Cost Analysis of Mode Division Multiplexing Bidirectional Transmission System

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Abstract—**This paper presents a cost analysis and performance evaluation of a Mode Division Multiplexing (MDM) system with Power Over Fiber (PWoF) for bidirectional transmission, to support high-capacity data and centralized power distribution in mobile networks. Two configurations are proposed: an unsymmetrical Multicore Fiber (MCF) and a Double Clad Fiber (DCF). The MCF setup features separate data and power transmission cores, reducing inter-core crosstalk, while the DCF setup combines data and power within a single fiber to simplify deployment. A cost model is developed to compare the capital expenditures (CapEx) of each configuration, revealing an estimated cost of 322,000 Euros for the MCF system and 212,000 Euros for the DCF system. Given that MDM technology is still in the research phase, commercially available equipment is limited, contributing to high initial costs. However, similar to Dense Wavelength Division Multiplexing (DWDM), the price of MDM is expected to decline over time as the technology matures. Additionally, both configurations leverage PWoF to centralize power generation at the Central Office (CO), enabling the use of renewable energy sources and supporting sustainable network infrastructure. This study highlights the potential of MDM with PWoF as a cost-effective, environmentally friendly solution for future high-capacity mobile networks.**

Index Terms—**Cost Model, Few-Mode Fiber, In-Building Solutions, Double Clad Fiber, Mode Division Multiplexing.**

I. Introduction

The rise of LTE-based radio access networks has put the spotlight on Cloud Radio Access Network (CRAN) due to its potential for reducing both operating and capital costs for 5G and 6G networks. [1]. In CRAN, the Remote Radio Unit (RRU) and Baseband Unit (BBU) are separated, with the centralized BBU pool handling the processing, control, and management of a large number of RRUs. The link between the RRUs and BBUs, known as fronthaul, uses the Common Public Radio Interface (CPRI) for digital data transmission[2]. To keep up with the high demands of 4G/5G mobile communication services, especially those using Multiple Input Multiple Output (MIMO) antennas, WDM has been proposed as a solution for transporting CPRI data over the fronthaul. WDM is a good fit here because it provides high spectral efficiency, service transparency, and energy savings.

When it comes to deploying and maintaining systems on the RRU side, cost-effectiveness and colorless operation are essential for WDM-based fronthaul. However, the proposed laser sources for RRUs are expensive, which raises concerns about their commercial viability [3]. MDM has attracted considerable interest as a promising solution to boost transmission capacity. This approach has been widely researched for high-speed optical transmission and access networks, aiming to support a larger number of users [4]. Unlike WDM, systems based on MDM are colorless by its nature, allowing them to be well-suited for network applications that need colorless operations. This feature can potentially lead to cost savings for the RRU [3]. Moreover, compared with the other emerging techniques like Space Division Multiplexing (SDM), MDM ensures higher spectral efficiency by utilizing multiple modes in a single fiber or core which will reduce the fiber footprint, thus reduces the cabling complexity compared to the parallel single mode or multimode fiber in SDM [5]. Additionally, powering the RRUs poses a challenge that can add to their complexity and, in turn, increase manufacturing costs [6]. To address the challenge of power, this research incorporates the PWoF concept. PWoF is a simple solution for transmitting both optical data and power over a single optical fiber. In mobile networks, PWoF offers a dual function: it supplies power to RRUs from a CO [6] while consolidating the power source within the CO. This approach is compared to other wireless domain solutions, such as the energy transfer methods in Radio Frequency ID (RFID), Near Field Communications (NFC) applications [7], or the use of several Power Stations (PSs) for energy transfer in Wireless Powered Communication Networks (WPCN) [8]. Adopting the PWoF approach helps reduce overall system complexity and lowers operational costs in mobile networks.

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II. Motivation

The rapid expansion of mobile networks, driven by 5G and beyond, demands high-capacity, cost-effective, and energy-efficient solutions. While WDM has been widely adopted for optical fronthaul, its reliance on wavelength-specific laser sources increases system costs and complexity. MDM presents a compelling alternative by enabling multiple data streams to share a single fiber, reducing the dependency on costly wavelength-tuned components. Another challenge in mobile fronthaul is power distribution to RRUs. Traditional methods require distributed power stations, adding operational overhead. PWoF with MDM centralizes power generation at the CO, simplifying deployment and lowering infrastructure costs. Despite its advantages, MDM adoption faces technical hurdles, such as modal dispersion and crosstalk, which require advanced Digital Signal Processing (DSP) techniques. This study evaluates the cost-effectiveness of MDM with PWoF, comparing different fiber configurations to assess its feasibility for mobile networks.

III. RELATED WORK

MDM has been widely investigated as an alternative to WDM for increasing transmission capacity. Chen et al. [3] demonstrated bidirectional mobile fronthaul using MDM, showcasing its ability to eliminate wavelength-specific dependencies. Mercy Kingsta et al. [9] explored multi-core and few-mode fiber implementations, proving their potential for high-capacity optical communication.

One of the main challenges of MDM is modal dispersion and crosstalk, which degrade signal integrity. Alon et al. [10] proposed equalization techniques, while Yaman et al. [11] demonstrated the advantages of Few-Mode Fibers (FMF) in reducing interference. Despite these advances, MDM is still in the research phase, with limited commercial deployment due to high initial costs and the need for complex DSP techniques. Li et al. [12] examined the CapEx advantages of multi-core fiber networks, concluding that as the technology matures, costs will decrease. This study extends existing research by providing a detailed cost model for MDM-based mobile fronthaul with PWoF, evaluating its feasibility against traditional solutions.

IV. SYSTEM CONCEPT

MDM has recently attracted significant attention as an alternative technology to increase transmission capacity in high-speed optical transmission and access networks, enabling support for more users [3]. In MDM, light modes are orthogonal, allowing each mode to act as a distinct data carrier channel. This contrasts with conventional approaches in Single Mode Fibers (SMF) and Multimode Fibers (MMF), where the light itself serves as the data channel without multiplexing, or techniques like Coarse WDM (CWDM) and DWDM, where channels are separated by wavelength. MDM utilizes the multimode properties of MMFs to expand the number of data channels, though employing MMFs for long-distance transmission can result in energy transfer between modes, causing crosstalk and modal dispersion [10]. These effects degrade the quality of received data, leading to increased Bit Error Rate (BER) and limiting the achievable bandwidth-distance product [10]. To mitigate crosstalk and modal dispersion, FMF have been developed. FMFs have a core size that is larger than SMFs but smaller than MMFs, supporting only a limited number of modes, which helps reduce crosstalk and improve transmission quality [11].

Despite the advantages of MDM, several challenges remain that prevent its widespread commercial adoption. The processes for multiplexing and demultiplexing light modes are still evolving and require further research. Furthermore, sophisticated DSP techniques are needed to manage crosstalk and control modal dispersion, adding complexity to the system [13]. Figure 1 shows a mobile fronthaul system utilizing MDM, where each RRU is assigned a specific mode over a few-mode fiber in a shared session. This MDM-based system is inherently colorless, unlike WDM, making it well-suited for network applications that require colorless operation [3]. There remains potential to further improve MDM-based mobile systems.

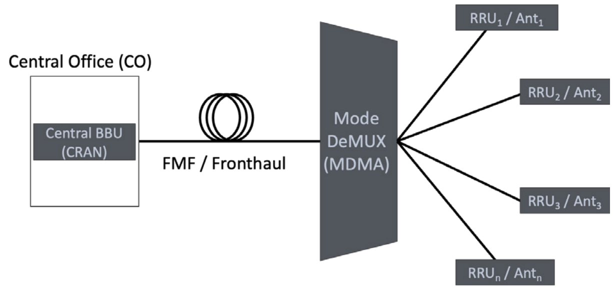

Fig. 1. Mobile System

We present an MDM system designed for bidirectional and symmetrical high-speed mobile fronthaul applications. In this configuration, one spatial mode transmits the signal carrier from the BBU pool, while another mode is utilized for downstream signal channels.

Unlike conventional wavelength-reused techniques, this system achieves symmetrical bidirectional transmission without introducing re-modulation crosstalk. Figure 2 depicts the proposed setup, showcasing the carrier along with RF/DL and RF/UL branches as part of the design.

Two optical modes are generated and delivered to the RRU through a FMF. The second mode, responsible for carrying downlink information, is detected at the RRU, amplified, and filtered before being sent as a radio frequency signal to the antenna. For the uplink, the signal collected from the antenna is filtered, amplified, and then used to modulate the first optical mode originating from the central unit. This modulated first mode is then directed back into the FMF using an optical circulator.

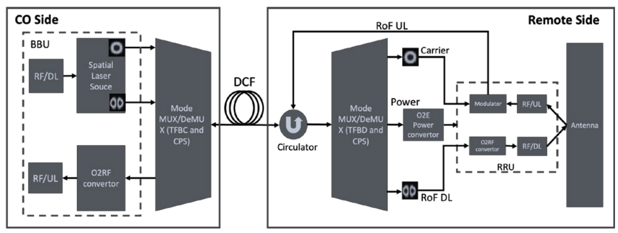

Fig. 2. Conceptual Model

To further simplify the RRU system, the proposed setup integrates the PWoF concept, where the RRU is powered by optical energy generated at the CO, as shown in the power branch of Figure 2. This centralizes the power source at the CO, allowing mobile operators to manage power resources independently without depending on third parties. This approach is anticipated to reduce Operating Expenditures (OpEx), as discussed in later sections of this paper.

V. IMPLEMENTATION CHALLENGES

The suggested system comes with several technical challenges, which must be investigated and solved.

A. Double-clad and MultiCore few-mode fiber

The cost model under discussion in this study suggests using two types of waveguides. Dual Clad Fiber (DCF) where this concept provides the transmission of power required to drive the RRUs. Recent literature on this context shows that to obtain the high power required to drive the RRUs; larger fiber cores are needed, as the upper limit of the ultimate fiber damage power density is around 5 MW/cm² [14][15]. Moreover, the second approach suggests the use of Multicore Fiber MCF with two unsymmetrical cores, one ordinary FMF core for data transmission and another larger core for power transmission due to the same reasons mentioned earlier [14] [15].

A related concept is discussed in [15], where MCF with symmetrical core diameters is proposed instead of using DCF or asymmetrical MCFs. The approach explores two scenarios: in the first, one or more cores are dedicated to delivering the power needed to operate the RRU, while the remaining cores handle data transmission. In the second scenario, the same cores are shared for both power and data transmission simultaneously. Optical fibers with larger cores offer an advantage, as they can safely carry more power without the risk of damage. However, when high-power light is injected into small-core optical fibers, nonlinear effects like Stimulated Brillouin Scattering (SBS) and Stimulated Raman Scattering (SRS) may occur, significantly degrading the quality of concurrent data transmissions [6].

B. Required RRU Power

The PWoF link is constrained by the efficiency of both the optical source and the power converter at the RRU. Table 1 presents the power requirements of commercially available RRUs from various vendors.

TABLE I.
NEEDED POWER FOR THE COMMERCIAL RRUS

Model of RRU	Required Power	Manufacturer
Flexi MultiRadio 10	Up to 1KW	Nokia [16]
5G+4G Dot 4475	55W	Ericsson [17]
Street Macro 6701	Up to 400W	
AIR 1281	Up to 125W	
AIR 5322	Up to 220W	

Currently, available High-Power Laser Diodes (HPLDs) and Photovoltaic Converters (PPCs) require further research and testing to improve their conversion efficiencies. According to [18], efforts are being made to increase High-Density Laser Power (HDLP) efficiency to 74.7%, as current commercial laser sources reach only about 40%. For optimal Power Transmission Efficiency (PTE), the transmission wavelength should fall within the 8XX nm or 9XX nm range [19]. Additionally, the operating wavelength of the Photovoltaic Power Converter (PPC) must match the transmitted wavelength [19]. In [14], an optical feed of 150W is considered where several HDLPs used by coupling them into the fiber using Tapered Fiber Bundle Combiner (TFBC) and Divider (TFBD); Cladding Power Stripper (CPS) is used to separate the power feed from the data signal. Despite of the injected 150W, only 29.1W is transmitted to the DCF, yielding a PTE of 19.46%. On the receiving end, this results in an electrical power output of just 7.08W, with a PTE of 4.84%. Table 2 below summarizes the parameters of these power components.

TABLE II.
POWER COMPONENTS PARAMETERS

Component	Conversion Efficiency	Manufacturer
Commercial PPC	50% O/E	[20]
Commercial HPLD	40% E/O	[21]
Under research HPLD	74.7% E/O	[18]

Implementing this concept enables a compact RRU design, reducing overall system costs by moving many RRU functions to the CO, which further decreases RRU complexity and cost. Additionally, using the Radio over Fiber (RoF) approach helps minimize latency and increase capacity [22]. However, transmitting power and data simultaneously over the same fiber can lead to energy transfer from the inner, smaller core of the DCF to the outer, larger core, resulting in crosstalk, which can severely affect the quality of the received data. Recent research on PWoF using DCF is discussed in [23].

This research focuses on optimizing energy transfer from the "inner cladding" to the fiber core by identifying the ideal fiber design that maximizes energy absorption in the core. According to the study, certain fiber designs allow "skew-rays" to exit, which negatively affects the system by reducing energy absorption. These optical rays travel in a helical path around the fiber axis without entering the core, diminishing overall efficiency [23]. Moreover, in the case of using unsymmetrical MCF, less crosstalk is expected.

C. Modulation Bandwidth of few-mode transmission

As outlined in Section II, two light modes are necessary, one is designated for the uplink and the other for the downlink. The RF signals from both ends are transmitted via these optical signals using RoF technology. Each mode is modulated according to its respective RF signal, with the downlink signal from the BBU, and the uplink signal from the antenna. The required bandwidth varies depending on the specific mobile communication technology (4G, 5G, or 6G). Table 3 below lists the bandwidth requirements for each technology [24].

TABLE III.
POWER COMPONENTS PARAMETERS[24]

Technology	RF Frequency	Data Capacity
3G	1.6-2.5GHz	385Kbps-30Mbps
4G	2-8GHz	200Mbps-1Gbps
5G	>6GHz	>Gbps

D. Intra-Core and Inter-Core Crosstalk

Although crosstalk is reduced with FMF, energy still couples between modes during propagation [25], impacting the received signals for both downlink and uplink [26]. Proper DSP is needed to mitigate the effects of this crosstalk [27]. The intra-core crosstalk of a similar system has been extensively studied in a previous work where systems with FMF supporting two and four modes were considered [28]. Results show that the higher the order of the mode, the more crosstalk is observed, resulting in one of the main constraints of MDM systems. Moreover, in a system where MCF is adopted, inter-core crosstalk between the adjacent cores is expected. Fortunately, many literatures studied this issue proposing solutions to mitigate it by optimizing core and spectrum assignment [12]or by using MIMO algorithms [29].

VI. APPLIED OPTICAL WAVEGUIDES

We suggest using a specialized DCF with an FMF in the inner core, supporting two modes—one for downlink and one for uplink transmission—while the larger outer core is reserved for power signals. As outlined, the proposed system requires the excitation of two modes in the FMF, factoring in the Numerical Apertures (NAs) for commercially available DCFs of similar specifications [30]. Using the normalized frequency (V) equation, the required inner core diameter is calculated to be 10 µm. Alternatively, calculations can yield the same result by using core and cladding refractive indices from [31], where n1 = 1.45 and n2 = 1.44 at 1550 nm. For power transmission, the outer core of the DCF, with a diameter of 200 µm, is utilized. Additionally, an asymmetrical MCF will be considered in the second scenario, with cores similar to those in the DCF. In the DCF scenario, multiple HPLDs will be injected into the DCF in parallel. The design leverages commercially available HPLDs and PPCs; PPCs operate at 8XX nm with 50% optical-to-electrical (O/E) conversion efficiency [20], while HPLDs operate at 808 nm, handling a maximum input power of 100 W with 40% electrical-to-optical (E/O) conversion efficiency [21].

VII. SYSTEM COST MODEL

In this section, a cost comparison between the current DWDM commercial systems, DWDM system with PWoF on a dedicated fiber, and MDM with PWoF on a single fiber are shown. Regarding the DWDM system, a 40 channel DWDM system capable of handling a traffic of 400Gbps (40X10Gbps) is considered. On the other hand, an MDM system with the same capacity has been considered as well.

A. DWDM System

As previously mentioned, DWDM is the multiplexing technique of choice that being used for several years to handle the high-capacity needs of mobile networks. Having an exact cost for the DWDM system can vary depending on several business wise factors, vendors, and the location where these systems are implemented. However, and easier approach of having this calculation can be done by dividing these systems to the main parts that have the significant impact on the total cost. As compared with any other data transmission system.

A DWDM system consists of a transmitter, Medium, and a receiver. For the transmitter part, it is usually consisting of a laser source, multiplexer, and an optical amplifier. On the other hand, a receiver is consisting of a demultiplexer and photo detection device plus an amplifier. The component of a typical bidirectional DWDM system is showing in Figure 3 below.

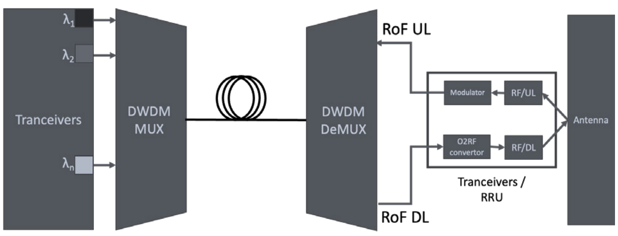

Fig. 3. DWDM System

Based on the above, the below formula can be used for the cost model:

$$\begin{aligned}\text{Total System Cost} &= (N_{Tx} \times C_{Tx}) + (N_{Rx} \times C_{Rx}) \\ &+ \left(N_{Mux/Demux} \times C_{Mux/Demux}\right) \\ &+ \left(N_{Amplifiers} \times C_{Amplifiers}\right) + \\ &+ (L_{Fiber} \times C_{Fiber})\end{aligned}$$

Where:
N_{Tx} Number of Transmitters
C_{Tx} = Cost per Transmitter
N_{Rx} = Number of Receivers
C_{Rx} = Cost per Receiver
$N_{Mux/Demux}$ = Number of Mux/Demux units
$C_{Mux/Demux}$ = Cost per Mux/Demux unit
$N_{Amplifiers}$ = Number of Amplifiers
$C_{Amplifiers}$ = Cost per Amplifier
L_{Fiber} = Total length of fiber cable (in meters)
C_{Fiber} = Cost per meter of fiber cable

In 5G networks, download speeds are anticipated to reach up to 20 Gbps, with upload speeds achieving 10 Gbps on average[32]. For a Four-floors building with approximately 40 active users simultaneously online, this would necessitate a data throughput of around 400 Gbps. Assuming a distance of 15 km between the building and the CRAN pool at the mobile operator's premises, the cost model in this study has been calculated accordingly to account for the infrastructure and operational demands over this span and as shown in Table 4 below.

TABLE IV.
DWDM COST MODEL

System Part	Price	Quantity	Manufacturer
Transceiver	308€	40	FS.com [33]
40CH MUX	2420€	1	FS.com [34]
Amplifier-Near-end	2808€	1	FS.com [35]
Fiber / m	1.5€	15000	ThorLabs.com [36]
Amplifier – Far-end	2808€	1	FS.com [35]
40CH DeMUX	2420€	1	FS.com [35]
Transceiver	308€	40	FS.com [34]

Based on the previous information, a DWDM system costs around 57 thousand Euros of CapEx excluding the labor cost of the fiber implementation as they vary a lot depending on the country where the system is being implemented considering no impact on the system cost itself and as follow:

$$\begin{aligned}\text{Total Cost} &= \text{Total system cost} \\ &+ (\text{labor cost per Km} \times \text{Fiber Length}\end{aligned}$$

Moreover, according to Eurostat website [37], the electricity average cost in Europe in 2023 is about 0.2€ per KWh. For Ericsson AIR 5322 [17] shown in table 1 above, the total power OpEx needed to drive this device is about 520€ yearly with a total of 2080€ yearly assuming installing one device per floor.

B. DWDM system with PwoF on a dedicated fiber

This system is similar to the previous one, however, it has the capability of handling PWoF on a dedicated optical fiber to drive the RRUs.
Table 5 below shows the cost model of the additional equipment needed for the power side.

TABLE V.
PWOF COST MODEL

System Part	Price	Quantity	Manufacturer
HPLD	3122€	1	laserdiodesource.com [21]
Large Core Optical Fiber	0.95€	15000	Thorlabs.com [38]
PPC	10000€	1	MHGOPOWER.com [39]

The cost of the system is 57,000 Euros for the DWDM system plus 27,000 Euros for the power system, with a total of about 85,000 Euros excluding the labor cost of the fiber implementation.

C. Bidirectional MDM system with PWoF over Unsymmetrical two cores MCF

This section shows the cost model of the first proposed system of this study where MDM system is being adopted with a two-core unsymmetrical MCF. Smaller two-modes FMF core for the data transmission and larger core for the power transmission, and as shown in Table 6 below.

TABLE VI.
MDM WITH UNSYMETRICAL TWO-CORES MCF

System Part	Price	Quantity	Manufacturer
MDM Spatial Laser Source	12000€	2 (1/mode)	ThorLabs [40]
Photo Detector	350€	2 (1/mode)	ThorLabs [41]
MCF Fan-in	3500€	2	FiberCore [42]
MUX	7000€	1	CabiLabs [43], [44]
MultiCore FMF / m	18€	15000	FiberCore [42]
DeMUX	7000€	1	CabiLabs [43], [44]
HPLD	3122€	1	laserdiodesource.com [21]
PPC	10000€	1	MHGOPOWER.com [39]

As MDM is an emerging transmission multiplexing technique, optical amplifiers were not considered to reduce the system's cost for the relatively short fronthaul transmission, however, they can be used for long-haul ones to achieve higher distances. Moreover, laser sources (SLMs) prices are quite high due to the fact that they are currently available for lab usage only. Based on the above, the MDM system over 15 Km costs around 328,000 Euros of CapEx excluding the labor cost of the fiber implementation.

D. Bidiretional MDM system with PWoF over DCF

This system is similar to the previous one with the difference of using different types of fiber where DCF is being utilized. As mentioned earlier, DCF can reduce the complexity even more as both power and data will be carried on the same fiber simultaneously. The cost model is shown in Table 7 below.

TABLE VII.
MDM WITH DCF

System Part	Price	Quantity	Manufacturer
MDM Spatial Laser Source / Mode	12000€	2 (1/mode)	ThorLabs [40]
Photo Detector /Mode	350€	2 (1/mode)	ThorLabs [41]
MDM MUX	7000€	1	CaiLabs [43], [44]
DCF / m	11.6€	15000	ThorLabs [30]
MDM DeMUX	7000€	1	CabiLabs [43], [44]

Based on the above, this MDM system cost around 212 thousand Euros of CapEx excluding the labor cost of the fiber implementation.

VIII. RESULTS AND DISCUSSION

This study evaluates two configurations for MDM with PWoF: one based on DCF and the other on an unsymmetrical MCF. Each configuration offers distinct cost, performance, and sustainability benefits that make them promising solutions for high-capacity, centralized power transmission.

The DCF configuration, with an estimated CapEx of 212,000 Euros, consolidates both data and power transmission within a single fiber, simplifying infrastructure and reducing deployment complexity. In contrast, the MCF setup, with a projected cost of 322,000 Euros, separates data and power channels into distinct cores, which enhances resilience to interference and minimizes inter-core crosstalk. This unsymmetrical design is particularly advantageous for high-data-rate applications due to its added layer of signal isolation. A critical consideration for both configurations is crosstalk.

In the DCF system, intra-core crosstalk occurs when power and data signals interfere within the same core, which can degrade signal quality and increase the BER. Additionally, inter-core crosstalk arises when signals in adjacent cores interact, a risk present in both DCF and MCF setups. However, the unsymmetrical core design in the MCF configuration inherently reduces inter-core crosstalk by dedicating separate cores for data and power, though not eliminating it entirely. Both systems rely on advanced DSP like MIMO techniques to manage and mitigate these crosstalk effects, ensuring stable transmission quality.

Given that MDM technology is still under research, selecting standard commercial lab equipment for deployment is currently not feasible, as many components remain in research-grade forms. This research-stage limitation contributes to the high initial costs of MDM-based systems. However, it is anticipated that MDM technology will follow a cost reduction trend similar to that of DWDM as it matures, making it more economically accessible over time by reducing the price per Mbps, as per Jefferies.com, the price of the Mbps has been reduced from 6.5 Euro (7USD) in 2004 to less than 0.9 Euro(1USD) in 2015 [45]. This decrement occurred due to the decrement in the DWDM prices, similar trend in expected with MDM systems, allowing to provide economic solution to the extensive needs of capacities which the current DWDM system will not be able to handle in the future.

Figure 4 shows a side-by-side comparison of the scenarios discussed in this study, highlighting the impact of the costliest active and passive parts for each system.

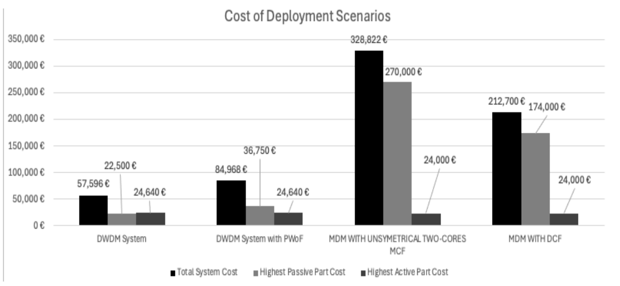

Fig. 4. Cost Comparison Per System

In terms of sustainability, both configurations benefit from the PWoF concept by centralizing power generation at the CO. This centralized setup enables the integration of renewable energy sources, reducing the reliance on distributed power infrastructure and lowering the overall carbon footprint. Adopting centralized, green power generation aligns with modern sustainability goals, providing an eco-friendly solution for powering RRUs across the network.

IX. Conclusion

This study assessed the cost-effectiveness and feasibility of deploying MDM with PWoF for bidirectional fronthaul, comparing DCF and MCF configurations. The DCF-based system, with a CapEx of 212,000 Euros, simplifies deployment by carrying both data and power within a single fiber but faces intra-core crosstalk issues. The MCF-based system, costing 322,000 Euros, improves signal isolation by using dedicated cores for data and power transmission, making it more suitable for high-data-rate applications. Although MDM systems are currently expensive, historical trends from DWDM suggest that costs will decline over time, making MDM a viable long-term solution. Moreover, PWoF enhances network sustainability by centralizing power generation, reducing energy consumption and carbon footprint. Moving forward, future research should focus on Improving DSP algorithms to mitigate crosstalk and enhance signal stability, scaling MDM transmission beyond fronthaul applications, and optimizing PWoF efficiency for better power transmission. With its potential for cost savings, scalability, and environmental sustainability, MDM with PWoF offers a promising path for next-generation mobile networks. As technology advances, it could become a cornerstone of future high-capacity optical infrastructures.

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