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Editor(s):	**Olivier Bouchet,**
Author(s):	**Olivier Bouchet, Maryline Lebouc, Henri Guan**
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Abstract

In this document, we present the LIFI technology, refer also as wireless optical communications which means a communication based on the unguided propagation of optic waves. This solution is a wireless alternative to radio systems.

This technique has seen a significant improvement in last years. And actually, some companies have already identified the needs and are striving to define the first “killer application”. This document presents an overview of wireless optical communication technologies, the ecosystem and some market or business use cases. The conclusion proposes suggestion on two axes, Visible Light Communication (VLC) and Infra-Red Communication (IRC) systems.

Keyword list

Wireless optic communication, infrared, visible light communication, VLC, IRC, algorithm and protocol, convergence layer, quality of service.

Executive Summary

Wireless optical communications refer to communication based on the unguided propagation of optic waves.

Currently, this technique has seen a significant improvement in two main areas:

- outdoor applications, i.e. Free Space Optic (FSO), communications between satellites or ground/air transmission,
- indoor application like the remote controller or IrDA point to point communication.

Orange Labs have investigated the potential for point to multipoint indoor application of this technology using open innovation (collaborative French project "Techimage" and European project "Omega"). Demonstrators have been developed, proving the concept and feasibility but still technically behind radio solutions, which benefit from a mature and solid market.

Nevertheless, Wireless Optical Network (WON) remains a wireless alternative to radio systems and could gain attractiveness thanks to its recognized immunity, regulated by international standard, or in case of saturation of the radio spectrum.

Actually, some companies have already identified the needs for an alternative solution to radio and are striving to define the first "killer application". There is no so much company who have available commercial product but OLEDCOMM starts their commercial product in the end of 2013.This Company has realized several project for the different companies in different business sectors and sale product for lighting companies, as we described in Section 3.

This document presents an overview of wireless optical communication technologies, the ecosystem and some market or business use cases. The conclusion proposes suggestion on both axes, Visible Light Communication (VLC) and Infra-Red Communication (IRC) systems.

List of Authors

First name	Last name	Beneficiary	Email address
Olivier	Bouchet	Orange Labs	olivier.bouchet@orange.com
Maryline	Lebouc	Orange Labs	maryline.lebouc@orange.com
Henri	Guan	Oledcomm	hongyu.guan@oledcomm.com

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List of Acronyms

Acronym	Meaning
<ACEMIND>	<Advanced Convergent and Easily Manageable Innovative Networks Design>
AC	alternating current
ACK	acknowledgement
ADSL	asymmetric digital subscriber line
ANSI	American National Standards Institute
AP	access point
BPSK	binary phase shift keying
CDMA	Code Division Multiple Access
CE	consumer electronics
CO	confidential
CPE	customer premises equipment
CSMA	carrier sense multiple access
CSMA/CA	carrier sense multiple access collision avoidance
CSMA/CD	carrier sense multiple access collision detection
DSL	Digital Subscriber Line
DVB	digital video broadcasting
EC	European Commission
EMC	electromagnetic compatibility
EN	European norm
EU	European Union
FCC	Federal Communications Commission
Gbps	Gigabit per second
GHz	Gigahertz
HD	high definition
HDTV	high definition television
HGI	Home Gateway Initiative
HILI	High Level Interface
HIP	Host Identity Protocol
HN	home networking
HSI	high speed interface
HW	hardware

HWMP	Hybrid Wireless Mesh Protocol
ICT	information and communications technologies
ID	identifier
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IEEE-SA	IEEE Standards Association
IETF	Internet Engineering Task Force
IP	Internet Protocol
IPTV	internet protocol television
IR	infrared
IrDA	Infrared Data Association
ISM	industrial, scientific, and medical
ISO	International Organization for Standardization
IT	information technology
ITE	information technology equipment
ITU-T	International Telecommunication Union - Telecommunication Standardization Sector
JEITA	Japan Electronics and Information Technology Industries Association
JTC	joint technical committee
L3MP	Layer 3 Mobility Prediction
LAN	local area network
LDPC	low density parity check
LiFi	Light Fidelity
LLC	Logical Link Control
MAC	media access control
Mbps	Megabit per second
MHz	Megahertz
MIB	management information base
MIMO	multiple input multiple output
MIP	Mobile IP
MIPv4	Mobile Internet Protocol version 4
MIPv6	Mobile Internet Protocol version 6
OFDM	orthogonal frequency division multiplexing
PAR	project authorization request
PC	personal computer

PHY	physical layer
PLC	powerline communication
QAM	quadrature amplitude modulation
QoS	quality of service
QPSK	quadrature phase shift keying
SC	single carrier; study committee
SME	small and medium enterprise
SOHO	small office / home office
Std	standard
SW	software
TC	technical committee
TCP	Transport Control Protocol
TDMA	time division multiple access
TG	task group
TS	technical specification
TV	television
UM	usage model
USB	universal serial bus
USB-IF	USB implementers forum
VDSL	very high speed digital subscriber line
VHT	very high throughput
VLAN	virtual local area network
VLC	visible light communications
VLCC	Visible Light Communications Consortium
VoIP	voice over internet protocol
WCDMA	Wideband Code Division Multiple Access
WG	working group
Wi-Fi	wireless fidelity
WLAN	wireless local area network
WMM	Wi-Fi Multimedia
WP	workpackage
WPA	wireless protected access
WPAN	wireless personal area network
xDSL	any DSL technology

Table of contents

1 Technical description and State of the art

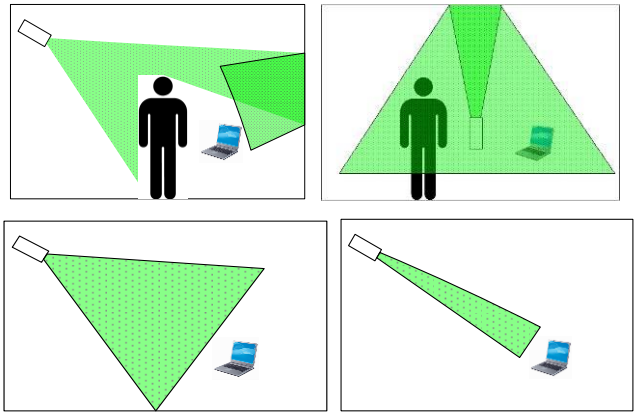
1.1 Technical description

Wireless optical communications refer to communications based on the unguided propagation of electromagnetic radiation with frequencies over 30 THz [BOU 13]. The term Li-Fi (http: // www.lificonsortium.org/) is a trade name and not a standard which includes all these solutions.The electromagnetic spectrum (figure 1.1) is made up of different frequencies or wavelengths and for communication system, it is divided in two categories: the radiofrequency band (from 3 kHz to 300 GHz) and the optic band (from 10 µm or 30 THz to 10 nm or 30 000 THz), based on the impact of these waves on transmission medium and biological tissue [MAR 88], [REF 04] and [AFS 09].

Figure 1.1: Electromagnetic spectrum (IR: Infra-Red, Vis: Visible, UV: Ultra Violet)

Optical communication has been the only wireless communication solution for millennia and during the past 30 years, this solution has shown important improvement in two main areas: Outdoor applications [BOU 06] like FSO (Free Space Optic) or communications between satellites and indoor applications. This document is only covering the latter application area.

The system performance (distance, coverage…) is related to the propagation type (see figure 1.2). There are several categories, from the diffuse system, with wide field of view and low data rate (such as the remote controller) to line of sight systems, which could provide less coverage and high data rates.



a b c d

Figure 1.2: a) Diffuse link, b) Controlled-diffuse link, c) Wide Line of Sight (WLOS) link and d) Narrow Line Of Sight (NLOS) link

Three main bands are used for wireless optical communications (figure 2.1). These bands are Ultra Violet band (UV), visible band (VLC or Visible Light Communication) and Infra-Red band (IR). Each of these bands has advantages and drawbacks. For instance, UV is well suited for very low data rate and diffusion while VLC is adapted for low data rate (several Mbps) with lighting and infrared could be a good high data rate room communication solution (several Gbps).

The infrared point-to-point solution is proposed by IrDA (Infrared Data Association) for Gbps short link [IRD 14]. The point-to-multipoint approach (WLAN), such as Wireless Optical Network (WON) for hot spot or room communication remains a challenge. It can be technically compared to WiFi 802.11ad (60 GHz) but with less maturity. Both 60 GHz radio and WON offer room connectivity (around 30 m^2) and inter-room communication relying on a wireline technology (Power Line Communication, Ethernet or fiber) or WiFi 802.11ac (5 GHz) for a full wireless coverage.

Facing the growing needs for high data rate and wireless connectivity, the Wireless Optical Network (WON) is an alternative solution to the radio system with several advantages:

- This technology can benefit from a large spectral availability, more than 700 000 GHz, 2 000 times more capacity than radio spectrum, neither regulated nor taxed, and has thus the potential for quasi-unlimited bandwidth wireless communications (several Tbps).
- The safety aspect or immunity is already regulated by recognized international standards (IEC 60825) and based on the best available information from decades of experimental studies [EUR 07]. This item becomes sensitive in the light of recent announcements from World Health Organization - International Agency for Research on Cancer (WHO-IARC) which classified radiofrequency in 2B category (possibly carcinogenic to humans) [IAR 11].
- Another benefit comes from satellite applications. Optical wireless equipments have proven to be energy efficient thanks to lower power consumption and better compactness. These characteristics could also be beneficial for indoor application.
- In addition, due to the optic medium, it is also possible to re-use part of the optical energy sent for data communication to load a battery and achieve energy independency.

There is no available commercial product as the availability and maturity of radio solutions currently do not leave market share for alternative solutions. But the latest WHO recommendation [IAR 11] and the radiofrequency spectrum saturation could change the situation (figure 1.3). Several industrial actors are interested and involved in initiatives, such as companies present in standardisation bodies, previously mentioned, or projects such as US project UC-Light [UCL 09] or European project ACEMIND [ACE 13].

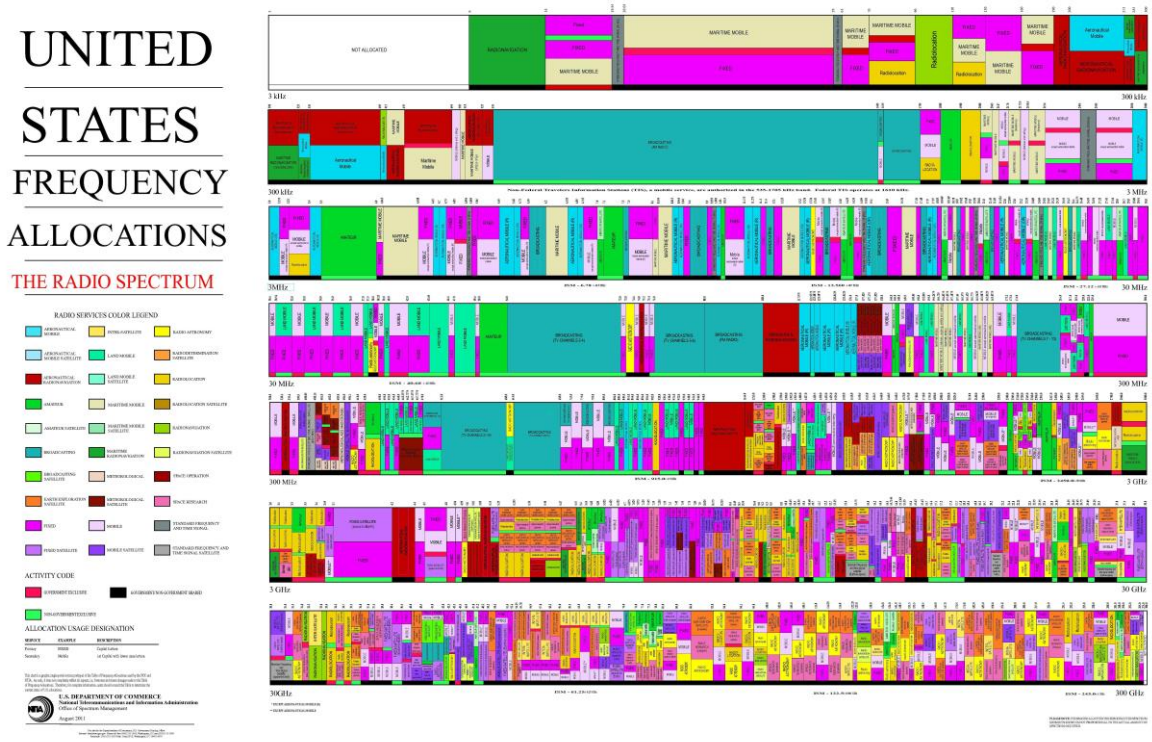


Figure 1.3: US Spectrum saturation

In the context of European project Omega [OME 11]., studies and development have shown the VLC broadcast proof of concept, with 16 LEDs on a ceiling broadcasting 100 Mbps on 5 m^2 coverage. On infrared area, the prototypes are high data rate bilateral solution with 1.25 Gbps on 1 m^2 coverage and 300 Mbps on 30 m^2 coverage [OWP 11]. One should point out that infrared (IRC) and visible (VLC) equipments timing development is different.

1.2 Standard and specification panorama

1.2.1 Standard panorama

Several standards were finalized during the last years. Now the companies are looking for the first cost effective application.

- VLCC - Visible Light Communication Consortium is an Japanese association, which aims to search, develop and propose standardization of communication systems, using a solution everywhere, LED (Light Emitting Diode) in the visible spectral range. Communication is achieved by intensity-modulated at high frequency, with a consideration of human security. The use of communication is available in the personal lighting, offices, the car lights or road infrastructure (Intelligent Transport Services - ITS), the electronic signs for advertising, etc. The advantage of this approach is to offer a unique solution for lighting and communication. From 2007, papers were proposed and new working groups from the IEEE 802.15 [WON 07] have been created (IEEE 802.15.7) to provide communications solutions in the visible area with Point-to-Point (PtP) and Point-to-Multipoint (PtM) standard solution. The VLCC members are **Sony, Samsung, Toshiba, Sharp, Nitto Denko, Tamura**… (figure 1.4). The proposed applications are image sensor, shopping mall information and Intelligent Transport Services (ITS). Actually, **Panasonic** seems to work on smartphone applications. Most activities are done now through the standard process IEEE 802.15.7.

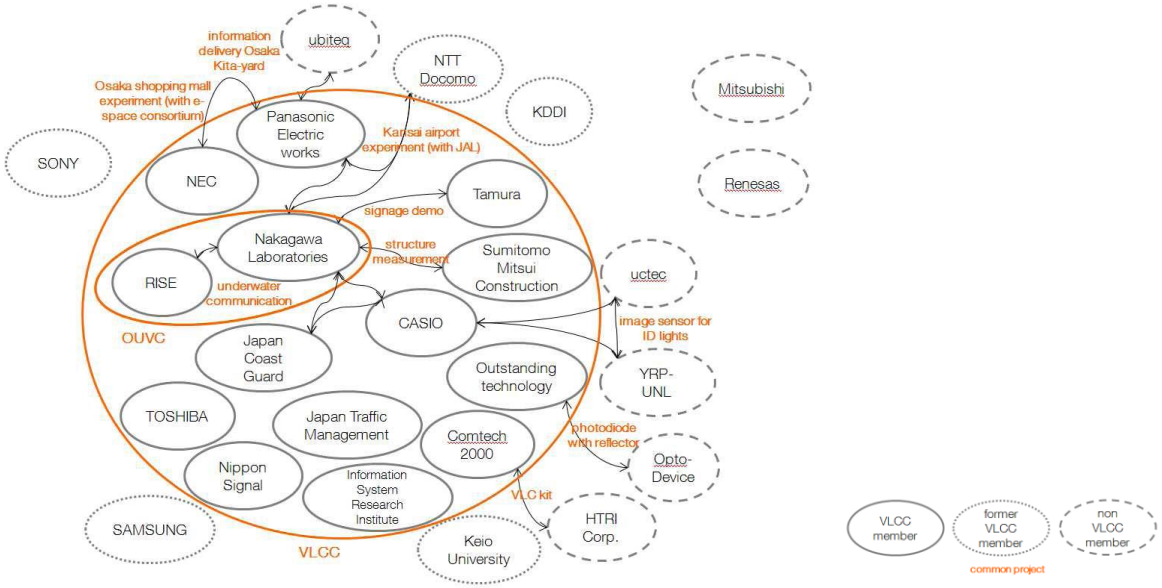


Figure 1.4: VLC asia overview

- ECMA: A white paper presented by Lumilink technology was proposed to Task Committee 47 (TC47) in 2009, as well as a presentation from Samsung promoting the potential of Near Field Communications (NFC) using visible LED. But no new activities were done up to now.
- IRDA: Created in 1993, the IrDA (Infra-red Data Association) is an association working on infrared area and the latest target is to propose compact Gbps point-to-point standard [GIG 10] on portable devices (Phone, Computer, Printer…). On 2012, the association announced the creation of a new Working Group (WG) to meet the demand of multi-gigabit per second communication speeds. This WG's focus is to extend the 1 Giga-IR specifications which was internationally adopted in 2009 and to achieve both 5 and 10 Gigabit per second optical wireless communications by using IEC eye-safety compliant lasers. IrDA association promotes these solutions and products should be released by 2015. The IrDa members are **Casio, Fuji, KDDI, Mitsubishi, NEC, NTT, Panasonic, Sony Ericsson**…
- IEEE 802.15.7: this IEEE committee focuses on point-to-point and point-to-multipoint (WLAN) standards in the visible area. In January 2009, **Samsung, Intel, Motorola** and **Siemens** create a task Group dedicated to VLC then a standard is proposed in 2010 and products could be available by 2014. Finally, the IEEE 802.15.7 Visible Light Communication Task Group has completed a PHY and MAC standard for Visible Light Communications (VLC) during 2011. Actually, the works are on:
  - IG-LED – From July 2012 to November 2013, to investigate forming an LED PHY and MAC Interest Group. And to determine whether there is sufficient interest in creating an Optical Camera

Communication (OCC) Study Group for the purpose of developing a LED ID PAR and 5C (IG-LED and OCC SG).

- The market was focused on technical objectives to Optical Camera Communication SG for:
  - Optical Camera Communication
  - LBS application using Optical Camera Communication
  - Digital signage application using LED-ID
- Then the group obtain a "green light" to go to a new Study Group named SG 7a

- SG 7a – From January 2014 to Up to now and activities:
  - Draft 5C for IEEE 802.15.SG7a Optical Camera Communication: This project will amend the standard IEEE 802.15.7 with following targets.
  - This project will amend the IEEE 802.15.7 standard for implementing optical camera communication (OCC) for scalable data rate, message broadcasts, tracking of things, navigation, and localization (or positioning) via lighting sources such as flash light, projector, visible light, IR(Infrared), UV(Ultra Violet), display, LED Tag, and LED/Laser sources as the prospective transmitting and receiving devices such as camera. The PHY layer amendment will consider the image sensor as the receiver associated with a camera and it will enable the reception of modulated light without significant hardware modifications to the camera enabled platform.
  - Some use-case have been proposed: https://mentor.ieee.org/802.15/dcn/14/15-14-0140-00-007a-some-camcom-applications.pdf
  - A draft PAR (Project Authorization Request) has been produced for IEEE 802.15.7a Optical Camera Communication.
  - Request to TG during the next meeting: Athens – September 2014. This TG will write an air interface standard that supports the transmission of data by modulated lights that can be received and processed via an image sensor.

1.2.2 Specification

- IEEE 802.15.7: OWMAC: The OWMAC specification was developed and implemented during European Omega project [ICT 09]. The OWMAC protocol firmware and the source code are available free [ICT 11]. This specification is clearly high data rate WLAN Home/Office oriented (point to multipoint service or WON) with adapted up to date MAC layer and wavelength independent. The Omega partners are University of Oxford, University of Ilmenau, University of Athens, HHI, Apside and Siemens.

1.3 State of the art and prototypes

1.3.1 Visible Light Communication

VLCC - Visible Light Communication Consortium is an Japanese association and provide communications solutions in the visible area with Point-to-Point (PtP) and Point-to-Multipoint (PtM) standard solution.

Website: http://www.ieee802.org/15/pub/TG7.html

OLEDCOMM works on the VLC/LiFi technology and proposes several commercial products and some solutions with this technology. It has participated in the various trade show, business lounge and exhibition.

In February 2013, it has demonstrated his products and solutions using the LiFi technology in Mobile World Congress 2013. It has shown his LBS (Localization Base System) solution and audio streaming with the visible light communication. In this audio streaming demonstrator, it was possible to send the music by LED lighting.

Figure 1.5. LiFi technology solution show in MWC 2013

In April 2013, OLEDCOMM has demonstrated his LBS solution using LiFi in Seminar University Company 2013 (Rencontres Universités Entreprises 2013). The Minister of National Education and the Secretary of State for Education of France have tested this demonstration.

It demonstrates his LBS (Localization Base System) solution by the LiFi technology in the show room of France Television for French Open-Roland Garros in 2013. The tablet will display a relative video of the match for each picture of table.

In January 2014, OLEDCOMM has demonstrated his products and solutions using the LiFi technology in CES 2014 (Consumer Electronics Show). OLEDCOMM has shown his LBS (Localization Base System) solution and the Internet connection at 10 Mbits/s data rate with the LiFi technology as shown in the figures below.

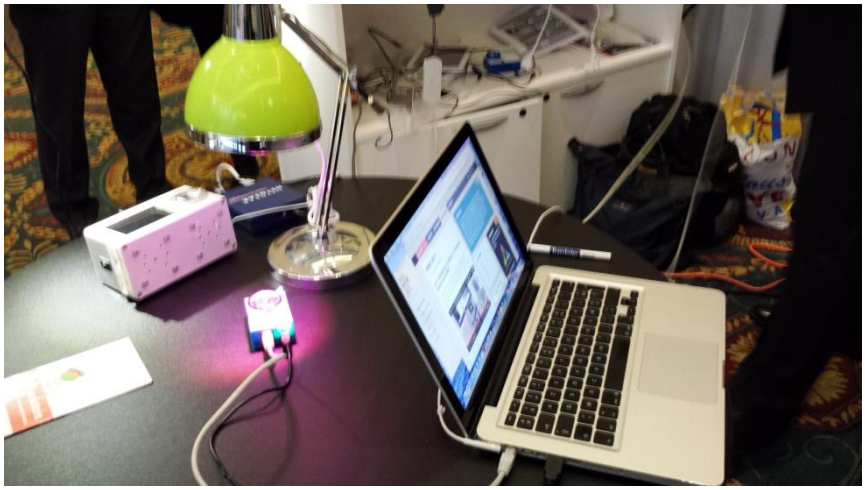


Figure 1.8. LiFi technology solution show in CES 2014

Also, this company demonstrates Internet solution at 10 Mbits/s data rate by the LiFi technology in the show room of France Television for French Open-Roland Garros in 2014. The Internet solution provides the high resolution video content for a full HD television as described in the following picture with around 30 centimetres distance.

Figure 1.9. LiFi technology for Full HD TV in French Open 2014

In the light of recent produced demonstrators and expressed below, several approaches are considered:

- Omega demonstrator in visible light (VLC) [OME 11b]:
  - Broadcast at 100 Mbps,
  - 10 m^2 coverage at 2 m,
  - 16 LED TX (transmitting) inserted in the ceiling,
  - 12 MHz bandwidth with DMT signal processing (Digital Multi Tone);
- Demonstrator of Keio University (Japan) in visible light (VLC) [SPA 09]:
  - Half-duplex at 100 Mbps,
  - 1 m^2 coverage at 2 m,
  - 20 LED TX and a RX receiver for the base station,
  - 2 LED TX and a RX receiver with an automatic pointing (mirror) for the terminal;

1.3.2 WON (Wireless Optical Network)

Concerning the home networking, the next decade could see home equipment and devices spreading throughout the house, leading to the presence of one extender per room to ensure room connectivity among every device. Like 60 GHz radio solutions, wireless optical network (WON) device can provide high date rate for room coverage, but additional application could be geo-location based services: Each optic extender can be uniquely identified, so the location of any device can be identified inside a room and the hybrid imaging/beam-steering approach can increase the 3D accuracy. This function will open the door to augmented or virtual reality applications.

The VISPLAN product was the first system providing a wireless optical communication network, and it was only sold in Japan by JVC. VIPSLAN is typically a Wireless LAN (WLAN - Wireless Local Area Network) or Domestic (WDAN – Wireless Domestic Area Network) in direct competition with WiFi solutions. But the first version of WiFi pushed this device in the background. Based on the work of the ICSA (Infrared Communication Systems Association [ICS 11]) and the recommendations of the IR PHY IEEE 802.11 [IEE 11a], it offered a rate of 10 Mbps then 100 Mbps.

The device (Figure 3.10) consisted of two elements:

- the base station (or COIL - a) providing a data rate of 100 Mbps Ethernet with a range of five meters (coverage of about 25 m^2) in Wide Line Of Sight (WLOS) propagation;
- modules (or MOIL - b) with the same characteristics of speed and range, but constitued of an automatic pointing device.

a) COIL b) MOIL

Figure 1.10. Visplan (source JVC)

So far, on this last area, the home or business wireless network (Wireless Domestic Area Network - WDAN) and WLAN (Wireless Local Area Network), the commercial success was not to go and several reasons can be advanced:

- an non economically viable offer for a point to multipoint optical link budget in a room;
- an non available or inadequate network management layer (MAC layer);
- a broadband access point (xDSL or FTTH) or a connectivity insuring an interroom link and using the powerline technique (PLC) or fiber optic (FO) was not available;
- the concepts of energy savings or safety were less important.

Also, in the light of recent produced demonstrators and expressed below, several approaches are considered:

- Techimage demonstrator in infrared (IRC) [TEC 11]:
  - Half-duplex at 1 Gbps,
  - 0.01 m^2 coverage at 0.5 m,
  - 1 TX / RX,
  - Bandwidth of 1.25 GHz modulated OOK (On Off Keying);
- Omega demonstrator in infrared (IRC) [OME 10]:
  - Half-duplex at 1 Gbps,
  - 1.5 m^2 coverage at 3 m,
  - MIMO with 3 TX/RX,
  - 1.25 GHz bandwidth signal processing with OOK (On Off Keying);
- Omega demonstrator in infrared (IRC) [OME 11b]:
  - Half-duplex at 300 Mbps,
  - 30 m^2 coverage at 4 m,
  - MIMO with 7 TX/RX,
  - Bandwidth to about 300 GHz with signal processing OOK (On Off Keying).

Website: (http://www.youtube.com/watch?v=AqdARFZd_78

1.4 Market panorama (indoor and outdoor)

About the outdoor systems, there are more than several dozen systems adapted for high data rate or long distance, with radio backup solution…, so it is difficult to represent these products by a clear photograph. For more information, it could be possible to refer to the manufacturers sites indicated below.

For indoor communication, the list of manufacturers is shorter with few available product.

Names	City	Country	Web site	Devices
AirLinx	Boston	USA	www.airlinx.com	Outdoor
Aoptix	Campbell	USA	www.aoptix.com	Outdoor
CableFree	Mampton Hill	UK	www.cablefree.co.uk	Outdoor
Communication By Light	Munster	Germany	www.cbl.de	Outdoor
FiverHome	Wuhan	China	http://www.fiberhomegroup.com/	Indoor
Fsona	Richmond	Canada	www.fsona.com	Outdoor
GeoDesy	Budapest	Hungary	http://geodesy.hu/fso_en	Outdoor
Katharsis	St Petersbourg	Russia	www.optica.ru/	Outdoor
LightPointe	San Diego	USA	www.lightpointe.com	Outdoor
LSA	Exton	USA	www.lsainc.com	Outdoor
Lucion	Colombelles	France	http://www.luciom.com/fr/	Indoor
Oldecomm	Versailles	France	http://www.oledcomm.com/FR/	Indoor
Optel	Hamburg	Germany	www.optel.de	Outdoor
Oya Light	Chateaugiron	France	http://www.oyalight.com/	Indoor
PAV Data Systems	Cumbria	UK	www.pavdata.com	Outdoor
Philips	Amsterdam	Netherland	http://www.lighting.philips.fr/	Indoor
Plaintree Systems	Arnprior	Canada	www.plaintree.com	Outdoor
PureLiFi	Edinburgh	UK	http://purelifi.co.uk/	Indoor
RedLine	Kyalami	South Africa	www.redlinesa.com	Outdoor
Thomson Lighting	Suresnes	France	http://www.thomson-lighting.fr/fr/	Indoor
Visilink	Tokyo	Japan	http://visilink.com/	Indoor

Table 1.1. Some wireless optic manufacturers

2 User requirements (Home Network)

2.1 Methodology and tools

2.1.1 Methodology

In order to achieve the task of Acemind project, Orange organized user face-to-face interviews: this evaluation was based on a user centric approach and aimed at identifying user's point of view and expectations.

The subject of the evaluation was focused on news functions, news services and news technologies provided for the home network.

In order to have a global vision of user expectations among several countries of Europe and identify specificities according to the countries, the study was achieved by Orange France and by all the voluntary partners

The objectives of the user face-to-face interviews were to have a judicious customer view about LiFi extender. "LiFi extender" is an Acemind activity to propose and define the specification of new wireless technology alternative to radio (WiFi).

For each country, the users' interviews lasted between 1h30 and 2h00 and followed the same criteria of recruitment. The interviews followed the 3 stages mentioned below:

- Welcome and introduction of the subject: presentation of the scope and appropriation of the subject by the participants
- Evaluation step: thanks to the questionnaire and some illustrations, the organizer interviewed people so that they give their point of view about Acemind concepts, functionalities, key points and weak points etc.
- Synthesis: The organizer recapitulated the various tackled subjects so that interviewed people objectively summarize their points of view and put emphasis on their priorities

2.1.2 Tools

In order to have a homogeneous methodology and comparable results, a complete toolkit was delivered to each country organizing users' interviews. This toolkit was constituted by:

- The methodological guide (English): gives all requirements and prerequisites to put in place the user face-to-face interviews (protocol, recruitment, recommendations, etc.)
- The questionnaire (English): contains all the questions to ask during the interview. This questionnaire deals with the connected home of tomorrow, the home automation services and the LiFi (Light Fidelity) technology versus the Wifi.
- The template for the synthesis (English): enables to summarize the analysis of all the passed interviews

Regarding the questionnaire, several brainstorming sessions were organized before the interviews in order to build it. Thanks to these brainstorming sessions, the main themes of ACEMIND project were identified from a users' point of view with their respective key words (please, see the figure 2.1 below).

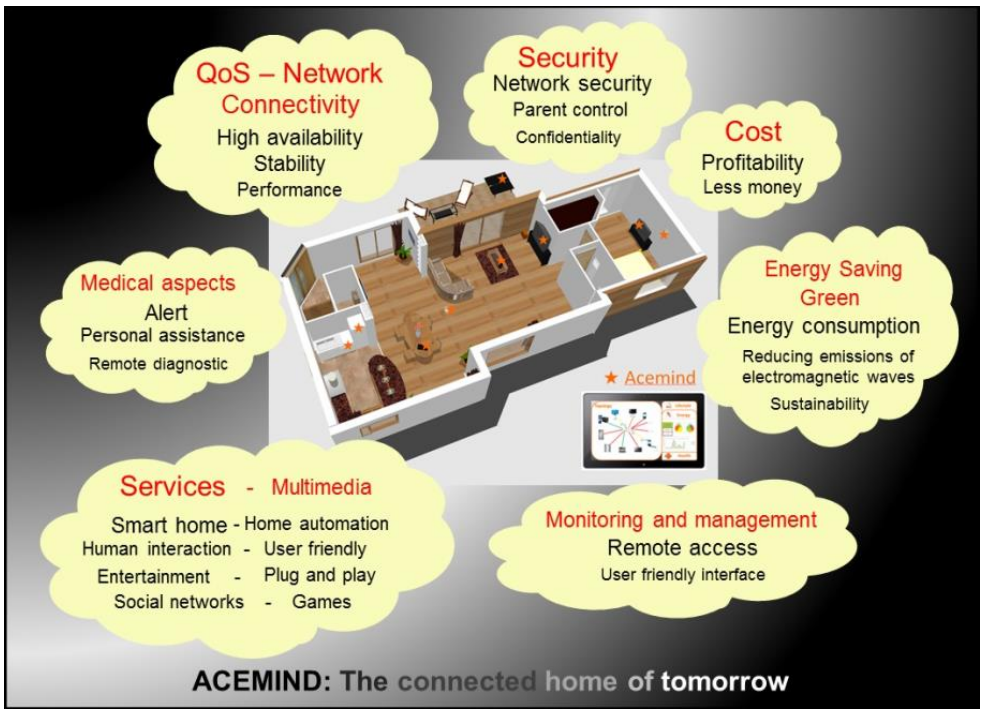


Figure 2.1: illustration used during users' interviews to present the global scope of the Acemind project

(Illustration built thanks to several brainstorming sessions organized previously the interviews)

The scope of ACEMIND also includes a new technology: the Lifi. As a consequence, the questionnaire also dealt with this subject so that the participants can give their opinion about this new technology in comparison with the Wifi.

All this preliminary work aimed at giving inputs to the participants of the interviews so that they can define their expectations and their brakes regarding ACEMIND project

The following paragraphs present:

- Qualitative answer from three countries, so no standard deviation or confidence interval is mentioned.
- First, the results of these interviews country by country, with a sum of more than 50 interviews.
- Then globally, a synthesis is achieved including all the countries and draws up the conclusions in terms of users' expectations and brakes concerning LiFi solution.

Country	France	Germany	Turkey	Total
Nb Interviews	25	10	20	55

2.2 Analysis by country

This paragraph gives the detailed results of the interviews.

2.2.1 France

This part gives the French results regarding the users' feedback about the Wifi technology and another alternative: the Lifi.

Globally, 25 people are satisfied by wifi since 96% say to be satisfied or very satisfied (see figure 2.2 below please).

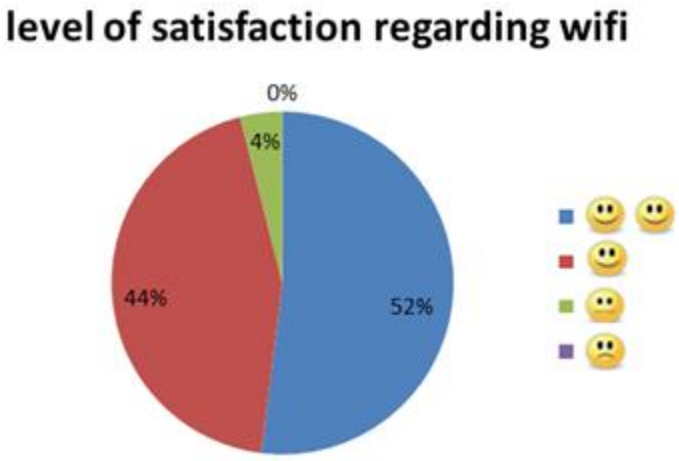


Figure 2.2: level of French users' satisfaction regarding the wifi technology

Several criteria have been evaluated by the French participants in order to point out the strengths and the weaknesses of this technology. The figure 2.3 below emphasizes several aspects:

- What the French users plebiscite: the wifi technology is particularly appreciated for installation, ubiquity, convenience and mobility with a level of satisfaction equal to 80% or more.
- What the French users deplore: the main weaknesses of the wifi technology are
    - its security, its speed
    - Radiofrequency radiation (level of satisfaction under 30%)
- Lastly, the French users' opinions are divided as regards the other criteria: expandability, compatibility, cost, range and reliability

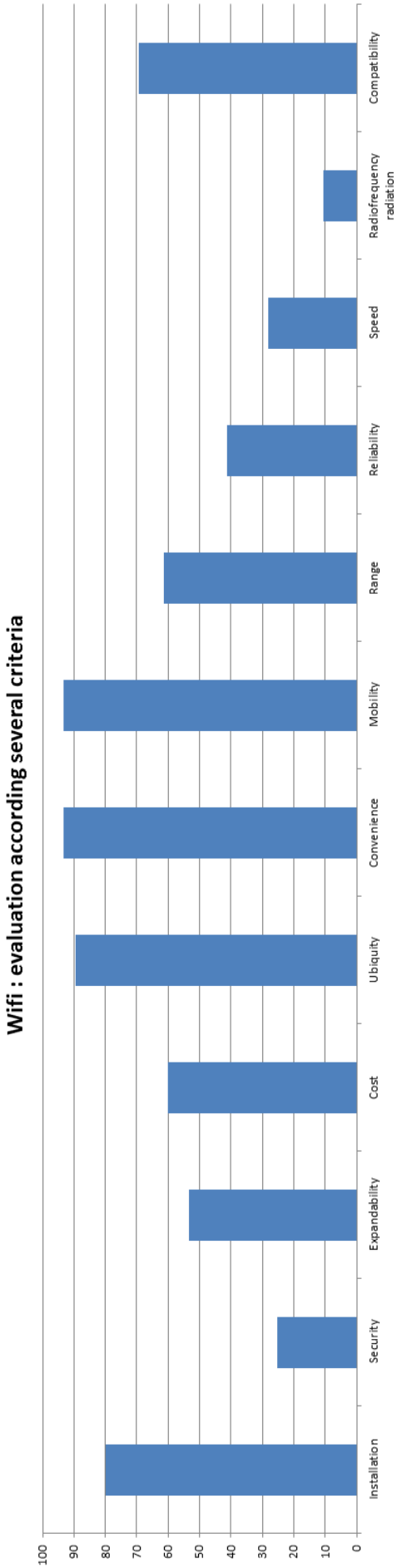


Figure 2.3: level of users' satisfaction regarding the wifi technology based on a multi-criteria analysis

96% of the participants are interested to learn more about a new technology which could be an alternative to wifi. In order to define the French users' requirements, the level of importance of several criteria was evaluated by people:

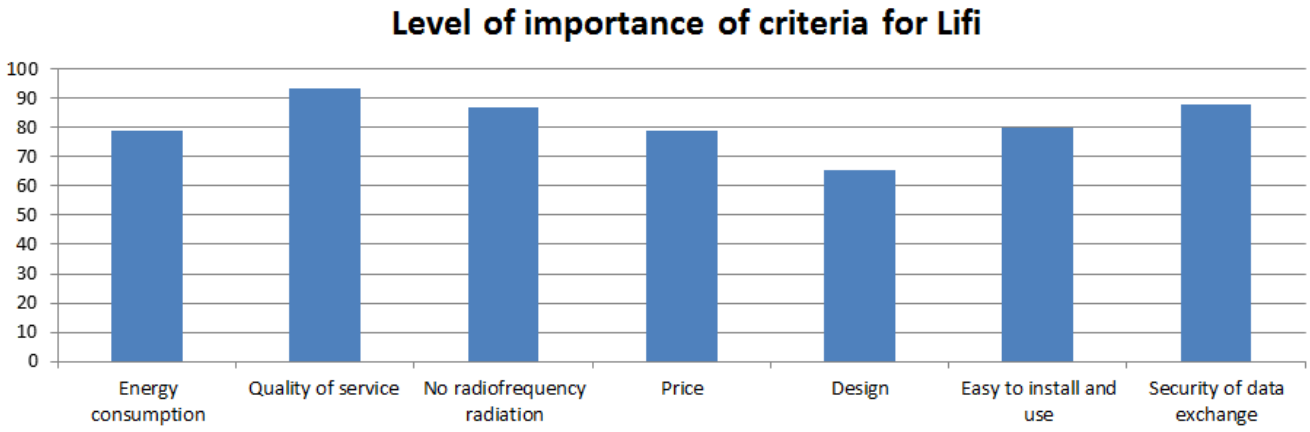


Figure 2.4: level of importance of several criteria evaluated by the French participants regarding lifi

As shown in the figure above, people are demanding as far as the lifi technology is concerned. Except for some points (security, speed and radiofrequency radiation), people mainly remain satisfied by wifi. As a consequence, supposing they accept to change of technology, they wish among other:

- Retrieve the same level of quality of service. At this stage, people remain doubtful regarding the maturity of the lifi technology. Moreover, wifi is now omnipresent everywhere which is not the case of lifi
- Remedy to the weakness of wifi: security of data exchange and radiofrequency radiation. About this last point, people question if Lifi does not hide other negative health effects
- And, at the same time, have more visibility on the impacts inherent in this new technology. In particular, Lifi impacts both the home and the equipment since it requires a pair of transmitter and receiver. The logistical impact in each room may represent a constraint.

For the replacement of Wifi at home, The price of a Wifi extender (about 80€ in France) was given to the French participants for their information. people say to be willing to pay an average invoice of 79 € with the following distribution (25 participants):

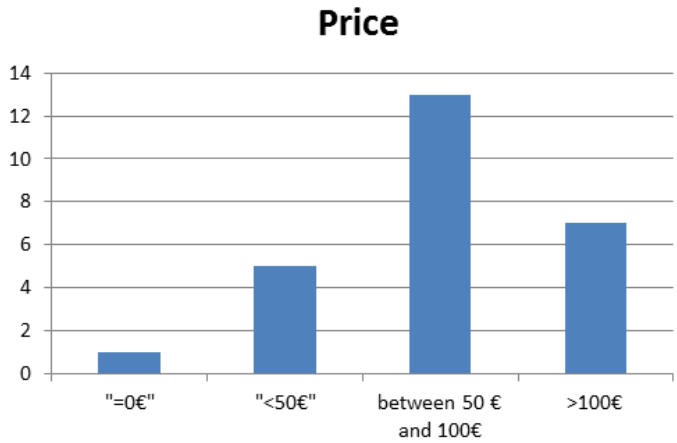


Figure 2.5: Evaluation of the price maximum that French people would be willing to pay for the replacement of Wifi at home

2.2.2 Germany

This part gives the German results regarding the users' feedback about the Wifi technology and another alternative: the Lifi.

On the contrary to the French participants, the level of satisfaction of the 10 German participants regarding Wifi is not unanymous:

- 50% are satisfied or very satisfied
- 40% are mixed
- 10% are unsatisfied

Figure 2.6: level of German users' satisfaction regarding the wifi technology

Several criteria have been evaluated by the German participants in order to point out the strengths and the weaknesses of this technology.

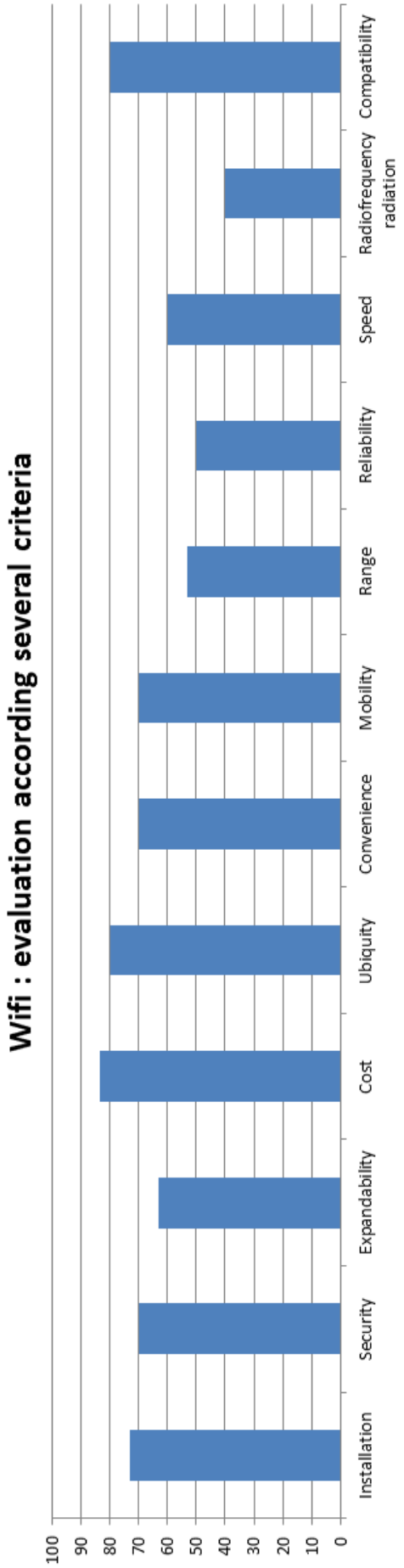


Figure 2.7: level of users' satisfaction regarding the wifi technology based on a multi-criteria analysis

The figure above confirms that globally, the German users' point of view is more mixed than the French one with intermediate percentages regarding the multi-criteria evaluation of the level of satisfaction. All the percentages are included between 40% and 83% (the gap was between 10 and 93% for the French participants):

- What the German users appreciate with the wifi technology are the following aspects:
  - With a level of satisfaction around 80% or higher: cost, ubiquity and compatibility
  - With a level of satisfaction included between 60% and 80%: installation, security, expandability, convenience, mobility and speed
- What the German users deplore the most with the wifi technology are the following aspects: range, reliability and radiofrequency radiation (this last reaching the smallest percentage of satisfaction with 40%)

50% of the participants are interested to learn more about a new technology which could be an alternative to wifi, whereas 40% don't mind and 10% are totally not interested. In order to define the German users' requirements, the level of importance of several criteria was evaluated by people:

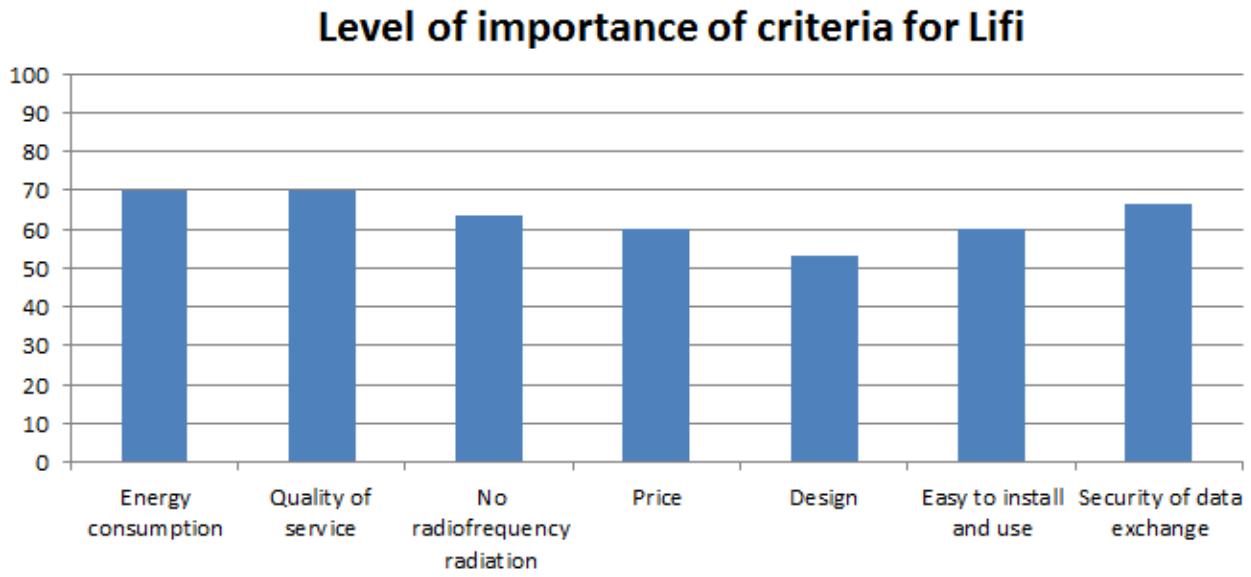


Figure 2.8: level of importance of several criteria evaluated by the German participants regarding Lifi

As shown in the figure above, the level of importance of all the selected criteria is evaluated between 60% and 70% by the German participants. Only the criteria "design" is a little bit below the whole with a percentage of 53%.

For the replacement of Wifi at home, the price of a Wifi extender (about 80€ in France) was given to the German participants for their information. 60% of German participants say to be willing to pay an average invoice of 75 € with the following distribution (10 participants):

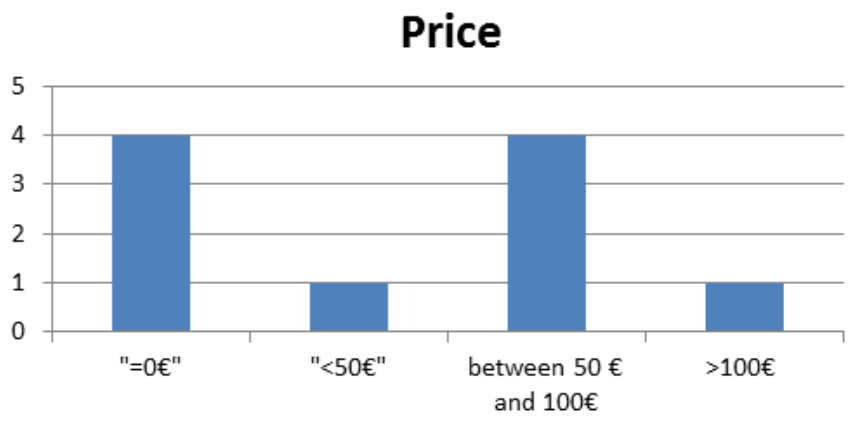


Figure 2.9: Evaluation of the price maximum that German people would be willing to pay for the replacement of Wifi at home

2.2.3 Turkey

This part gives the Turkish results regarding the users' feedback about the Wifi technology and another alternative: the Lifi.

Globally, 20 people are satisfied by wifi since 75% say to be satisfied or very satisfied (see figure 3.10 below please).

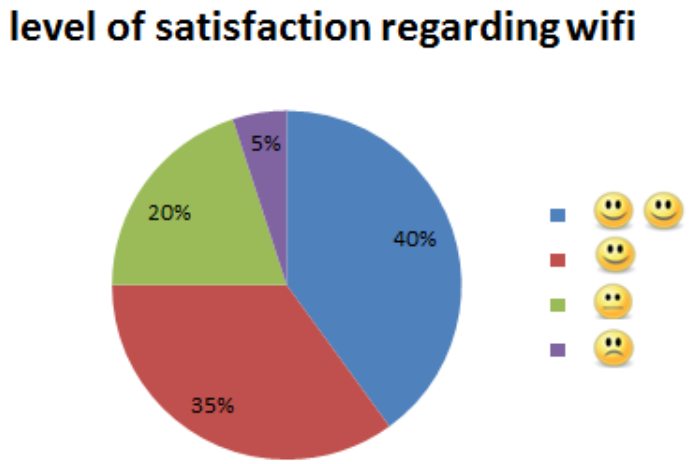


Figure 2.10: level of Turkish users' satisfaction regarding the wifi technology

Several criteria have been evaluated by the Turkish participants in order to point out the strengths and the weaknesses of this technology. The figure below emphasizes several aspects:

- A set of criteria which the level of satisfaction is high (more than 70%): ubiquity, convenience, mobility and compatibility
- A set of criteria which level of satisfaction is intermediate (around 50 and 60%): installation, security, expandability, cost, reliability and speed
- Lastly, two criteria have a level of satisfaction lower than the others: range (45%) and radiofrequency radiation (30%)

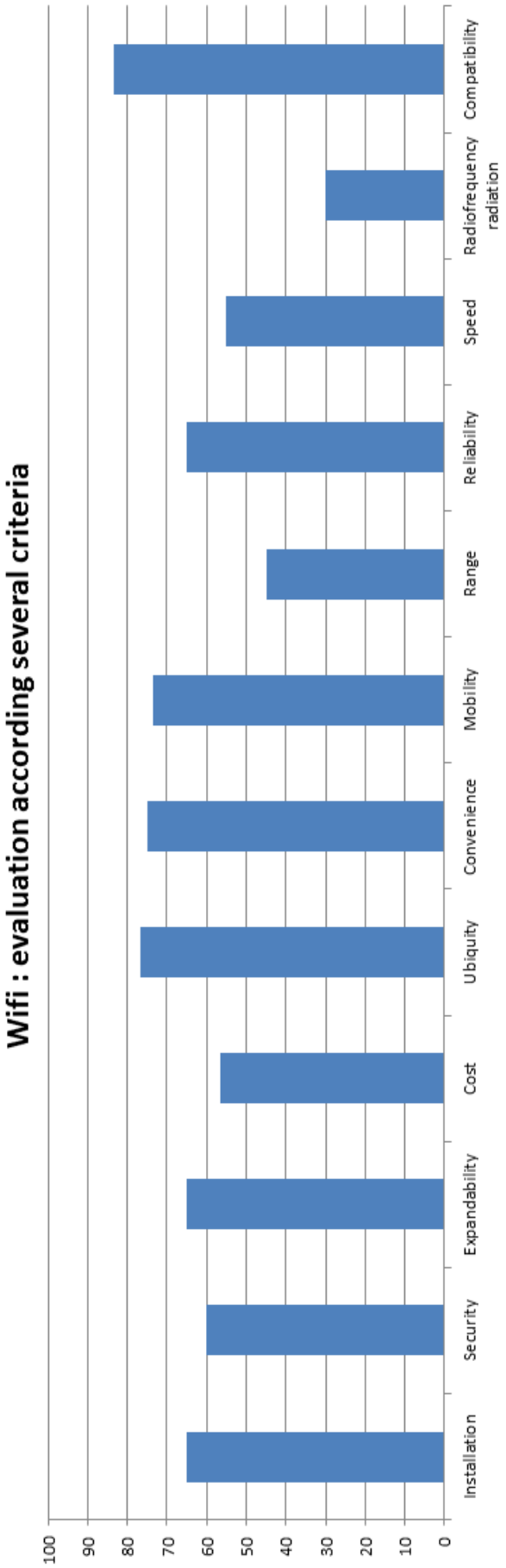


Figure 2.11: level of users' satisfaction regarding the wifi technology based on a multi-criteria analysis

90% of the Turkish participants are interested to learn more about a new technology which could be an alternative to wifi. In order to define the Turkish users' requirements, the level of importance of several criteria was evaluated by people:

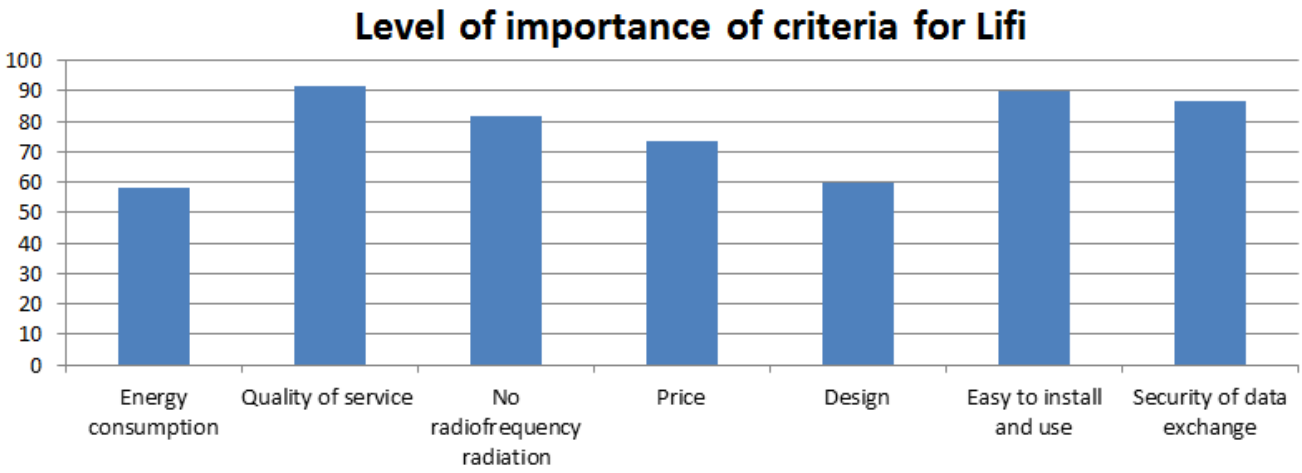


Figure 2.12: level of importance of several criteria evaluated by the Turkish participants regarding Lifi

As shown in the figure above, the level of importance of all the selected criteria is quite high with two main categories:

- A level of importance estimated higher than 70% for the following criteria: quality of service, no radiofrequency radiation, price, easy to install and use, security of data exchange
- A level of importance a little less high, around 60%) for two criteria: energy consumption and design

For the replacement of Wifi at home, the price of a Wifi extender (about 80€ in France) was given to the Turkish participants for their information. 95% of Turkish participants say to be willing to pay an average invoice of 75 € with the following distribution (20 participants):

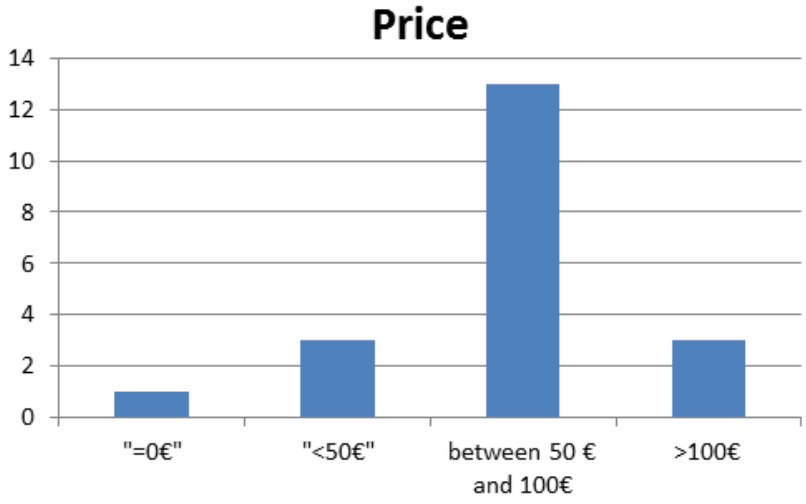


Figure 2.13: Evaluation of the price maximum that Turkish people would be willing to pay for the replacement of Wifi at home

2.3 Conclusion

	France	Germany	Turkey
Wifi strengths	ubiquity, convenience, mobility, installation	Ubiquity, compatibility, cost	ubiquity, convenience, compatibility, mobility
Wifi weaknesses	radiofrequency radiation, security, speed	radiofrequency radiation, range, reliability	radiofrequency radiation, range
Expectations regarding Lifi	• Retrieve the same level of quality of service as with wifi • Remedy to the weakness of wifi: security of data exchange and radiofrequency radiation	• Level of importance of all the selected criteria evaluated between 60% and 70% by the German participants (consumption, QoS, radiofrequency, price, easy to install and use, security) • Only the criteria "design" is a little bit below the whole	• Level of importance higher than 70% for the following criteria: quality of service, no radiofrequency radiation, price, easy to install and use, security of data exchange
Part of the participants willing to pay	100%	60%	95%
Accepted average price by users for the replacement of Wifi at home	79 €	75€	75€

Table 2.1: Comparison between France, Germany and Turkey regarding Wifi versus Lifi

If we establish a first level of appreciation between lifi and wifi: the participants would like ideally technologies which guarantee the absence of impacts on the human being's health. They are inclined to discover new technology (like LiFi) but remain very demanding and doubtful regarding the level of quality and the absence of impacts on health of these other new technologies.

Futhermore, the accepted average price by users for the replacement of WiFi at home is around 70-80€. This amount include several LiFi Access Point (AP), one per room, for instance, living room, kitchen and 2 bedrooms; with several LiFi dongles if this new link interface is not integrated inside the device.

3 Uses cases

3.1 Outdoor uses cases

3.1.1 Earth-satellite wireless optical communication

The first known project was initiated in the 1970s [MAY 05]. It was called Spaceborne Flight Test System (SFTS) program and had the code number "405B Program". It was at that time, "the study of a space laser communication" in the projects WS - Weapons System, funded entirely by the Air Force and the Pentagon. This project was conducted with the participation of NASA, DARPA, Goddard Space Flight Center and Jet Propulsion Laboratory.

During the same period and always with the financing of the U.S. military, telecommunications links between aircraft have been tested using high power lasers. Then logically, these experiments were extended in the 2000s with programs such as Oracle or Orcle. These programs offered a development towards wireless optical communications ground-ground, ground-plane, plane airplane, satellite, aircraft and satellite-submarine or towards HAP (High Altitude Platform) [02 GIG, HAP 11, HEN 05, HOR 04] or drones [LOH 11].

Finally, around 2005, studies were conducted on communications between Earth and modules on Mars (NASA's Space Exploration Initiative - SEI) with the Laboratory Lewis Research Center. It was to use lasers in order to achieve data rates of 100 to 1000 Mbps. The findings of preliminary studies showed the availability of a complete system for 2020 [KWO 92].

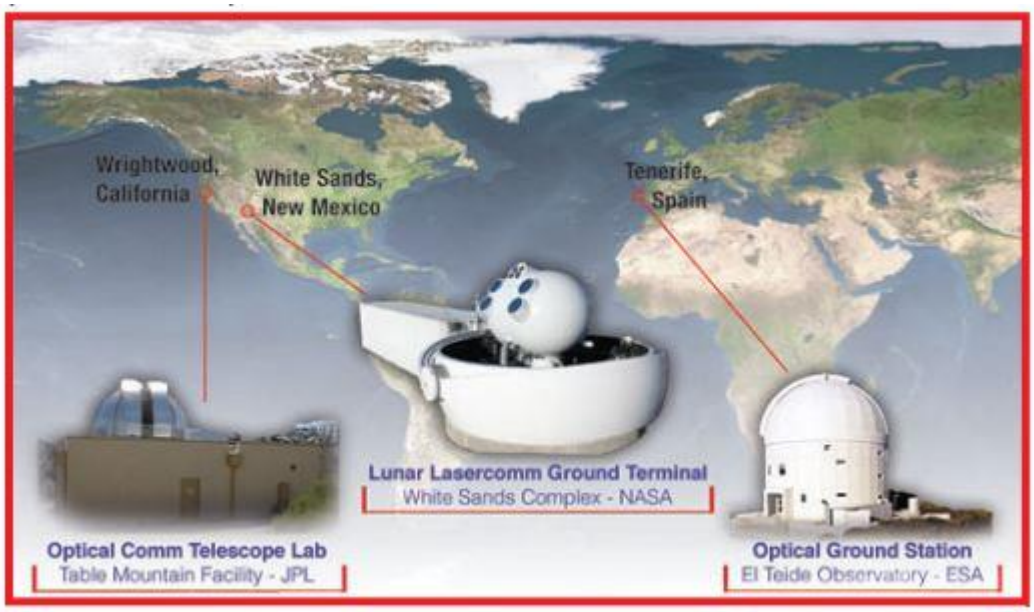


Figure 3.1. Earth-satellite wireless optical communication

Website: http://en.wikipedia.org/wiki/Free-space_optical_communication

3.1.2 Inter-satellite wireless optical communication

In the 1990s, civil studies were initiated for intersatellite communications and November 2001, the first civilian application of laser high-speed communication was implemented. A 50 Mbps link was established between the French satellite SPOT-4 and the European satellite Artemis, separated from the other tens of thousands of miles. Figure 3.18 represents a communication between the SPOT satellite Artemis and the Silex laser system (source: ESA).

This European success is the result of a project called - Project SILEX (Semiconductor Inter-Link Experiment) initiated in early 1990. The partners were Matra Marconi Space, Astrium, the European Space Agency (ESA) and the Centre National d'Etudes Spatiales (CNES).

Since 2008, the German Space Agency (DLR) operates an inter-satellite link between the satellite TerraSAR-X and NFIRE. This connection is based on a second generation of laser communications technology. This solution will also be used for the new European satellite data relay (EDRS - European Data Relay Satellite) in 2013. The low power consumption and compact size have favored this approach over the radio.

Figure 3.2. Communication between Spot and Artemis with Silex laser system

3.1.3 Free Space Optic (FSO)

In France, the first trials of free space laser communication has been made in the late 1960s to Lannion between a building of the Centre National d'Etudes des Télécommunications (CNET) and trailer laboratory [TRE 67]. The device used a helium-neon laser of wavelength 632.8 nm at the emission side and a photomultiplier at the reception. Another study looked at a carbon dioxide laser wavelength of 10.6 microns. Video transmission tests were carried out over a distance of 1.2 km and 19 km.

Other products, commercially mature, appeared in the world in the mid-1980s. But despite advances in technology transmitters and sensors, transmission quality and availability of communication links did not still meet the expectations of a telecommunications operator.

But in the early 2000s, a new wave of products is proposed, mainly to European and American origin. These devices were tested by CCETT (Centre commun d'études de télédiffusion et télécommunications) from Rennes (France), in order to determine what market segments the digital communications technology could be proposed.

The telecommunications market has become competitive, these technical solutions have been proposed as an extension to optical fiber or private Ethernet inter-site communications.

The framework for using these wireless optical systems has been developed with the ITU (International Telecommunication Union) [ITU 11] and more specifically the ITU-R, CE3 [ITU 03, ITU 04, ITU 05b, ITU 07a, ITU 07b], CE5 [ITU 05a, ITU 08] and CE9.

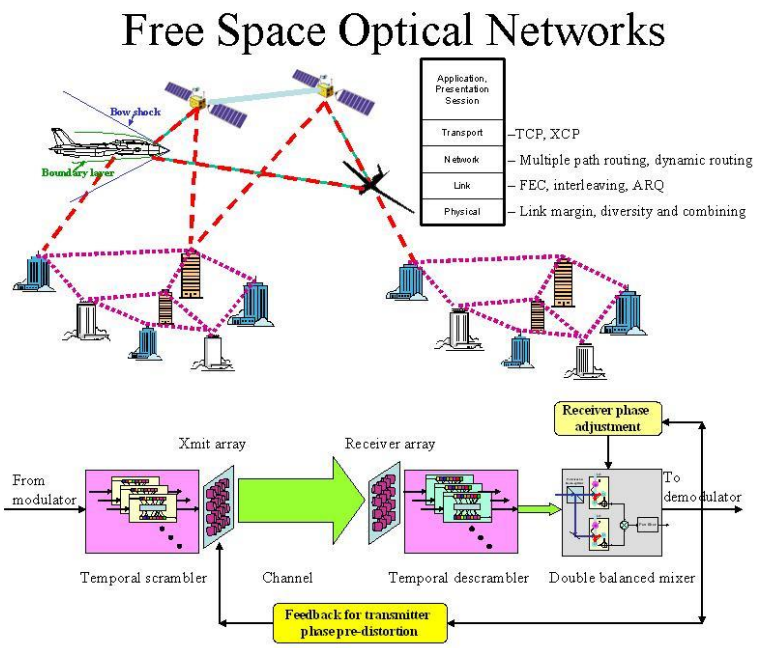


Figure 3.3. FSO network (source MIT- Boston)

Website: http://en.wikipedia.org/wiki/Free-space_optical_communication

3.1.4 ITS (Intelligent Transport Services)

Intelligent Transport Services (ITS) could be a massive application opportunity (figure 3.4) by using LED lamps cars, traffic signal, traffic lights, and street lamps for communication. **Toyota** proposes a car navigation system with this technology [TOY 11].

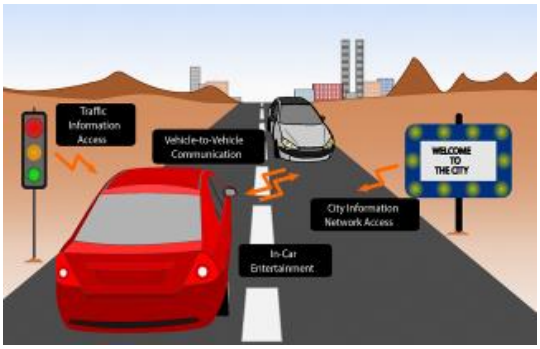


Figure 3.4. ITS

Simulation results show that any receiver of all recommended positions can reliably communicate with required data rate, less than 100kbps (

OLEDCOMM has done a project with SNCF on the subject ITS. OLEDCOMM has tested the performance of LiFi through two applications in the train: the geo-localisation in one carriage of the test train; the visible light communication for audio streaming on the seat. It has deployed the geo-localisation in one part of railway station in Paris. There is also a visible light communication use case for video in a demonstration VIP car of Peugeot for French Open-Roland Garros in 2013. The tablet can display a video with a LED inside of car.

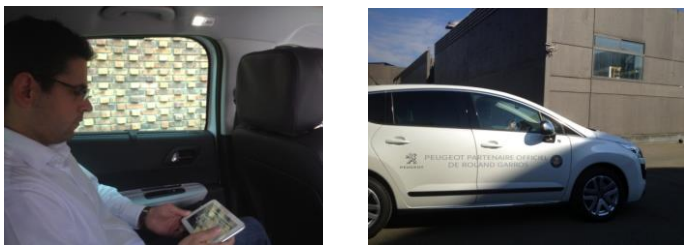


Figure 3.5. LiFi technology for Peugeot car in French Open

It demonstrates the internet connection at at 1 Mbit/s data rate by the LiFi technology inside a model car of Peugeot in the show room of France Television for French Open-Roland Garros in 2013. The president of France Television and the president of French Open have visited this demonstration.

3.2 Indoor uses cases

3.2.1 The remote controller

By definition, a remote control is an electronic device for point-to-point unidirectional used to modify the remote operation of an equipment, such as a TV channel or the volume. The first public television remote control appeared in 1955 (Zenith with Flash-Matic). It used visible light and four-cell reception (on/off, volume and the channels selection). One year later, wireless radio technology, with a greater coverage, replaced the light solution. But radio waves pass through obstacles such as walls, resulting in potentially changing the TV program in the neighborhood. The infrared solution was then finally retained.

Since the early 1980s, the vast majority of remote controls use infrared technology and dispatch of orders is done by transmitting a digital signal, whose frequency is modulated at a few tens of kilohertz. Due to the proliferation of owner controllable devices by a remote controller, up to ten per household, there is now universal remote controller which controls all or part of the buttons. There are configurable or appear on an LCD touch screen.

3.2.2 Point to Point Full Duplex solution (IrDA proposal)

Another use case comes from association IrDA (Infra-red Data Association), offers a 1 Gbps point to point solution called Giga-Ethernet (previously known as EFIR) for a distance of 0.2 meter [KDD 11]. To meet the demands of rapid data transfer, the members of this association are intended to provide such a system in 2012. Examples of use are: portable multidevice interface and fast music or films download.

As part of a collaborative project called Regional Techimages, Orange Labs in Rennes, with regional research partners, have achieved a Point-to-Point at 1.25 Gbps over a distance of 0.5 meters [BOU 09]. Then, as part of a European collaborative project called Omega [OME 11], the same data rate was achieved over more three meters.

Website: http://irdajp.info/

Orange Labs Irda test dongle: Dongle SIGMATELL USB/IRDA

Figure 3.6. IrDA dongle and new device installation process

The configuration is done under Windows XP (no W7/W8 driver). The new network connection is propose as server by the infrared port, on Pc N°1 and on the other Pc N°2.

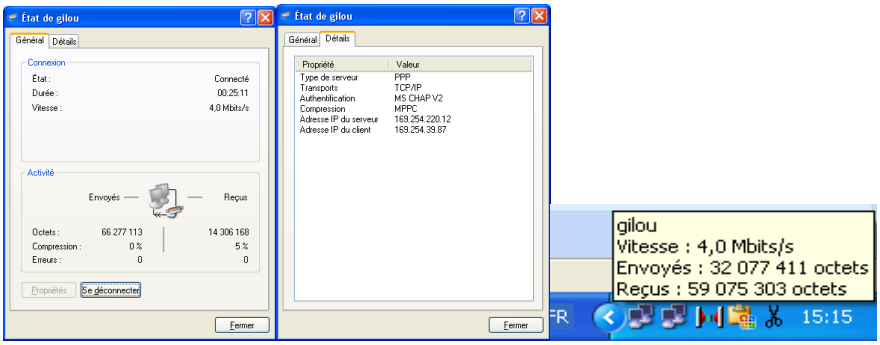


Figure 3.14. Connection process and status

Once the connection is established, each of Pc receives an IP address. These Infrared modules propose a basic connection up to 4Mbps (maximal speed by défault) and flow test.

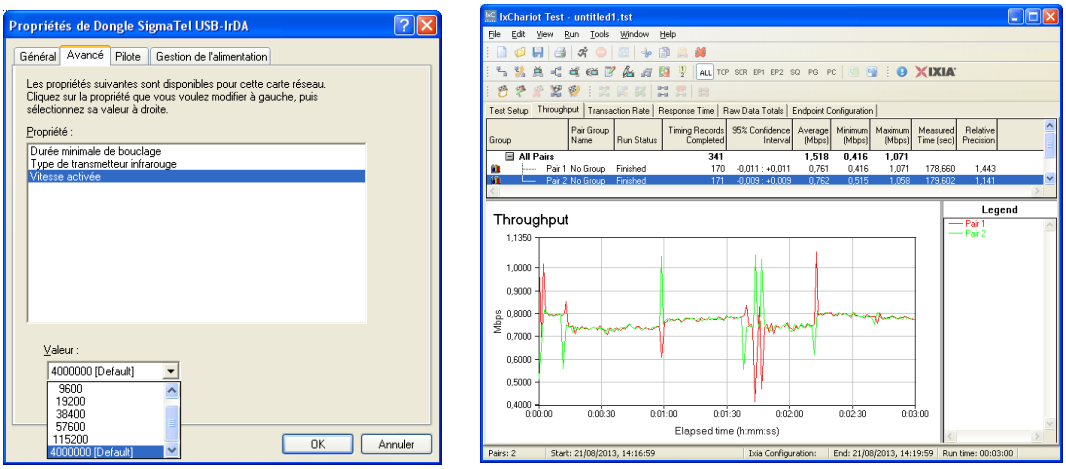


Figure 3.7. Communication test

For bidirectional connection and with the protocol TCP / IP, the flow is around 1.5Mbps. This flow is testing by the application IxChariot from Ixia. These infrared modules allow a wireless connection with a useful flow up to 1.5Mbps and with a distance lower than the meter.

3.2.3 LBS (Localization Base System)

The approach use LEDs of lighting to supply a secure and precise indoor service of geo-localization. The receiver is a smartphone for instance with adapted receiver. Lights send an “invisible QR code” that provides radio access network (WiFi, 3G, 4G…) setup information.

As the LBS solution provides a service of geo-localization inside precise and secure, it is suitable for some use case like the guide for Museums and Special Events

In 2013, as part of the temporary Marseille exhibition at Marseille Provence Metropolis, OLEDCOMM has deployed the innovative LBS solution. The geolocation is done using Li-Fi technology with some 10 inch tablets using a jack receptor. The application allows the user to note his favorite art work and to communicate more information with the reception.

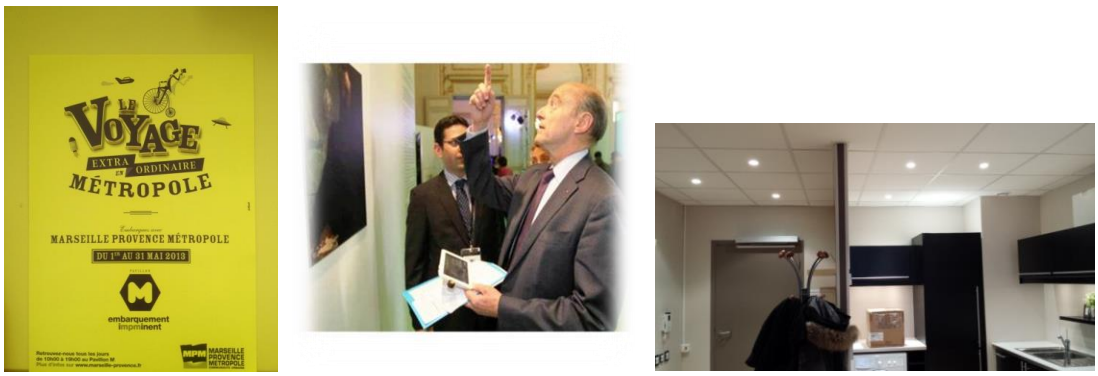


Figure 3.8. LiFi technology LBS solution in Marseille, Bordeaux and Paris (2013)

The city of Bordeaux has bought a LBS solution for museum to show the innovative LiFi technology in 2013. The city demonstrated this solution in his technology exhibition.

OLEDCOMM has equipped a show room in Thales at Paris with the LiFi technology LBS solution in 2013 and realized a project with Vision Institute at Paris in 2013. In the Vision Institute, the service is an application to guide visually impaired and hard of hearing person in an apartment.

Another application is done inside an administration building of Paris Airports with the LiFi technology LBS solution in 2014. The target is to guide staff in this building.

In 2014, as part of the Liège Museum (Grand Cursius), OLEDCOMM has deployed the innovative LBS solution in the museum. The geolocation is done using Li-Fi technology with some 7 inch LiFi compatible tablets. The Museum provides an application to guide the person in the different journey according to the personal profile. The official opening is at the beginning of September. The solution is described by the following figure.

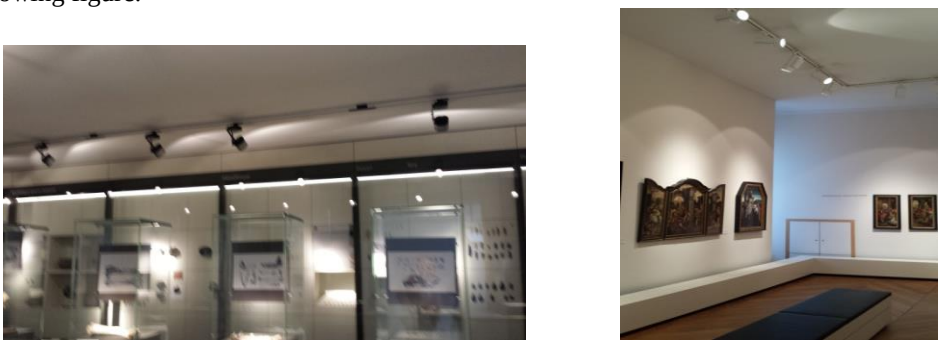


Figure 3.9. LiFi technology LBS solution in Liège Museum

Figure 3.10. LiFi technology LBS solution in Liège Museum

Press release
http://www.itrmanager.com/articles/146597/app-geolocalise-clients-magasins-grace-eclairages-led.html
http://www.itrnews.com/articles/146380/thomson-mise-lifi-lance-gamme-led-compatible.html

Figure 3.11. LBS use case example from Philips

3.2.4 Hot Spot

Another application is Optic Hot Spot with customer "Pull communication" (figure 3.9). Instead of continuous spamming, the customer can select whenever and wherever he wants, commercial information by positioning his smarphone under the hotspot optic beam.

Transfer content between devices use case

- Rapid sync-n-go file transfer
- picture by picture viewing
- movie content download to car
- Refueling

OLEDCOMM has developed also the hot spot solution using LiFi technology. This solution allows transferring the different contents like files, pictures, videos etc. The project is to equip one building of a hospital in the end

of 2014. In this solution, the information about patients can be exchanged between the ceiling LED and the laptop computer on a trolley.

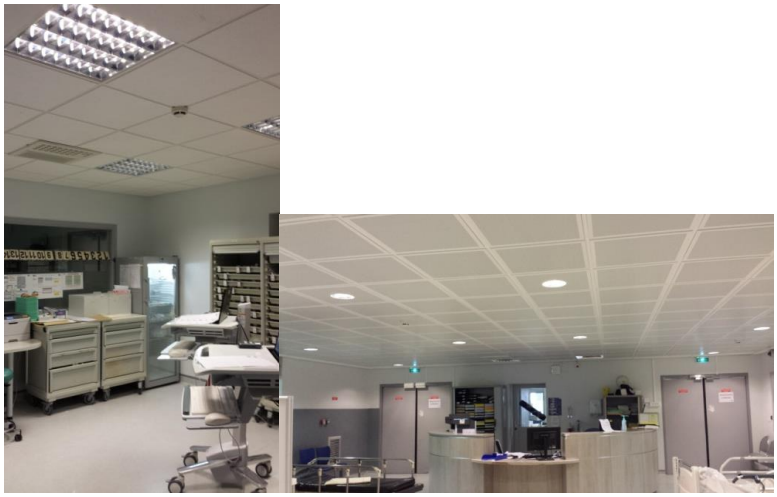


Figure 3.24. LiFi technology hot spot solution for one hospital at Paris

Figure 3.25. IrDA 1Gbps file transfer from Docking station to mobile phone

4 Conclusion

To be a success story, wireless optic systems needs important levers to become more pertinent than available mature radio solution, these levers could be radio spectrum saturation or human health radiofrequency customer sensitivity.

For the Visible Light Communication area, all the bricks are available (Optic, PHY, MAC, Standards…) and companies looking after the first cost effective application, with both functions “lighting” and “communication”; this is for instance Hot spot or LBS application for instance.

Concerning Infra-Red Communications systems, a number of complete experimental and commercial solutions have been produced and tested in-house. These tests and experiments have demonstrated both the feasibility and the remaining challenges for a room point to multipoint Wireless Optical Network (WON).

In a short term, the next step could be a B2B market with high value added small business case (Offshore, School, Hospital…) and could grow towards low data rate mass market. In the long term, the Wireless Optical Network could become a competing and alternative solution to radio for wireless high data rate room connectivity.

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