- Longer distance ⇒ SNR penalty (BER)

Bandwidth improvement: post equalisation

> Pre- and post-equalization: single LED link

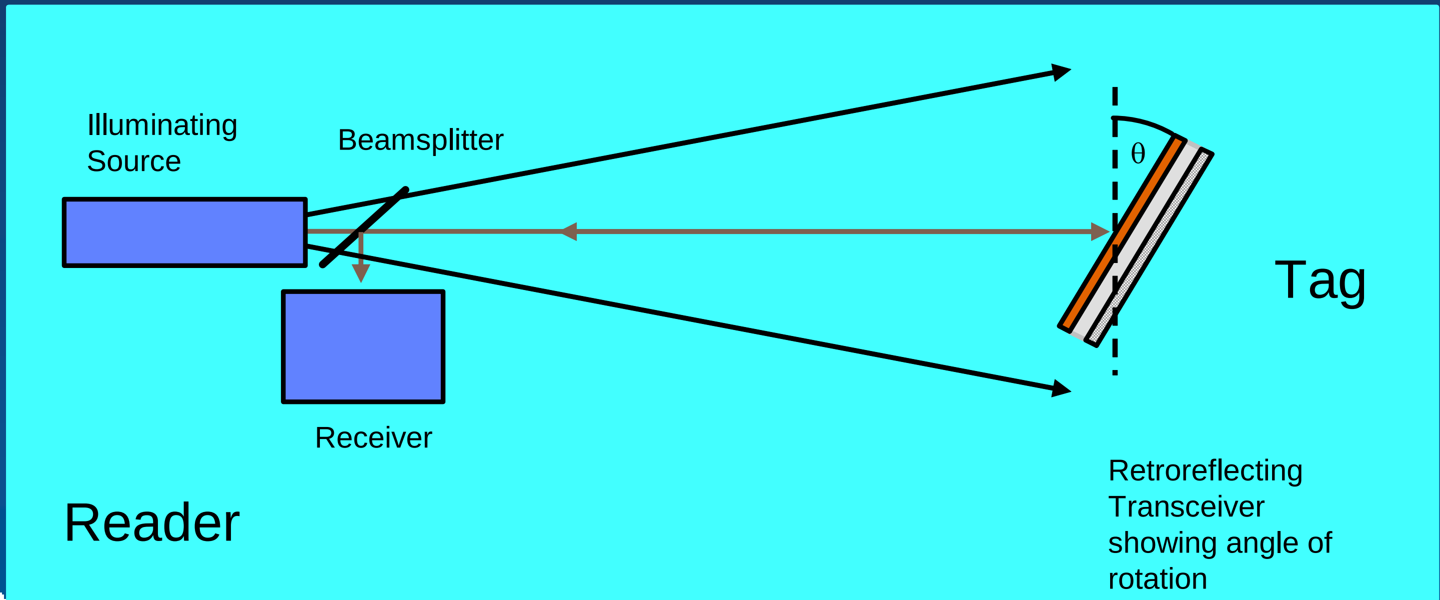


Pre-equalisation: experiment

Post-equalisation: simulation

Retro-reflecting link

- Novel optical communications between reader and tag
- Low power (tag has no source)
- Long range (determined by illumination source)
- Visibly secure (user can see beam of light)



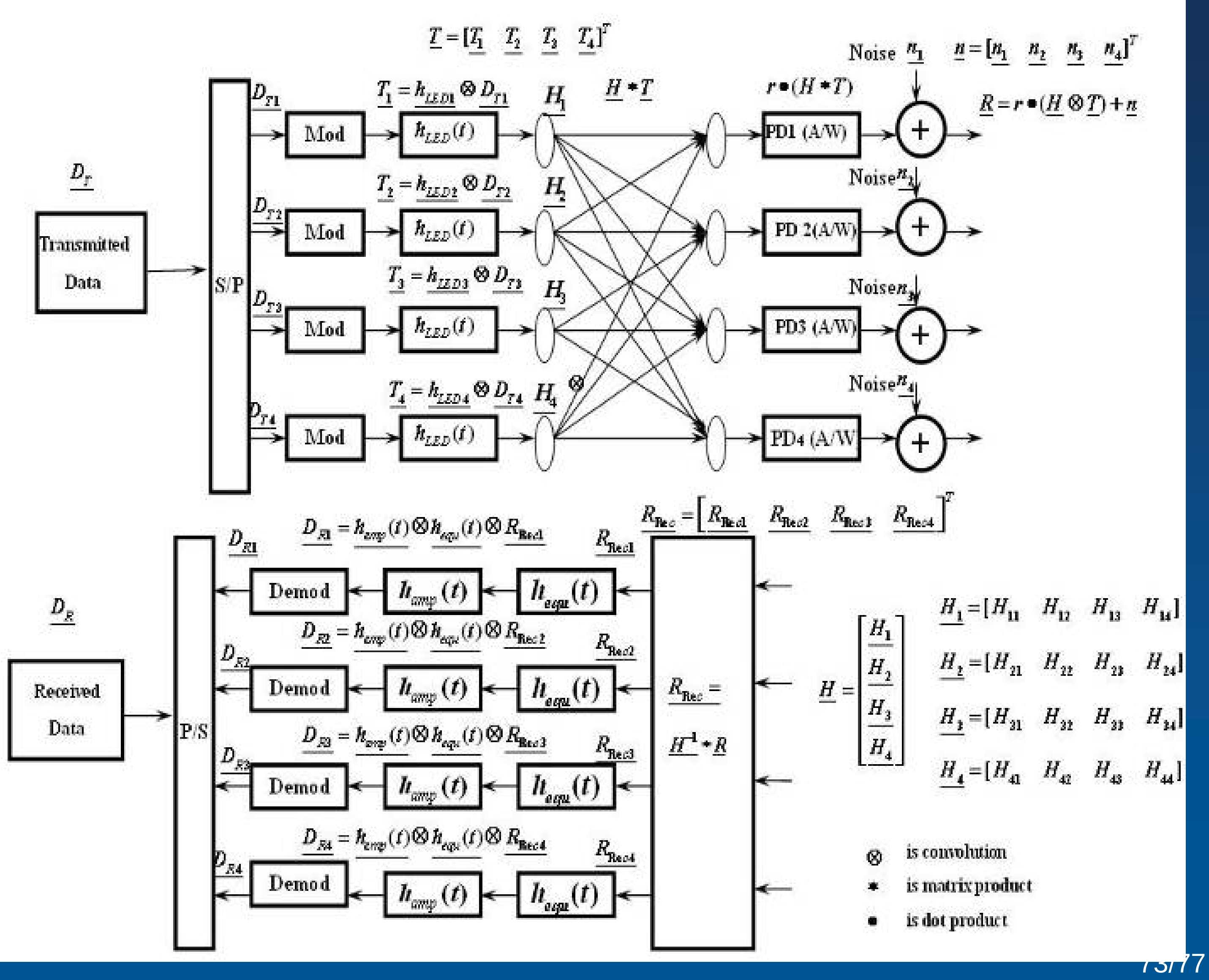
Future developments: optical MIMO

- RF MIMO
- Scattering provides invertible H matrix and decorrelation (capacity gain)
- Difficult to shape radiation pattern with small antenna
- Optical MIMO
- No decorrelation
- Invertible H matrix achieved by system and geometry design
- Simple low-cost elements (lenses) can provide high directivity and/or complex beamshaping

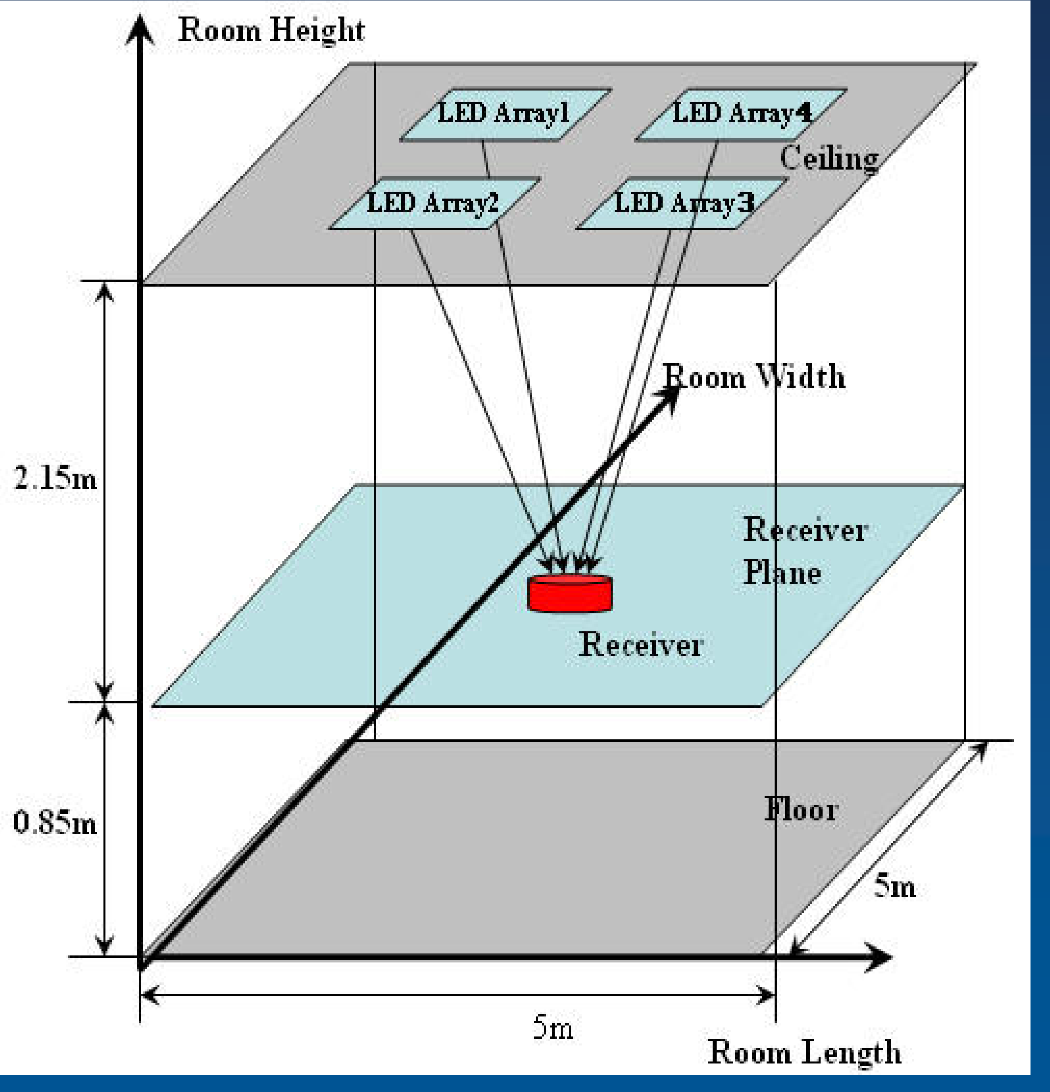
MIMO VLC: simulation Model

Transmitting process

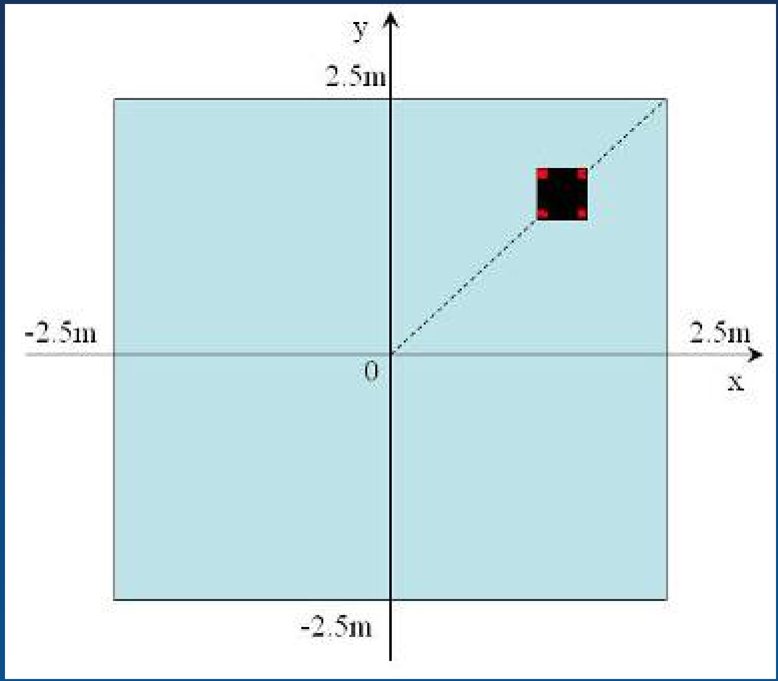
Receiving process



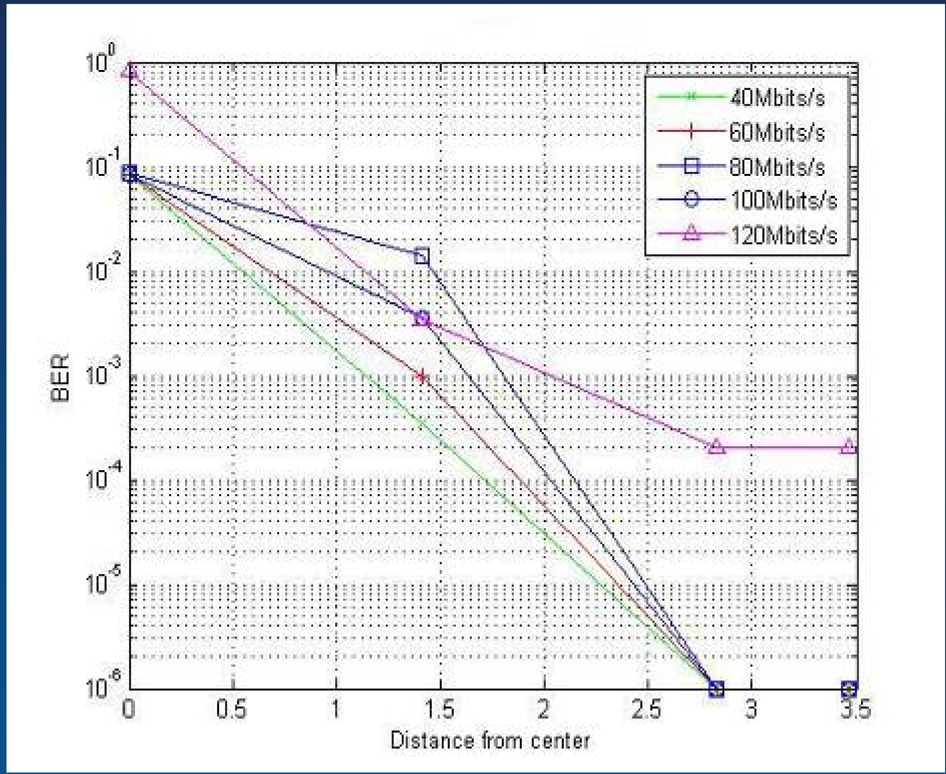
MIMO VLC: simulation system



MIMO VLC: preliminary Results



Position of the receiver



Aggregate data rate is linearly proportional to the number of channels and channel rate

Future technical challenges

- Data rate
  - Equalisation
  - MIMO
  - Complex modulation
- Integration in infrastructure
  - Uplink
    - Retro-reflecting link
  - RF/VLC integration

Conclusions

- VLC offers
  - High SNR channel
  - Intuitive alignment
  - Visibly secure channel
- Challenges
  - Integration with Wireless infrastructure
  - Higher performance