# Light Communication Technology: An Enabling Technology for Sustainable Wired and Wireless Solutions

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Abstract: Optical wired and wireless technologies are analysed in this paper to address sustainable solutions for vertical markets. After a description of the context, of the different technologies adopted, of use cases and their associated services, this paper demonstrates through a comparative analysis with a classical Ethernet LAN interconnecting Wi-Fi access points for a fixed network, that optical technologies in a heterogeneous context can provide key added value services in a sustainable way.

## 1 INTRODUCTION

Because of the climate impact due to global $CO_2$ emissions, new industrial approaches are required at different levels to reduce our emissions. Concerning the Information Communication Technology (ICT), the projection in term of electricity demand to the worldwide electricity production could reach 20.9% in 2030 according to figure 1 (Jones, 2018). Because of an exponential growth of the electricity demand for the network infrastructure and for the data centres between 2020 and 2030, industrials have to react.

In addition, the increase of the electricity cost per kWh when combined to a traffic growth in strong acceleration associated with the perspective for new technologies operating at higher frequencies (from 5G to 6G) can create blocking situations at the market level and requires the identification of new sustainable approaches to drive the next generation of ICT products.

It is therefore important to identify technologies that could help this evolution. For example, optical technologies have the potential to reduce the

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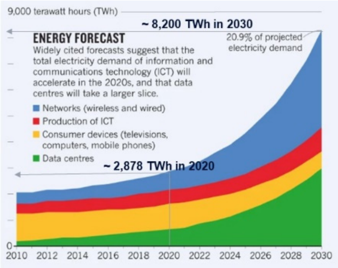

Figure 1: Projection of the ICT electricity demand (Jones, 2018).

electricity consumption of ICT illustrated by three concrete examples:

- The optical transmission systems have already demonstrated their capabilities to offer high energy efficient systems. By combining Time Division Multiplexing (TDM), Wavelength Division Multiplexing (WDM) and potentially Spatial Division Multiplexing (SDM), it is then possible to transport ultra-high data capacities at a minimum energy.
- The introduction of optical bypasses in networks offered by the Optical Add/Drop Multiplexer (OADM) technology suppress a lot of Opto-Electro-Optic (OEO) conversions in the passthrough and minimise then the electronic processing. This optical transparency offered in the passthrough of OADMs is today exploited in the metro and in the core to have low energy consumption optical communication transmission systems and low latency networks.
- Optical wireless communication systems: Light Fidelity (LiFi) or Optical Camera Communication (OCC)) have also a high potential to reduce the energy consumption of end-to-end systems. As an example, a Vertical Cavity Emitting Laser (VCSEL) used for some generations of LiFi systems exhibits only few 100fJ/bit (Si-Cong, 2023), and laser array-based adopting a Multiple Inputs Multiple Outputs (MIMOs) scheme for an ultra-high bite rate access point can require less than 2 Watts for an aggregated bit rate close to 2 Tbps leading to an energy efficiency close to 1pJ/bit (Haas, 2023).

The previous remarks indicate that it is of interest to analyse different end-to-end solutions and to see how the optical technology could contribute to design a sustainable 6G technology.

In this paper after a recall of the main challenges that are in front of us, and a rapid state of the art demonstrating the high potential of optical technologies, we will analyse the combination of optical wired and wireless technologies focused on the fixed access part of verticals for hospitals, commercial centres and for the Industry 4.0.

After a description of the assumptions, we will present the potential gains in terms of electricity consumption of an optical end-to-end solution when compared to a reference scenario (classical Local Area Network (LAN) and Wireless Fidelity (Wi-Fi)).

We will then analyse the impact of a heterogeneous case where different access point technologies coexist to offer added value services at a minimum energy consumption. Finally, the conclusion will draw some perspectives for a positioning of this optical technology.

## 2 CHALLENGES RECALL

The acceptable electricity demand to the grid of the ICT by 2030 has been estimated with the data of (Jones, 2018) and (Ritchie and Rosato, 2024).

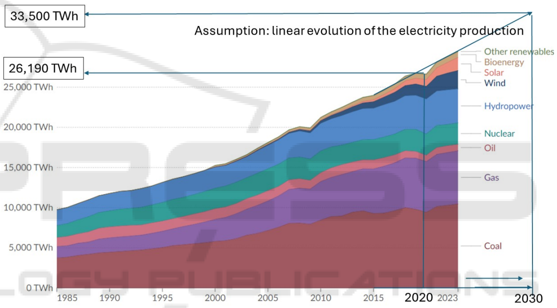

Figure 2: Projection made in 2030 by adopting a linear production evolution aligned with the two previous decades.

If we fix a reduction of the electricity demand of 50% by 2030 (value adopted by several operators) with respect to the projected value: 8,200 TWh, we can estimate then an electricity demand of the ICT close to 4,100 TWh.

In 2020 the electricity demand of the ICT was close to 2,878 TWh according to (Jones, 2018) for a global electricity production of 26,190 TWh representing a percentage of electricity demand of 10.98%.

With a reduction of 50% of the electricity demand by 2030, and an estimated worldwide production of electricity close to 33,500 TWh (linear assumption made according to figure 2) then the percentage of electricity demand could become 12.23%. This is required to recontrol the electricity demand to the grid and create new market opportunities by adopting new sustainable approaches.

However, to reach a reduction of the electricity demand of the ICT of 50% a strategy in four steps has to be adopted.

The four steps driving a short, medium and long-term strategy could be:

1. Massive adoption of new eco-design rules including the software, the hardware, the adoption of longer life cycles and the adoption of a circular economy to reduce as much as possible the footprint. A new methodology is then required to lead to the optimal solution for each use case.
2. Deploy micro-grids, when possible, to produce locally and reduce then the electricity demand to the grid. This step can be applied to already deployed network elements or for the new products adopting step 1.
3. Adopt efficient storage with zero $CO_2$ emission to secure an electricity continuity delivery when the national grid is in failure.
4. Limit the wasted energies, though an optimized design of a solution, but also by converting any form of wasted energy into electricity.

We recall that according to figure 1, the two parts of the ICT that need to be optimized are the network infrastructure and the Data Centers (DC):

- For the network infrastructure we need to distinguish the vertical/enterprise and the public network infrastructure. For the public network, the mobile network is the most representative since it could contribute to 72% of the overall electricity bill of an operator.
- For the DCs two main sub-systems are dominating the energy consumption of a DC: the cooling system and the servers of data are close to 80% for big DC (figure 3 and (Rong, 2016)).

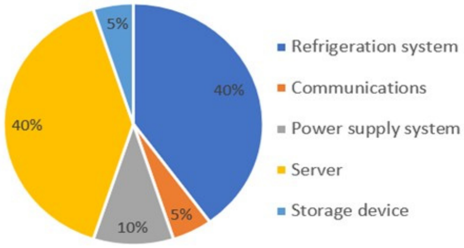

Figure 3: Repartition of the energy consumption of a data center according to (Rong, 2016).

Because the use of one unique technology can lead to an over dimensioning of the solution when pushing the technology beyond its own limits, it is then important to analyze the role of a complementary technological approach. And it is already the case today where Wavelength Division Multiplexing (WDM) links or Passive Optical Networks (PONs) are proposed for the FrontHauling (FH) or XHauling (XH) part of a Radio Access Network (RAN). The objective is then to include, when necessary, an optical technology in an end-to-end solution to drive high performance systems with added value services at a minimum energy consumption. In this paper, we analyze then the potential of wired and wireless optical technologies to anticipate concrete solutions for an optical converged fixed and mobile network (IOWN, 2022).

# 3 USE CASES AND SERVICES TARGETED

## 3.1 Use Cases

Because end-user have access to two technologies: a radio frequency technology (4G/5G and tomorrow 6G) but also a fixed technology today mainly based on PONs, it becomes relevant to analyze an integrated technology from the end-user up to the aggregation node to connect anything at any time with the correct Quality of Service (QoS) for an acceptable Quality of Experience (QoE) in a full flexible way. For this analysis we will be focused on the fixed network part for three specific use cases: Commercial centers to offer a low cost and a low energy consumption end-to-end solution; hospitals for their specificities (in some places of a hospital High Frequencies (HF) are not tolerated/possible); the Industry 4.0. requiring ultra-high bit rate connections to process data and to optimize the productivity of a factory. Even if the focus was on three use cases, the solution proposed has the potential to cover a larger scope.

## 3.2 Requirements and Services Targeted

For the three precited use cases, the requirements and the service targeted are the followings:

- Commercial center: need to provide a low Total Cost Ownership (TCO) network infrastructure with accurate in-door positioning, and highly secured data transmission.
- Hospitals: need for a data transmission continuity in the wireless domain, from 5G/6G at the periphery of the hospitals, to Wi-Fi in the public waiting rooms, to LiFi or any light communication technology inside the building when RF is blocked. We need to offer different services from moderate bit rates to persons inside intense care rooms, to high bit rate connections

offering ultra-low latencies in surgery rooms.

- Industry 4.0.: need for solutions offering diverse services, massive connectivity, easy capacity upgrade, ultra-low latencies for deterministic services and Machine-to-Machine (M2M) communication offer. The technology complementarity is here extremely important not to over dimension one technology.

# 4 LIGHT COMMUNICATION TECHNOLOGIES

## 4.1 Light Communication Technologies

In this paper we will consider two types of light communication technologies: the LiFi and the OCC technologies.

- LiFi technology is a bidirectional technology requiring an additional physical layer (transponder including Light Emitting Diodes (LEDs) or VCSELs and Photodetector(s)) and in some versions a new data link layer (new Medium Access Control (MAC) layer). The spectrum exploited for this technology includes the Visible Light (VL) (350 nm – 700 nm), but also the InfraRed (IR) spectrum (800 – 1000 nm). Typically, IR is used for the upstream traffic. For the downstream traffic, either VL or IR light can be used depending on the use case. The technology delivers a user experience substantially similar to Wi-Fi except using the light spectrum, offering potential high data rate, mobility, handover and more. One standard, the IEEE 802.11bb, targets a mass market by adopting an optical antenna instead of a RF antenna and is based on the Wi-Fi protocols.
- The OCC technology describes a unidirectional technology exploiting the camera as a photodetector associated with an application able to interpret the information received to be easily exploited by the user through a graphic interface. The light signal is in the visible domain for classical cameras. The bit rate is limited to the potential of the camera technology. The OCC technology can be summarized as follows:
  - Wireless communications
  - Offering In-door positioning capabilities
  - Decoding of data from embedded cameras of a smartphone
  - Based on the standard: IEEE 802.15.7

  Services offered:
  - Geo mapping
  - Data analysis
  - Location based services

## 4.2 Infra-Red (IR) versus Visible Light (VL)

The type of the source is a key question. With the massive deployment of Light Emitting Diodes (LEDs) in all the spaces (from the residential part to the public area) it is important to analyse two scenarios: one exploiting the existing VL provided by a LED lighting, and another one based on IR source when the LED-based light is off, or when sun lighting is dominating a space. For that last scenario, we need then to add a new source: an IR source that needs to be added in the energy budget. To minimise their impact, the IR sources considered will be VCSELs for their high energy efficiency and their low energy consumption.

## 4.3 Perspectives of Deployment: FWA, Full Deployment, Business-to-Business (BTB) and Business-to-Customer (BTC)

The LiFi technology requires standards for a massive deployment. For example, the IEEE 802.11bb standard is targeting this objective and other standards are currently discussed for further deployments. The deployment has started for fixed wireless access, and for dedicated applications, generally for BTB applications. The integration tomorrow of chipsets in terminals (smart phones or personal computers) at a large scale will be a major catalyst for a BTC market. In the following, we will then analyse a deployment of this new technology in a BTB scenario and for a Fixed Wireless Access (FWA) configuration in the majority of use cases considered and for a full deployment for a restricted space (hospital use case mainly).

The OCC technology offering a geo-localization service is already targeting a BTC market, since this technology is compatible with a majority of smart phones, and since we can find on the apple store or in the android store applications to support OCC services.

# 5 OPTICAL NETWORKS

## 5.1 Optical Network Technologies Considered

Optical networks are today deployed in the pure fixed access part or in the metro and backbone part. For the pure access part, PONs are massively adopted to offer a Fibre-To-The-Home (FTTH) technology. If the Gigabit PON (G-PON) is massively used in Europe, other versions of PONs are also on the market. We find also the 10x Gigabit Symmetrical PON (XGS-PON), the 100G-PON and higher bit rates are under study. For the backbone, Reconfigurable Optical Add/Drop Multiplexers (R-OADMs) nodes are massively deployed to offer a transport optical network on the top of Multi-Protocol Label Switching over Internet Protocol (MPLS/IP) Switch/Routers. In this paper we will be focused more on the technologies developed for the access part or for the FH/XH. Another technology proposed for the RAN in a physical ring topology adopting OADM-based nodes for targeting the interconnection of cell sites to the Base Band Unit (BBUs). When targeting an optical convergence fixed-mobile it is then important to address topologies different from the tree topology as used for PONs and envisage bus or ring topologies to offer new services like M2M services enabled for example by a broadcast-and-select technique.

Finally, we note that FTTH technologies based on PONs have already demonstrated their potential to minimise the electricity demand when compared to other technologies (5kWh/line for the FFTH to compare to 15kWh/line for the ADSL technology or to compare to 50kWh/line for the 3G/4G in 2019) (Perrufel, 2022).

## 5.2 Passive Optical Networks and Passive Optical LAN (POL)

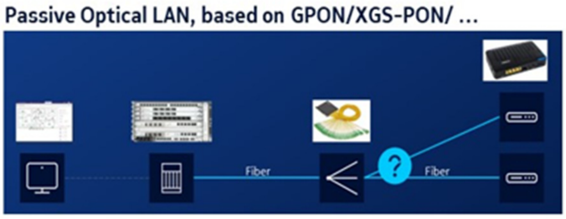

Figure 4(a): G-PON used for a Passive Optical LAN.

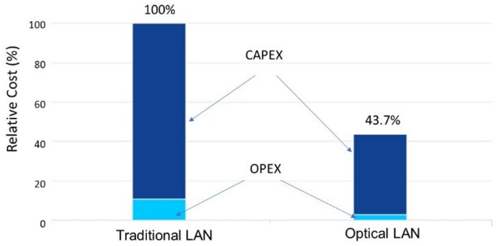

Figure 4(b): POL versus Ethernet LAN.

Table 1: Specificities of the Ethernet Switch node considered and of the X-Cast WDM Add/Drop Multiplexer node.

| Port attributes | Ethernet Switch: S5800-8TF12S | X-Cast WDM ADM |
|---|---|---|
| 1GbE port | 8xRJ45 auto-sensing | --- |
| 100GbE CFP2 (10 channels at 10Gbps) | 0 | 1 |
| 10GbE SFP+ Ports | 12 | 2 |
| Performance | Ethernet Switch: S5800-8TF12S | X-Cast WDM ADM node |
| Switch Fabric Capacity | 240 Gbps | 1 Tbps |
| Forwarding Rate | 179 Mbps | 10 Gpbs for the control channel) |
| Latency | 1700ns | 2000ns max. |
| Switching method | Store and Forward | Broadcast-and-select |
| Unit Weight | 5kg (include one PSU) | < 2 kG |
| Operating T° | 0 to 45° (long term) | 0 to 45° long term |
| Price estimated (Euros) | 4,159 | 1,598 |
| Power consumption estimated (W) | 87,4 | 18 |

Optical Passive Networks (PON) have several advantages, like their capabilities to transport high capacities, with high energy efficiencies. Figure 4(a) shows the technology based on a PON and figure 4(b) shows the possible gain in CAPEX and OPEX when comparing a Passive Optical LAN (POL) with a classical Ethernet LAN.

POL can save energies with respect to classical LAN. Comparatives studies have demonstrated the possibility to reduce by 82% the electricity consumption of a POL with respect to an Ethernet LAN. And the advantages are multiple: Fiber size smaller than a CATx cable used for Ethernet. The optical fibre offers large bit rates or easy capacity increase and their lifetime is in the range of 50 years. It is an eco-designed solution since a PON is partly made with a fibre infrastructure designed for a long-life cycle, and the modularity located at the periphery of the network allows easy upgrades to follow the evolution of the demand. In summary, PONs have a high potential in terms of energy consumption reduction when compared to classical Ethernet LANs.

## 5.3 Optical Ring Network

Figure 5(a) shows another optical network topology: a ring or a bus. We are considering here a new generation of Optical networks based on simple and amplified Optical Add/Drop Multiplexers (OADMs) (figure 5(b)).

- Simplified Optical Add/Drop Multiplexer nodes (based on optical couplers and an optical amplifier).
- Structure offering Cross-cast (X-Cast) functionalities.
- Support of a circuit or a packet transfer mode.
- Optical transparency in the path through for a minimum power consumption.

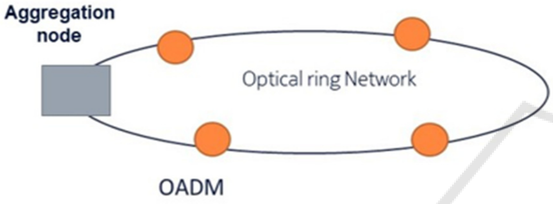

Figure 5(a): Optical ring network.

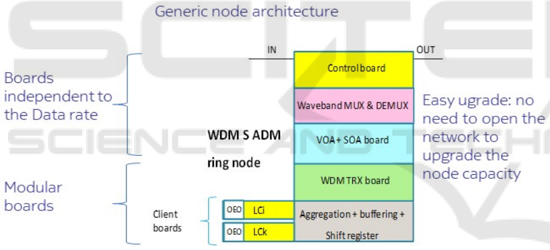

Figure 5(b): Optical Add/Drop node structure.

Figure 5(c) illustrates the global structure of the network proposed.

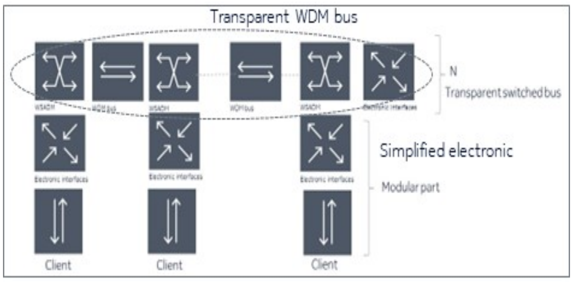

Figure 5(c): Key features of the network.

In the analysis we have adopted a simple OADMs, including mainly optical couplers and a semiconductor optical amplifier. A first comparison shows that it is a 10x technology when compared to a pure Ethernet technology since the optical bypass implemented for the transit traffic avoid a large number of line cards and transceivers. As for the PON, a capacity upgrade does not impose a replacement of all the network elements in the optical solution since some network elements are designed for a long-life cycle like the optical fibres but also the OADMs.

Figure 6 shows the gain that can be obtained in terms of energy consumption, when comparing an optical ring network for LAN applications and a classical Ethernet LAN.

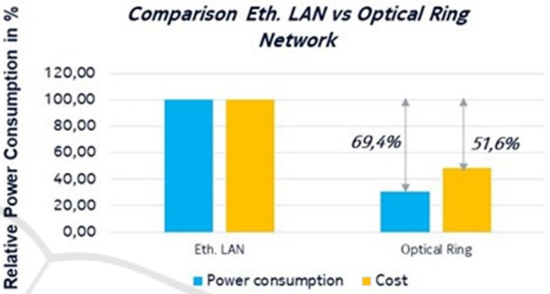

Figure 6: Optical Ring LAN versus LAN.

We notice that the power consumption can be reduced by more than 69% with respect to the classical LAN solution.

Both optical technologies: PON and optical rings networks are then good candidates for designing end-to-end solutions.

# 6 COMPARISON: PASSIVE OPTICAL NETWORK VERSUS OPTICAL RING NETWORK WITH ADDED VALUE NEW SERVICES

## 6.1 Fixed Network for In-Building Use Cases

For the study we will compare an Ethernet LAN + Wi-Fi access points and an optical network (PON or Optical Ring) with different access point technologies: Wi-Fi + LiFi + OCC.

For the quantification we adopted the following assumptions:

- Surface considered: 5,000 m² (100x50 m²).
- Number of Wi-Fi access points: 25 for a surface

connectivity of 200 m$^2$.

- Number of LiFi Access Points (AP): 12 in a FWA configuration, 250 for full deployment.
- Number of OCC access points: 200 (every 5 meters).

For the Wi-Fi access points (WatchGuard, 2024):

- Wi-Fi 6 2x2: Power peak at 10.9 W.
- Wi-Fi 6 2x2 including radio of security: Power peak at 15.9 W.
- Wi-Fi 6 4x4: Power peak at 19.5W, close to 20 W (value adopted for the calculations).

For the Wi-Fi repeater we adopted 2.6W.

The LiFi technology is deployed according to two scenarios:

- In a FWA configuration to offer BTB services.
- In a full deployment scenario in the space considered, to offer BTC services and anticipating the presence of LiFi chipsets in terminals.

Both scenarios include an association also with OCC for BTC services to offer added value services.

In the study we will consider an optical network (PON or Optical Ring) associated with:

- Wi-Fi for full coverage for the reference and for the optical solutions.
- LiFi in FWA when there is a need for new services (for more security, for more bit rate, when RF is not allowed) only for the optical solutions.
- OCC exploiting the existing lighting to offer in-door positioning/geo-localisation services only also for the optical solutions.

## 6.2 Estimation of the Global Power Consumption per Technology

*Backbone Only:*

For the Ethernet solution we assume 10 Ethernet switches leading to:

- A total cost of 41,590 Euros.
- A total power consumption of 874 W.

For the optical ring network based on X-Cast WDM ADM we assume 10 access nodes to interconnect imposing ten optical nodes, and one Ethernet switch (interconnection node) leading to a total power consumption of 267.4 W.

*Global Solution:*

For the global solution we take into account the backbone and the access points.

For the Ethernet LAN, for the optical solution adopting a Passive Optical LAN (based on a 100GPON) or an optical ring network and Wi-Fi + LiFi + OCC access points we have:

*For the Access Points:*

- Wi-Fi access points: 500 W.
- LiFi FWA points: 11 W (for the 12 drivers only). We assume an existing VL LED lighting system not included in the power budget.
- OCC access points: 50 W (250 mW max. estimated for one OCC driver).

*For the Backbone:*

- Ethernet LAN: 874 W
- Passive Optical LAN: 220 W
- Optical ring networks: 267.4 W

*For the End-to-End Solutions:*

- Ethernet LAN + WiFi: 1,374 W
- POL + Wi-Fi + LiFi FWA + OCC: 761 W
- OR + Wi-Fi + LiFi FWA + OCC: 828.4 W

Figure 7 gives an estimation of the power consumption of each solution analyzed:

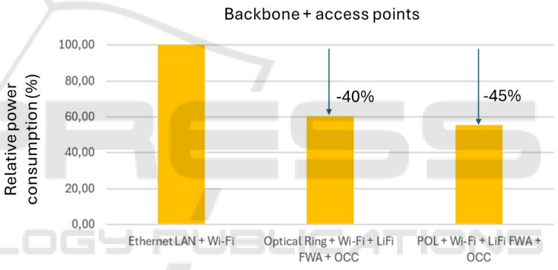

Figure 7: Comparison PON and Optical Ring Network with respect to Ethernet LANs.

We observe that the ring topology increases lightly the energy consumption when compared to a POL. However, the ring topology offers new services like M2M and provides higher capacity upgrades while being retro-compatible with POLs (possibility to multiplex a tree topology on the top of a ring topology). The Optical Ring/Bus network represents then an interesting candidate for wired and wireless solutions.

# 7 ANALYSIS OF THREE USE CASES

## 7.1 Description of the Use Cases

We analyse here three use cases: Hospitals or nuclear power plants, commercial centres and Industry 4.0.

- For use case 1 we assume that Electro-Magnetic (EM) emissions are constrained in hospitals. The EM waves are blocked in some areas of the hospital stopping the data continuity. In that particular use case, we compare then a solution based on a POL (based on a XGS-PON) and on a fully deployed LiFi technology in a specific area with respect to a classical LAN and a Wi-Fi technology.
- For use case 2, typically commercial centres, different technologies for added value services at low energy consumption are considered. This is a use case where the complementarity is really important. In that use case we adopt then a POL (based on a XGS-PON) for the fixed backbone part and LiFi FWA + Wi-Fi + OCC.
- For use case 3, typically the industry 4.0., a technology complementarity is also required. For that use case we adopte a ring optical network (with 10 Gbps access points) but supporting a 100 Gbps path through to support M2M communications. For the access points we assume a deployment of three access technologies: Wi-Fi, LiFi FWA and OCC. The LiFi deployment is considered only for a FWA configuration and is dedicated to the communication between the production machines and the network access points located in the ceiling. The Wi-Fi is used for mobility and to offer a large coverture. The OCC is used for the geo-localisation of robots.

For the three use cases, we adopted LiFi emitting in the VL domain or in the IR domain. For the LiFi IR we added the energy consumption of a new IR source which explains the difference with respect to the VL case.

In summary we analyse:

- Optical networks: POL or Optical rings LAN.
- Wi-Fi offering full coverage,
- LiFi in a FWA configuration when there is a need for new services (for more security, for more bit rate, when RF is not allowed),
- OCC to exploit the existing lighting to offer in-door positioning,

## 7.2 Results Obtained for the Three Use Cases Considered

We present here the results obtained (Figure 8) comparing heterogeneous technologies with a Wi-Fi technology associated to an Ethernet LAN.

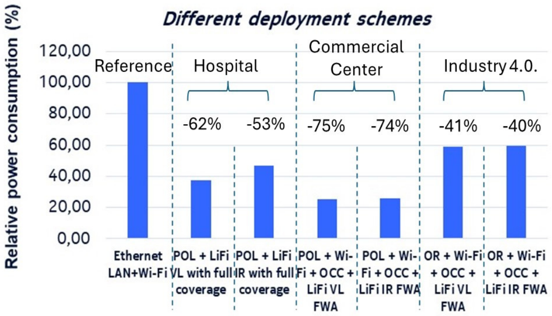

Figure 8: Energy consumption gain for the three use cases analysed.

When RF is not tolerated (like in hospitals), then the solution could be a combination of POL and LiFi (VL or IR). We observe, in the first scenario, that the electricity consumption gain could be close to 62% with respect to the reference scenario.

For commercial centres or airports, use case 2, there is a need to offer multi-services at low energy consumption. The association of Wi-Fi, LiFi in FWA (private pods are examples) and OCC is highly energy efficient. We demonstrate the possibility to offer more services at a low energy consumption thanks to the adoption of wired and wireless optical technologies.

For the industry 4.0, we assumed a global coverture through Wi-Fi, Optical ring networks to offer a sustainable backbone offering a convergence fixed-mobile, allowing M2M communications, and OCC for accurate in-door positioning of robots. LiFi IR FWA is adopted for highly secured high bit rate communications between production machines and the ceiling. 5G and 6G IoT complete the requirements. The technology complementarity is here quite efficient to offer multiple services combining LC and RF and to reinforce the security of sensitive data. It contributes also to limit the over dimensioning of the RF technology. We observe that the energy gain is less than for the two previous use cases but still higher than 40%.

# 8 CONCLUSIONS

We showed that the combination of wired and wireless optical technologies can provide significant advantages in terms of electricity demand reductions in addition to potential cost reductions and new service offers.

Optical networks based on PONs or optical rings/bus are excellent candidates to build an optical backbone for the interconnection of different networks elements (small cells or fixed access points) at a low TCO.

Light Communication (LC) technologies offer new possibilities in complementarity to Wi-Fi technologies and pave the way to a better energy efficiency. In the majority of deployments, it can be the optimal solution to offer a high QoS at a low energy consumption. The deployment will have to support heterogeneous configurations and LC is fully adapted to this heterogeneity (Perrufel M., 2021). The LC technology has definitively strong advantages like better security (the light does not cross the walls) and less power consumption.

For EM sensitive environments, the LiFi technology becomes an alternative to a Wi-Fi and more generally to a RF technology to create a continuity of service. The figure 8 showed that the association LiFi and OCC interconnected with an optical backbone is saving energies when compared to a Wi-Fi + Ethernet LAN solution. For this use case, POL are better positioned than Optical Ring LANs.

For commercial centres, the combination of different access point technologies is an efficient solution to offer new services at low energy. In that case, LiFi is deployed following a B2B market scheme, to have distributed points of information, through a FWA approach.

For the industry 4.0., here again, FWA makes sense, since there is a need for highly secured data communication between the production machines and the network. For the global coverture, the Wi-Fi can be used. OCC could be mandatory for the guiding of the robotic part. The new performance offered by the LiFi technology (high bit rates at high security) is the main catalyst for the solution adoption.

In general, for in-buildings the combination of optical networks, and heterogeneous access points will offer definitively new advantages and has the potential to provide a concrete answer to the electricity demand reduction needed as identified in the first part of this paper. Optical wired and wireless technologies pave definitively the path to sustainable solutions.

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