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Techno-Economics of LiFi in IoT Applications

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***Abstract*—This paper describes the first techno-economical study for the deployment of very dense wireless networks for new Internet of things (IoT) applications. We propose mobile optical wireless communication (OWC) also known as light fidelity (LiFi) because it offers unique advantages for the IoT such as robustness through exclusive channel access in the unlicensed optical spectrum, lower latency, and enhanced security. We investigate the deployment of LiFi in an industrial scenario, as currently specified by ITU-T recommendation G.9991, including the required fixed backbone and assuming full coverage. We propose six different LiFi topologies and compare them in different industrial scenarios. The comparison is performed in terms of Bill of Material, and in terms of costs. We show that a fully wired topology requires higher installation costs but incurs in lower operational costs, resulting in lower total costs of ownership (TCO) than other wireless topologies. Furthermore, power consumption has been identified as the cost driver for all topologies (more than 200% of the initial investments), triggering the need for power-saving techniques. Last but not least, the separation of Optical Front Ends (OFEs) has been identified as a critical design parameter, as shorter separation requires higher costs but reduces the cost per delivered bitrate. We discuss promising ways for the deployment of very dense wireless networks as key to bringing LiFi into future IoT applications.**

I. Introduction

Nowadays, wireless access to data networks has become a default requirement for many applications. In office applications, for instance, user devices typically rely fully on wireless connections. Low-cost implementation with Wi-Fi serves relatively large coverage areas per access point. However, Wi-Fi does not fully meet all requirements in industrial applications to serve an increasing need for real-time data and to support manufacturing or logistic processes. For example, machine-to-machine (M2M), last-yard, and smart vehicle control connections could be served more flexibly by wireless links. These require quality of service (QoS) similar to a cable, where the main challenges are real-time delivery and reliability, besides high data rate and high security [1]–[3]. Wi-Fi is fundamentally limited by its use of unlicensed spectrum, in which it is mandatory to "listen-before-talk". Here, other radio traffic may cause delays, thus is detrimental to timely delivery of critical control messages. Another issue is the radio medium. Industrial applications are sensitive to interference [2] which includes signals from other Wi-Fi access points penetrating through walls.

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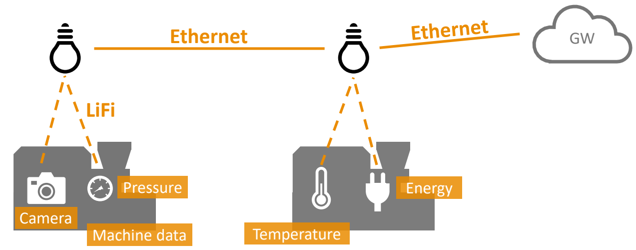

Fig. 1: Communication via LiFi cells in IIoT network: machines are wirelessly connected via the lamps of LiFi cells to the cable–based Ethernet network

Recent research investigated how to reach cable-like QoS over wireless media. High reliability is commonly achieved via redundancy, e.g. repetition in time and frequency, but these negatively impact data rate and latency. Yet, spatial diversity can solve this by coordinating multiple access points with overlapping coverage areas. Thereby, access points and users act as inputs and outputs, respectively, to a distributed multiple-input multiple-output (MIMO) link. This approach inherently allows seamless handover with low latency and zero packet loss. A proper combination of spatial diversity with deterministic channel access can realize timely packet delivery [4] [5] [6] [7].

5G is a promising technology to address these demands offering deterministic channel access as well as loss-less handover at low latency. However, 5G requires i) a spectrum license, ii) costly equipment and iii) complex core networking technologies. For 6G, however, traffic densities of Terabit/s in a few tens of square meters have to be handled at very low latency [8]. This requires very dense wireless networks with many access points serving mobile devices with cable-like QoS.

Here, we consider mobile optical wireless communications (OWC), also denoted as Light Fidelity (LiFi), as a complementary technology for the highest QoS requirements next to 5G. Light can deliver high-speed data, which is well-known from fiber-optics. LiFi operates in an unlicensed optical spectrum which is exclusive and not used by other wireless applications so far. Light propagates along the line-of-sight (LoS) and does not penetrate through walls, thus avoiding interference. In combination with deterministic, congestion-free channel access, e.g. dynamic time-division multiple access (TDMA)

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as defined by the ITU-T standard G.9991, data rates up to 2 Gbit/s with high QoS can be realized. LiFi can be received only inside the light cone (see Fig. 1). The LoS provides an additional security level, besides the commonly used protocols. A complementary advantage is that using the light creates no mutual interference with radio communication sources and services.

While the technology and advantages of very dense small-cell networks have been widely debated in the literature, the economical consequences were not yet studied. The objective of this paper is to investigate the economical consequences of future very dense wireless networks, far beyond current design practices for radio networks. We elaborate the case for LiFi in industrial applications. Note that directional mm-waves (60 GHz and up) will have similar opportunities and challenges to deliver high-speed data via a dense grid of access points.

In this paper, a first techno-economic framework is proposed, based on the dimensioning for different LiFi solutions. It allows to compare the total cost of ownership (TCO) and to identify the main cost drivers. The dimensioning of the complete (i.e., wired plus wireless) LiFi solution, which is our reference solution, is similar to optical access network solutions as they also have a tree topology [9]. The proposed framework can be used for a great variety of applications, for example, offices, hospitals, airports, and industrial. This paper focuses on implementation scenarios for LiFi in industrial applications.

The main contributions of this paper are: (i) five alternative LiFi solutions (wrt. the full wired solution), (ii) design and implementation of a techno-economic framework, which includes dimensioning, planning, and cost evaluation, and (iii) cost evaluation and comparison of the different LiFi solutions in the industrial scenario.

The remainder of this paper is organized as follows. Section II presents the LiFi architecture and how it is applied to the industrial scenario. This section also introduces the procedure to design and dimension the LiFi solution. Section III introduces the methodology to perform a techno-economic analysis of any proposed LiFi solution. This methodology has been applied to different implementation scenarios as presented in Section IV. Concluding guidelines are given in Section V.

II. LiFi Architecture and Network Design

A. *LiFi architecture*

Typically, LiFi access points are located at the ceiling and communicate to fixed or mobile IoT devices located underneath via the free LoS to at least one of the access points, see Fig. 2. The access points, which are denoted as light communications interface (LCI) are connected to a standard Ethernet switch, typically located at one or a few central positions in the manufacturing hall. LiFi signals are transmitted and received via multiple optical frontends (OFEs) illuminating the manufacturing hall with overlapping light cones to cover a larger area. The idea is to get full control over the transmission of all OFEs inside one room at the LCI, and thereby mitigate interference between the signals. While current implementations use analog splitters and combiners at the LCI side, future LCI implementations may be smarter and use joint multi-user MIMO signal processing of the OFE signals to improve performance [6], [10].

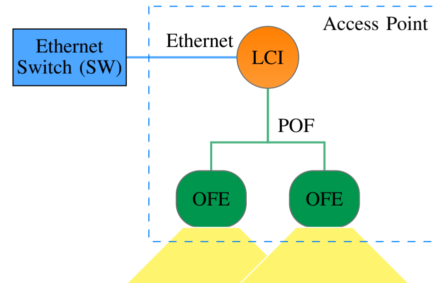


Fig. 2: LiFi architecture connected to Ethernet switch with light communication interface (LCI) and two optical front ends (OFE) that generate LiFi light beams.

Machines are usually connected by an Ethernet cable because it is a widely supported, reliable interface. However, fixed cabling limits the flexibility needed for the rearrangement of machines. Nowadays, mobile devices are networked via Wi-Fi because it became a de-facto standard for flexible mobile applications inside buildings. Nevertheless, in smart factories limitations of Wi-Fi are apparent, as outlined in Section I. Communication requirements for modern manufacturing scenarios with a focus on industrial data are described in [11].

LiFi uses the optical spectrum and allows for more than just communication, e.g. integrated and very accurate indoor positioning without further hardware installation [12]. Hence, LiFi is an interesting alternative for wireless communications in factories. Fig. 1 shows a scenario for LiFi-based IoT networks where machines and other devices connect wireless to the LiFi access points [11].

B. *Network design and cost parameters*

The LiFi network consists of several LiFi cells that are linked with the services network through an aggregation network providing backhaul communications. In typical arrangements, backhaul is realized through Ethernet cables to each of the LiFi cells, and concentration is achieved through Ethernet switches combining the traffic of multiple LiFi cells into a common interface towards the service network. The LiFi cell architecture is in Fig. 2 and detailed e.g. in [7].

The high spatial density of LiFi access points enables superior performance but causes economical challenges. There are not only the efforts to install and operate a high number of access points at the ceiling but also the demand to connect them to the service network requires extensive cabling and big aggregation switches. So far, the economical aspects of creating full coverage in factories through small-cell wireless access networks have not been thoroughly addressed.

Various aspects contribute to the total cost of ownership (TCO): i) the dimension of the factory hall, ii) the demand for communication bandwidth to sufficiently serve all the intended applications, iii) the technical parameters of the deployed LiFi technology like maximum throughput, coverage area, how many OFEs can be connected to one LCI, and iv) the structure and technology of the backhaul network.

While full wiring provides the highest performance, it is also the most expensive solution in terms of cable length and number of ports at the aggregation switch. More cost-effective solutions reduce the total cable length and the number of ports by leveraging a single Ethernet cable and switch port for multiple LCIs, and deploying point-to-point wireless links to multiple LCIs. Fig. 3 shows in (b), (c), and (d) three different examples of reducing the total length of the Ethernet cable and the number of switch ports.

Aside from the category of parameters reflecting the cost of the network infrastructure, there is a second category consisting of cost-related parameters such as the network operational time in years, the energy cost, two types of technician wages, the inflation rate per year ($p_{inflation}$) and the power saving scheme (i.e., weekly use of the network) as well as the cost of other operational parameters (required maintenance, failure rates, etc.) of the different equipment and infrastructure (i.e., OFE, LCI, switch, POF, Ethernet cable).

The costs of LiFi components (LCI and OFE) were estimated based on small–scale experimental prototypes manufactured at Fraunhofer HHI by assuming a typical cost reduction when producing on a mass scale. Commercial costs were considered for cabling and market costs were applied for other components. Table II lists all component costs used in the study.

C. Network dimensioning

The network dimensioning input data are the hall size as well as the clustering ratio (OFEs per LCI), OFE separation, and LCI capacity. Based on these data, the number of network components and cable length are calculated. The number and location of OFEs are determined based on the floor size and the OFE separation assuming a regular grid of OFEs. Furthermore, the number of LCIs is calculated by dividing the number of OFEs by the clustering ratio. The LCI location as well as the plastic optical fiber (POF) and Ethernet cable lengths depend on the clustering of OFEs. Throughput has been reduced at larger OFE separation based on experimental results. With the same OFE, larger cells have increased OFEs height and thus, reduced throughput.

The clustering algorithm generates clusters of OFEs. It aims at minimizing the distance between OFEs of the same cluster. Each OFE cluster will have one LCI collocated with the OFE closest to the switch or a central LCI for 3x3 star and 5x5 mesh topologies. Star and daisy chain topologies are considered to interconnect the OFEs with the corresponding LCI. They differ in the required POF length. Furthermore, the Ethernet cable length depends on the LiFi topologies depicted in Fig. 3.

Besides the fully wired topology, a second clustering is performed to generate clusters of LCIs. Each cluster has one LCI, the closest to the switch, connected to the switch with Ethernet cable. The remaining LCIs are connected to that LCI through wireless links (WL) (shown in the figure as dashed lines).

The result of the network dimensioning is the BoM, which includes the number of OFEs, LCIs, switches, and WLs as well as the POF and Ethernet cable lengths.

III. Methodology of Techno-Economic Analysis

The methodology used to perform the techno-economic evaluation of the proposed LiFi solutions, which has been implemented in an Excel/VBA based tool, is depicted in Fig. 4. Based on the different scenario and architecture parameters, the dimensioning of the LiFi solution is calculated resulting in the corresponding bill of material (BoM) as introduced in Section II-C. Then, the cost evaluation is performed based on the proposed operational Expenditures (OpEx) models introduced in the following section, and the provided cost parameters. The cost evaluation includes the total cost over the network operational time, the yearly cost evolution, and the cost categorization for capital expenditures (CapEx), OpEx, and the TCO. Furthermore, the proposed tool allows performing sensitivity analyses with respect to different parameters such as hall size, OFE separation, and power-saving schemes.

A. Cost models

This section proposes cost models for capital and operational expenditures. $CapEx$ is computed as the sum of the costs of all the devices required for a LiFi solution. It can be expressed as

$$CapEx = \sum_i CapEx_i \, , \tag{1}$$

by summing over $i \in \{OFE, LCI, SW, WL, Ethernet, POF\}$ as listed in Table II. The CapEx of each device type is

$$CapEx_i = m_i \times Cost_i \, , \tag{2}$$

where m_i is the number of such devices and $Cost_i$ their costs. The $CapEx$ of Ethernet and POF is the length of the cable times the cost per meter. The CapEx in (1) is the initial one (i.e., $t = 0$). During the network operation, devices will be replaced according to their lifetime and hence, their CapEx will be considered again in the replacement year.

The planning costs are modeled by using $p_{Planning}$ as the proportionality parameter, i.e.,

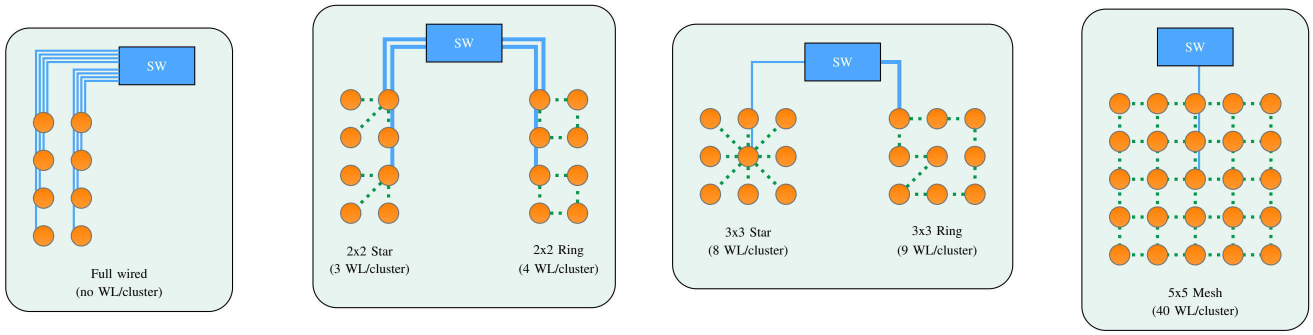
$$C_{Planning} = p_{Planning} \times CapEx_i \, . \tag{3}$$

OpEx are computed per component and distinguished into installation, maintenance and energy costs $C_{Inst,i}$, $C_{Maint,i}$ and $C_{Energy,i}$, respectively.

Installation costs at $t = 0, T_{life,i}, 2T_{life,i}, ..$ are obtained as

$$C_{Inst,i} = m_i \cdot t_{Inst,i} \cdot n_{i,z} \cdot w_z \, , \tag{4}$$

where $t_{Inst,i}$ is the installation time, $n_{i,z}$ is the number of technicians of type z required for the installation and w_z is the wage. Device replacement at the end of lifetime ($T_{life,i}$, in years) is considered to equal the initial installation cost.



(a) Full wired (FW) LCI

(b) 2x2 clusters with star (left) and ring (right) topology

(c) 3x3 clusters with star (left) and ring (right) topology

(d) 5x5 mesh cluster

Fig. 3: Illustration of the different LiFi topologies. The orange circle, the blue line and the green dotted line represent LCI, Ethernet cable and wireless (WL) links respectively.

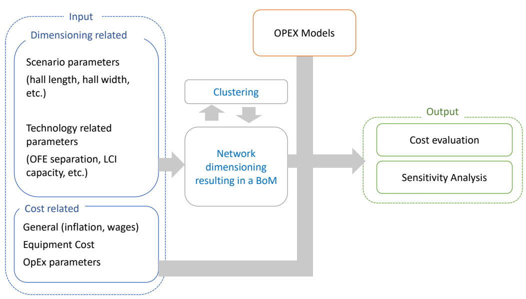


Fig. 4: Overview of the techno-economical tool.

Maintenance costs per component ($C_{Maint,i}$) are given by

$$C_{Maint,i} = m_i \cdot t_{Maint,i} \cdot N_i \cdot n_{i,z} \cdot w_z \,, \tag{5}$$

where $t_{Maint,i}$ is the maintenance time, $n_{i,z} \cdot w_z$ the hourly labor costs and N_i the required maintenance frequency (times per year). Energy costs per component ($C_{Energy,i}$) are equal to

$$C_{Energy,i} = m_i \cdot P_i \cdot P_u \cdot \frac{365 \cdot 24}{1000} \cdot p_{Activity} \,, \tag{6}$$

where P_i is the energy consumption, $p_{Activity}$ the activity percentage and P_u (€/kWh) the energy cost of that year.

B. Cost analysis

The TCO is the sum of all the incurred costs in year $t = 0$, i.e., purchase, planning, and installation, and during the operational time T ($t = 1, 2, ...T$), i.e., energy, maintenance, and any required device replacement, i.e.,

$$TCO = \sum_{t=0}^{T} (CapEx(t) + C_{Planning}(t) + C_{Inst}(t) + C_{Maint}(t) + C_{Energy}(t)) \,. \tag{7}$$

Operational costs are subject to inflation due to e.g., increase in salaries and increase in energy costs. For example, $C_{Maint}(t)$ can be computed as

$$C_{Maint}(t) = C_{Maint} \cdot (1 + p_{Inflation})^{t-1} \,. \tag{8}$$

The yearly cost per delivered capacity TCO_{dc} (in €/Mbps)

$$TCO_{dc} = \frac{1}{T+1} \cdot \frac{TCO}{c_{LCI} \cdot \frac{a_{hall}}{a_{LCI}}} \tag{9}$$

depends on LCI capacity c_{LCI} (in Mbps) and the ratio of the hall area a_{hall} and the LCI coverage area a_{LCI}, both in m^2.

IV. Results and Discussion

This section compares the 6 network topologies introduced in Section II for the reference industrial scenario of Table I. In this scenario, the number of OFEs and LCIs are 240 and 32, respectively, while the length of the POF depends on the topology: 980m and 416m for star and daisy chain topologies, respectively. Obviously, daisy-chaining cuts cabling costs. Furthermore, the 6 proposed LiFi topologies shown in Fig.3 differ in terms of the Ethernet cable length as well as on the number of WLs, as shown in Table III. E.g., it can be observed that the 5x5 Mesh topology requires more WLs but shorter Ethernet cable.

TABLE I: Reference Scenario

Operational time T	8 years	Hall size a_{hall}	30mx32m
Techn. Wage A	30€/h	Techn. Wage B	60€/h
$p_{Inflation}$	3%/year	$p_{Activity}$	100%
OFE Separation	2m	Clustering ratio	max. 8 OFE/LCI
LCI capacityc_{LCI}	150Mbps	Energy cost P_u	0,2€/kWh

Fig. 5 shows the cost evolution over an operational time of eight years for each solution. The first year consists only of investment costs. The full wired solution incurs the highest costs to install longer cables. However, from the second year on, operational costs fall below that of the other solutions. The TCO, calculated with Eq. 7, has the lowest value with the full wired solution (66.422€), whereas it is maximum with the 5x5 Mesh solution (72.839€). This figure also shows an increase in costs in 2026 mainly due to the OFE replacement (based on the lifetime given in Table II.

TABLE II: LiFi Reference Values

Device	Cost [€]or [€/m]	$p_{planning}$	Power [W]	Lifetime T_{life} [years]	Installation t_{Inst} [min]	$n_{i,z}$	Personnel (z)	Maintenance Times/year (N_i)	t_{Maint} [min]	$n_{i,z}$	Personnel (z)
OFE	20	10	7	4	10	1	A	1	5	1	A
LCI	40	15	7	5	10	1	A	1	5	1	A
Switch	300	20	5	10	20	1	B	1	60	1	B
WL	40	10	12,25	4	10	1	A	1	5	1	A
Ethernet	0,2	5	0	20	10	1	B	0	30	1	B
POF	0,1	10	0	20	10	1	B	0	30	1	B

TABLE III: Reference Scenario: Topology comparison in terms of Ethernet cable length, number of WL and TCO.

	Full Wiring	2x2 Ring	2x2 Star	3x3 Ring	3x3 Star	5x5 Mesh
Eth. [m]	910	250	250	88	132	76
WL	0	30	23	31	28	48
TCO [€]	66422	69016	66838	67673	67189	72839

To identify the cost drivers in each LiFi solution, Fig. 6 depicts the five cost categories described in Section III-A. It can be observed that the energy cost is the dominant cost for all LiFi solutions if the network is operated 24/7 (i.e., $p_{Activity} = 100\%$). However, the energy costs are less than the initial investment if the network is operated one third of the time (i.e., $p_{Activity} = 33\%$). This fact shows the high impact of power consumption on the choice of the solution and the potential benefits of power-saving schemes.

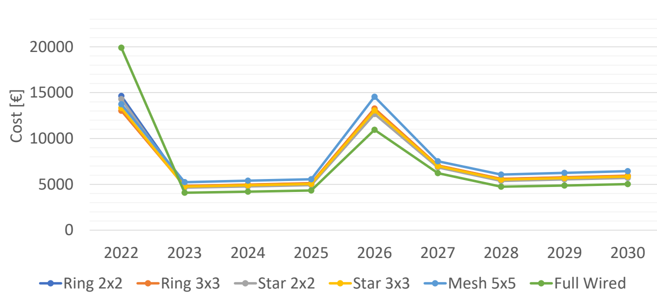


Fig. 5: Cost evolution over operational time of 8 years for different LiFi topologies.

Next, we consider the impact of the OFE separation and the corresponding LCI capacity. Table IV lists the required hardware for OFE separations 1m, 2m, 3m, and 4m, with an LCI capacity of 400Mbps, 300Mbps, 200Mbps, and 100Mbps respectively. Rate versus distance has been reported for LiFi modules with one LED and one photodiode in [13]. Recent LiFi modules with 4 LEDs and 5 photodiodes reach higher values listed in the table. Fig. 7 and Fig. 8 show the impact of the OFE separation on the number of wireless links and the Ethernet cable length. For all topologies, an exponential decrease in both, the Ethernet cable length and the number

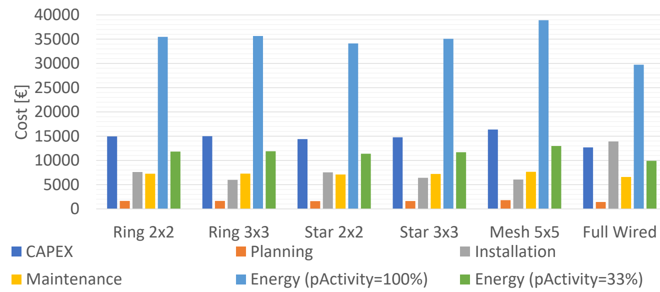


Fig. 6: Costs per category with energy costs for activity percentages 100% and 33%.

of wireless links can be observed when increasing the OFE separation.

TABLE IV: Bill of Material for different values of OFE separation, LCI capacity and total hall capacity.

OFE Sep [m]	1	2	3	4
$c_{LCI}[Mbps]$	400	300	200	100
$a_{LCI}[m^2]$	8	32	72	128
No. of OFE	960	240	110	64
No. of LCI	121	32	15	8
Hall cap. $[Gbps]$	48,4	9,6	3	0,8
POF Star [m]	1977	980	705	544
POF Daisy [m]	839	416	285	224

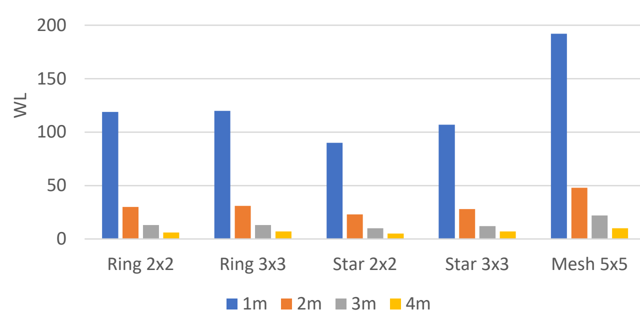


Fig. 7: Number of wireless links (WL) for different LiFi topologies and OFE separations 1m, 2m, 3m, and 4m.

Due to a higher amount of hardware, TCO increases for smaller OFE separation, as shown in Fig. 9. However, OFE separation is related to the delivered LCI capacity, as shown in

Table IV. Moreover, the smaller the OFE separation, the more LCIs operate in parallel, thus effectively reusing the optical wireless spectrum. Hence, the operator should compare the cost per delivered capacity in the whole manufacturing hall, which is shown in Fig. 10. Interestingly, the yearly TCO_{dc} is reduced with smaller OFE separation. Note also that the yearly TCO_{dc} does not differ significantly among the different LiFi solutions.

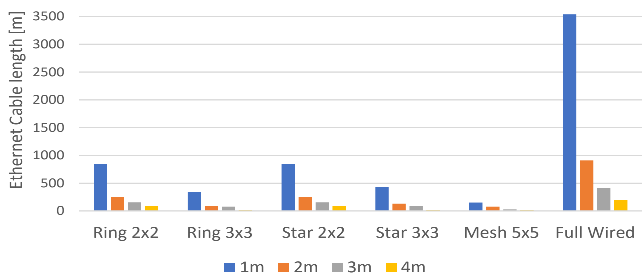


Fig. 8: Ethernet cable length for different LiFi topologies and OFE separations 1m, 2m, 3m, and 4m.

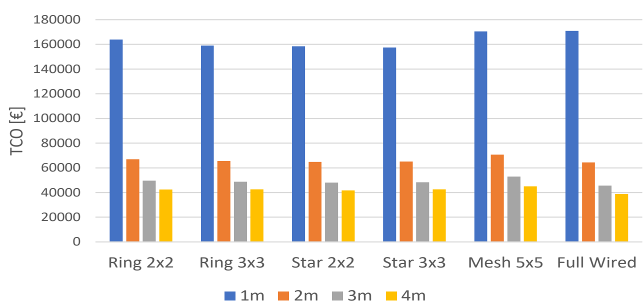


Fig. 9: Total costs of different LiFi topologies for OFE separations 1m, 2m, 3m, and 4m.

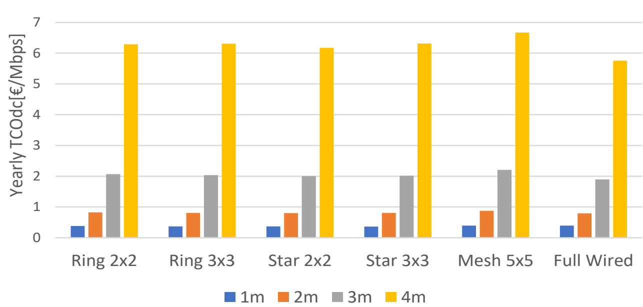


Fig. 10: Yearly TCO_{dc} for different LiFi topologies and OFE separations 1m, 2m, 3m, and 4m.

V. Conclusions

Densifying the network to provide high-performance wireless access for IoT devices comes with substantial costs in providing a backbone infrastructure. Although we studied this for optical wireless communication, the issue is broader and applies also to radio-based access when very dense deployment of access points is demanded, as the principal network architecture is the same and the cost and power consumption of radio access points are similar. We compared six different LiFi network topologies all providing full coverage in a large manufacturing hall, but the model can be applied to other cases such as hospitals, airports, etc. The results over 8 years of operational life show that full wired solutions need 40% more initial investments than wireless solutions, mainly due to the high installation costs of the cables. However, the lower operational costs of the full wired solution result in lower TCO. Moreover, energy is the main operational cost driver. When using the network 24/7, the energy cost is more than 230% the initial investment. This fact should encourage manufacturers to implement energy-saving schemes and reduce the power consumption of access points and wireless links. Third, there is a trade-off between the required Ethernet cable, which incurs higher installations costs, and the higher power consumed by wireless backhaul links. Interestingly, when dimensioning the network, the cell separation has been identified as the most critical parameter. Of course, the required infrastructure costs are higher, if the network is denser. But the delivered capacity grows faster than these infrastructure costs. Thus, the costs per delivered capacity are lower, when reducing the cell size.

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