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Evolution of optical fibre cabling components at CERN: Performance and technology trends analysis

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ABSTRACT

CERN optical fibre infrastructure has been growing constantly over the past decade due to ever increasing connectivity demands. The provisioning plan and fibre installation of this vast laboratory is performed by Fibre Optics and Cabling Section at Engineering Department. In this paper we analyze the procurement data for essential fibre cabling components during a five-year interval to extract the existing trends and anticipate future directions. The analysis predicts high contribution of LC connector and an increasing usage of multi-fibre connectors. It is foreseen that single-mode fibres become the main fibre type for mid and long-range installations while air blowing would be the major installation technique. Performance assessment of various connectors shows that the expanded beam ferrule is favored for emerging on-board optical interconnections thanks to its scalable density and stable return-loss.

1. Introduction

The European Organization for Nuclear Research (CERN), is home to a large accelerator complex, thereunder the Large Hadron Collider (LHC). Every year a substantial volume of optical fibre cabling components (i.e. fibre cables, connectors, etc.) are supplied through an industrial support contract and installed under the responsibility of the Fibre Optics and Cabling Section (FCS) in Engineering Department, Electrical Engineering Group [1].

CERN optical fibre installations cover a wide range of connectivity applications. Apart from the internet connection network, several other services employ extensive fibre installations. For example, the accelerator Timing and Synchronization system implements a modified GPON standard which requires a substantial fibre connectivity [2]. Another example is the Electrical Network Control system, which constantly measures vital control parameters of the power distribution systems (equipment alarms and temperature) through a specific fibre infrastructure [3]. Security, Surveillance and Access Control systems have recently requested a considerable volume of fibre connectivity due to a major hardware upgrade. Above all, with new Data Centers (DC) under design and construction, the DC interconnect is expected to require a significant fibre installation [4,5].

Transmitting such a high data volume through the fibre infrastructure necessitates regular provisioning and upgrade plans [6]. One insightful approach for such planning is to study the trend of past deployed technology. In fact, analyzing the procurement data in recent years can reveal evolution of various connectivity solutions. In particular, such analysis shows the direction of dominant solutions which in turn can be used for directed market surveys and resource allocation in the forthcoming installations.

On the other hand, once the fibre cabling components are installed, their reliability becomes vital for the accelerator harsh environment through their role in conveying critical data. Indeed any major defect in optical components can impose an unintended downtime, leading to a considerable maintenance cost [7]. Therefore, considering the complex procurement process, the reliability assurance of these components necessitates special provisioning which involves systematic performance monitoring of selected samples.

The first part of this paper studies the evolution of various components installed by FCS during a five-year interval. These components cover the major passive elements of structured fibre cabling including conventional and microduct fibre cables, pre-terminated fibre cables and optical connectors. The analysis results will be used to predict the direction of optical fibre installation in various sectors and provide valuable feedback for future procurement and planning activities.

The second part of the paper is dedicated to statistical performance analysis of the procured components in the same time interval with the focus on connector Insertion Loss (IL) and Return Loss (RL). The analysis results can be used to monitor the essential quality criteria and to provide an assessment benchmark among different connector types.

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Table 1
Total number of procured connectors during 2012–2016.

Year	2012	2013	2014	2015	2016
Count	14.5 k	34.8 k	28.1 k	12 k	5 k

2. Installation components & techniques

In this section we analyze the evolution of the CERN optical fibre infrastructure during a five-year interval between January 2012 and December 2016. This study is carried out on different categories of components followed by a market trend analysis, to compare CERN approach with the dominant market directions.

2.1. Optical fibre connectors

The optical fibre connectors could be one of the standard types among Subscriber Connector (SC) [8], Straight Tip (ST) [9], Lucent Connector (LC) [10], Ferrule Connector (FC) [11], LSH (known as E2000) [12] and Multi-fibre Push-on/Push-off (MPO) [13]. Note that the connectors that are analyzed in this paper are produced from various manufacturers and are assembled on fibre cables prior to delivery at CERN (pre-terminated cables).

Table 1 denotes the total number of procured connectors (of all types) during 2012–2016. A peak can be observed in 2013 and 2014 which is associated to the Long Shutdown 1 (LS1) period. In this period the accelerator operation was stopped for major upgrades which raised the procurement volume of fibre cabling components [14]. Therefore, to cancel out the effect of variable annual volume, we normalize all the forthcoming data to the annual sum of each category.

Fig. 1(a) shows the percentage of various procured connectors after normalizing to the total connector count given by Table 1. According to this figure ST connector has average usage of 12.4% over the five years. This connector is one of the oldest designs which uses a 2.5 mm ferrule for multi-mode (MM) optical fibres [15]. FC connector has the lowest usage at CERN with 3.3% overall average. This connector was introduced as an upgrade of ST since it isolates cable tension from the ferrule and provides the possibility of angled polishing [15].

Among single fibre connectors, SC has the second lowest usage with 3.7% overall average. This connector was initially developed to provide an easier mating condition compared to FC by eliminating the screwing action as well as reducing the connector price by molding manufacturing process rather than machining [15]. However, the E2000 connector which was developed afterward, outperformed SC through its smaller footprint, the integrated dust cap and the special latch mechanism [15]. Therefore, this connector became the standard type for intra-rack interconnection of SM fibres in CERN distribution points.

Fig. 1(a) shows that E2000 connector is the second most abundant type with a stable average of 29% over the five years. The LC connector was later developed with a retaining tab mechanism and 1.25 mm ferrule to further improve the connector density on the patch panels [15]. This connector which generally comes in duplex configuration is extensively used for connecting optical transceivers which require a fibre pair. As shown in Fig. 1(a), LC is the most frequent connector with a noticeable average of 46%.

Multi-fibre connector is another technology which is designed for high density interconnections. Among various types of multi-fibre connectors, CERN chose MPO as it is more adopted for parallel transmission thanks to the high fibre count, high connection performance and ease of handling [16]. Despite taking only 8.0% of all types, MPO provides a substantial fibre connectivity load. Connectivity count is defined as single connectivity for single-fibre connector and several connectivities for multi-fibre connectors (e.g. 12 connectivity for 12-fibre MPO). Fig. 1(b) depicts the connectivity percentage for various connectors, showing a considerable contribution of MPO (average 42%).

Fig. 1 can be also used to track the dynamics of using various connectors during the past years to predict their contribution in the following years. For example, LC and E2000 connectors show a very stable usage whereas the use of ST and FC connectors undergo a gradual decrease in the same period. Noticeably, MPO experiences a substantial growth in this interval, from 1% in 2012 to 12% in 2016. MPO percentage will likely exceed 20% of the annual volume in 2017 which corresponds to more than 70% of the connectivity load.

These trends can be compared to the global fibre connector market segmented on campus networks. Market trend shows the demand for higher data transmission rate is persuading network planners to adopt high density parallel links using LC and MPO connectors [17]. To cope with this trend, FCS has started investigating more recent multi-fibre solutions. Accordingly, in Section 3.2 we study the performance of Expanded Beam (EB) multi-fibre connector as a promising solution for ultra-high density multi-fibre interconnections.

2.2. Non-terminated fibre cables

We define non-terminated fibre cables as a bundle of buffered fibres inside a cable sheath without connectors at both extremities. Non-terminated cables can be either *conventional fibre cables* with reinforced strength elements or *microduct fibre cables*, with a light weight, low friction outer sheath. In traditional cabling, conventional fibre cables (loose tubes, ribbon or etc.), are pulled into conduits and ducts [18]. The microduct fibre cables are instead installed by Air Blowing (AB) into the existing microducts [15].

Essentially, the initial installation costs of AB is roughly 2.5 higher compared to cable pulling. However, from the design point of view instead of installing a large amount of dark fibres for future growth, AB allows for deploying the cable tube and waiting for the time the fibres are required to be blown. In general AB allocates less installation resources in terms of number of technicians and installation time per unit length. However, the exclusive benefit of AB is routing the fibre without any need to directly access the entire path [19]. This property is extremely important at CERN as considerable fibre installations are located in high radioactive environment. Such areas execute special

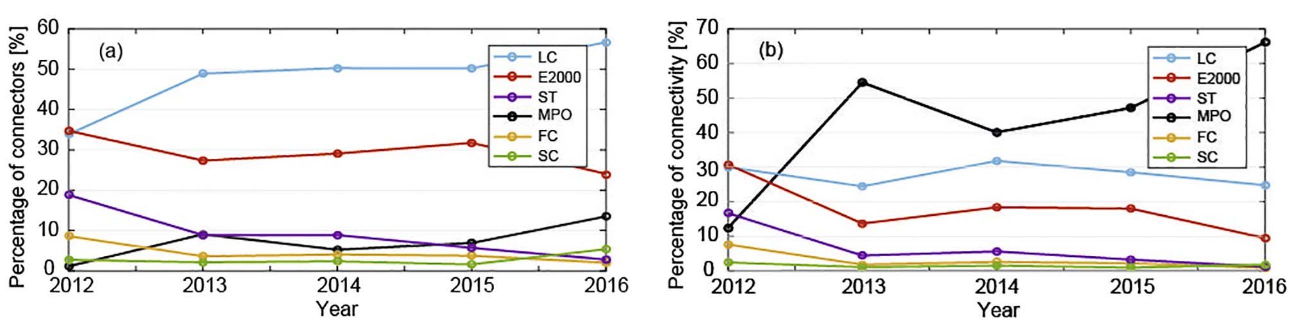

Fig. 1. Percentage of connector count (a) and connectivity count (b) for various connectors procured during 2012–2016.

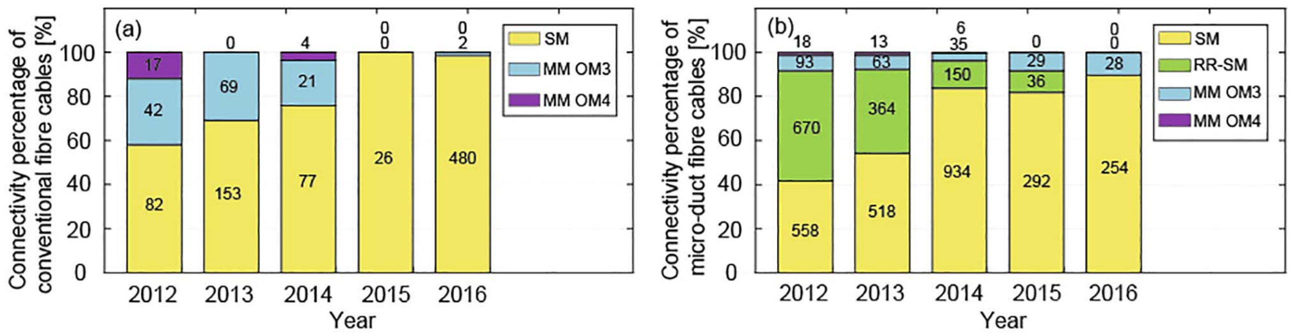

Fig. 2. Percentage of various fibres length (a) pulled and (b) air-blown during 2012–2016. The values on the graph represent fibre connectivity length in km.

safety regulations which can restrict or ban the technician's direct access to the installation path. AB enables remote fibre installation or removal, reducing the radiation doses received by the operators.

Fig. 2(a) and (b) respectively show the connectivity length distribution of conventional and microduct fibre cables installed during the past five years. This length is calculated through multiplying the number of fibres inside a cable by the cable length. Each bar is split into segments to show the length of different fibre types while all the bars are normalized to the total connectivity length in that year. It can be seen that SM fibre contribution is increasing almost every year compared to the MM fibre. In fact, as conventional and microduct cables are often used for long length interconnections, MM fibres which bandwidth-distance is limited to 4.7 GHz.km would became inapplicable for CERN typical distances.

Fig. 2(b) introduces a new fibre type denoted by Radiation Resistance (RR) fibre which is a SM fibre doped with Florine to improve fibre resistance against radiation effects [20,21]. This special fibre type was originally installed only in the LHC tunnel while according to the future plans it will be used for other CERN accelerators such as Super Proton Synchrotron (SPS).

Table 2 compares different CERN installation techniques by denoting the percentage of overall fibre length deployed by each method. As expected, blowing the microduct cables is the major installation technique with 79.7% total average. Despite the higher initial installation costs, AB is preferred at CERN due to the unpredicted manner of future growth, in addition to the long reaching and indirect access feature. As an example, single blow was performed up to 3.4 km in LHC underground using an improved lubricating scheme [22].

Market trend analysis of cable installation techniques shows the growing contribution of AB. Avoiding service disruption during network expansion or reconfiguration is a critical factor which promotes AB in domains such as airports, stadiums, hospitals and military [23]. Fibre-To-The-Home (FTTH) market is also a new segment which is employing AB especially in Europe where the labor cost is rather high [24].

In general, the market trend for optical fibre types is tightly correlated to the specific application. For example in campus network and metro network sectors, SM fibre is the most abundant fibre type thanks to offering a high bandwidth-distance product. Even in DC sector despite of the extensive use of MM fibres, an increasing trend of SM fibres can be observed specially for interconnecting DCs [25]. With the dominance of SM fibres inside CERN infrastructure, consolidation plans will be focused on SM fibre cables. Meanwhile, new studies are conducted on forthcoming DC designs to facilitate the DC interconnect through SM fibres.

Table 2
Percentage of installation techniques during 2012–2016.

Technique	Pulling	Blowing
Percentage	20.3%	79.7%

2.3. Pre-terminated fibre cables

Pre-terminated cables are fitted with connectors at both sides and are used for both inter and intra-rack connections. The structure of such cable type can vary depending on the connector type (Single-Fibre Connector (SFC) or Multi-Fibre Connector (MFC)) and cable physical requirements. In general, pre-terminated cables can be grouped into SFC-SFC type where both cable ends are terminated by single-fibre connector, the MFC-SFC type with multi-fibre connector at one end and several single-fibre connectors on the other end and finally, the MFC-MFC type which both ends are terminated by one or several multi-fibre connectors.

The SFC-SFC cables can be categorized to three sub-groups. Simplex Patch Cord (SP) is used in relaxed physical condition and short reach connectivity, typically intra-rack connections. Duplex Patch Cord (DP) is similar to SP except that it comes in a pair of attached fibres which is optimal for transceiver modules. Breakout Cables (BC) are another type in which several SP are grouped together in a stronger cable sheath. BC is normally applicable for inter-rack connections when the cable trays cannot secure the normal patch cords.

In MFC-SFC group, fibres are terminated by multi-fibre connector at one end while in the other end each fibre is branched into an individual single-fibre connector. These cables also known as Fan-Out Cables (FOC) are used for indoor installations where the fibres of a high-density connector have to be distributed over several different modules.

The last group is MFC-MFC in which both fibre ends are terminated with one or several multi-fibre connectors. These cables when used in short reach applications are called Multi-fibre Patch Cord (MP) whose structure is more adopted to relaxed physical environment. However, in case of longer length or higher connector count, all individual multi-fibre cables are grouped into a reinforced cable sheath, called Trunk Cable (TC) which can withstand higher crash and strain forces.

Fig. 3 demonstrates the percentage of fibre connectivity (defined in

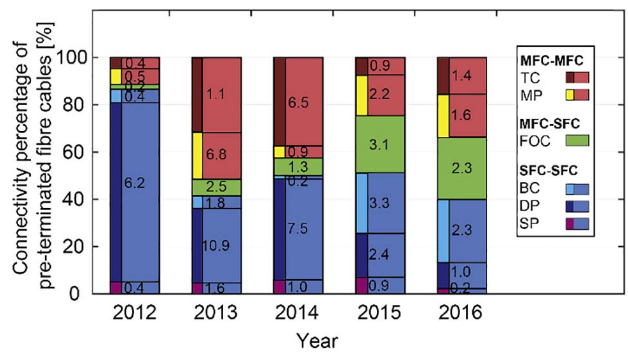

Fig. 3. Connectivity percentage of different cables procured during 2012–2016. The values on the graph represent overall cable length in km.

2.3) through various pre-terminated cables in the past five years. The main groups are demonstrated in blue, green and red while each subgroup is distinguished by a second color at the left side of bars. It can be verified that SFC-SFC cables have been utilized uniformly with 54% overall average. Among SFC-SFC sub-categories, SP which is normally used for scattered single-fibre connectivity takes 5% of the annual average. DP is used more frequently in LS1 period (2013 and 2014) as it provides backbone connectivity for transceiver modules. After LS1, the connectivity demands are more concentrated on distributing the infrastructure interface to the various systems which therefore enhances the use of BC in post LS1 period.

FOC which is in MFC-SFC group is often used to provide multi-fibre connectivity of equipment to the part of infrastructure which is deployed by multi-fibre connectors. On the other hand, in MFC-MFC group TC and MP are respectively in the same analogy as BC and DP. In other words, TC is employed during LS1 to develop the infrastructure of multi-fibre cables while MP is used more frequently after this period to provide short reach connectivity of equipment. It is worth noting that TC is mainly used for consolidating building's infrastructure such as computing and data centers. As an example, in the Compact Muon Solenoid (CMS) experimental area, the detectors front-end are connected to the processing centers by more than 3 km of TC [26].

Market trends in pre-terminated fibre cables shows different directions depending on the underlying application. The current popular trend in DCs which utilizes parallel MM fibres assisted by multi-fibre interconnections, highlights the role of MFC-MFC and MFC-SFC cables. Additionally, the new advances in silicon photonics is pushing C-band transceivers and Wavelength Division Multiplexing (WDM) technology which are based on LC pairs and SM fibre [27].

The major CERN upgrade plan that is expected in 2018 for Long Shutdown 2 (LS2) foresees the extensive implementation of parallel links. Therefore, as implied by Fig. 3a growing segment in short reach indoor components such as FOC, BC, MP and TC is predicted. Accordingly, a survey is carried out to identify new relevant products and solutions.

3. Performance of optical connectors

As previously mentioned, the pre-terminated cables are widely used to connect transceiver modules and equipment to the optical fibre infrastructure. For many of these systems power budget is a critical issue. Therefore, in a link which contains several interconnections the performance of optical connectors, most notably IL and RL would become important as they can directly affect the link performance. These two parameters are continuously monitored at CERN laboratory for various types of connectors to ensure certain quality grade. The IL and RL tests are performed according to IEC 61300-3-4 method B [28] and IEC 61300-3-6 method 2 [29] respectively.

3.1. Single-fibre connector

Fig. 4 shows the IL and RL of three types of single-fibre connectors, E2000/APC (Angled Physical Contact), LC/PC (Physical Contact) and ST/PC which are significantly used in CERN optical fibre infrastructure. In all cases, the Discrete Probability Distribution (DPD) is obtained by measuring IL and RL of 400 to 1000 samples with the mean and variance values noted on each plot.

Each DPD plot is normalized so that the total area under the bars is equal to 1. In all cases the IL can be well fitted by a constant value added to a Rayleigh random variable while the RL is better presented by Gaussian random variable. Fig. 4 shows among all tested connectors, LC has the lowest IL (0.10 dB), the next is E2000 (0.14 dB) and the last is ST connector (0.20 dB).

The other important property of the optical connectors is the RL which shows the relative amount of power reflected at the interconnection interface. The reflected light should be confined to a certain level as it can damage the laser source and create detrimental interference effects on the optical signal. It is known that APC connectors have better RL thanks to the angled fibre tip [30]. Fig. 4 shows that E2000 connector has the best RL profile. The peak at 80 dB is due to limited sensitivity of our measurement device. ST connector has a RL profile which is slightly better than LC. The low RL of E2000 compared to other two connectors is the result of the APC ferrule design, while the difference between ST and LC connectors can be associated to the larger ferrule surface of ST ferrules which provides a better physical contact.

3.2. Multi-fibre connectors

A similar IL, RL analysis can be performed to study multi-fibre connector performance. Fig. 5 shows DPD of 12-fibre and 24-fibre MPO connectors calculated from 200 to 800 measurements. The graphs are normalized to have an area of 1. For 12-fibre MPO it can be observed that the overall distribution is a combination of two separate distributions corresponding to two different quality grades. The 24-fibre MPO has slightly higher average IL (dB) compared to 12-fibre MPO (dB) as the alignment precision would be reduced in case of higher fibre count. However, MPO RL shows a large standard deviation (12 dB) that can become a significant problem in applications with card edge/backplane interconnection as the back reflected light can damage the laser circuit.

For interconnect densities beyond 24-fibre, designing MPO ferrules are not attainable with the state of the art polishing and termination technology. The problem is that the mated interface of high fibre count based on physical contact ferrules becomes instable, resulting in an amplified RL, higher than the simple unmated connector. Moreover, maintaining the physical contact particularly in case of SM fibres, requires accurate alignment of each fibre tip within the ferrule which leads to higher sensitivity [31].

An alternative solution to overcome limitations of physical contact ferrules is the EB technology. EB ferrules typically use two lenses to expand, collimate and then refocus the light from the transmitting fibre into the receiving fibre. The lenses are generally either ball lenses or graded index rod [32]. The use of EB interface results in reduced signal loss from the contamination at the optical interface since the beam cross section is significantly increased. The lens design also facilitates cleaning process meanwhile the lack of physical contact allows for more connector mating cycles. EB technology is being used for more than a decade in military, medical and commercial applications where frequent mating and unmating may expose the optical interfaces to contamination [33].

Fig. 5 shows the DPD of IL and RL for 24-fibre and 48-fibre EB connector from 50 to 150 measurements. The connectors are manufactured by US Conec Ltd, with the commercial name of MXC. In this case both IL and RL can be fitted by a constant value added to a Rayleigh random variable. Note that the IL of 24-fibre EB connector (0.97 dB) is higher than 24-fibre MPO due to additional free space coupling loss [32]. The measured 48-fibre EB connector has an anti-reflection (AR) coating which improves the IL by reducing scattered light at the connector facet. The results show the effectiveness of AR coating by reducing the average IL to 0.54 dB.

The RL of EB connector is also much higher than connectors with physical contact ferrule. This abrupt increase in RL is associated to the discontinuity of the refraction index due to airgap at the interconnection position. Yet, EB ferrules take advantage of tenfold more stable RL owing to the steady airgap interface [34].

In general, the connector IL and RL performance is determined by the quality of termination steps. Therefore, depending on the manufacturer, connectors with wide range of parameters can be identified in the market. However, reviewing the quality control reports of typical products confirms the results from Figs. 4 and 5. For example in [35] and [36] the average IL for E2000 and LC are both measured 0.1 dB which is in line with data from Fig. 4.

Even though the quality of connectors has a slowly varying

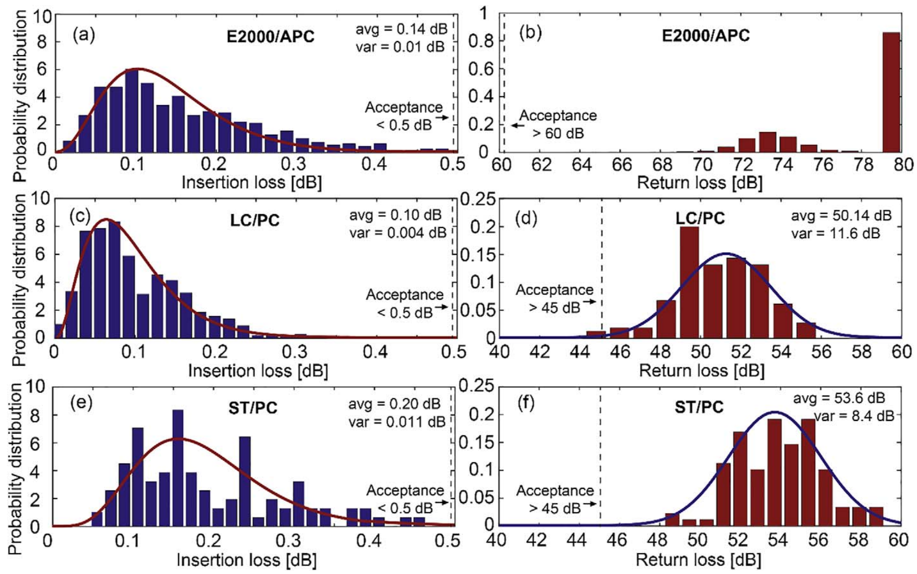

Fig. 4. Measured discrete probability distribution of single-fibre connectors insertion loss and return loss for (a,b) E2000/APC, (c,d) LC/PC and (e,f) ST/PC.

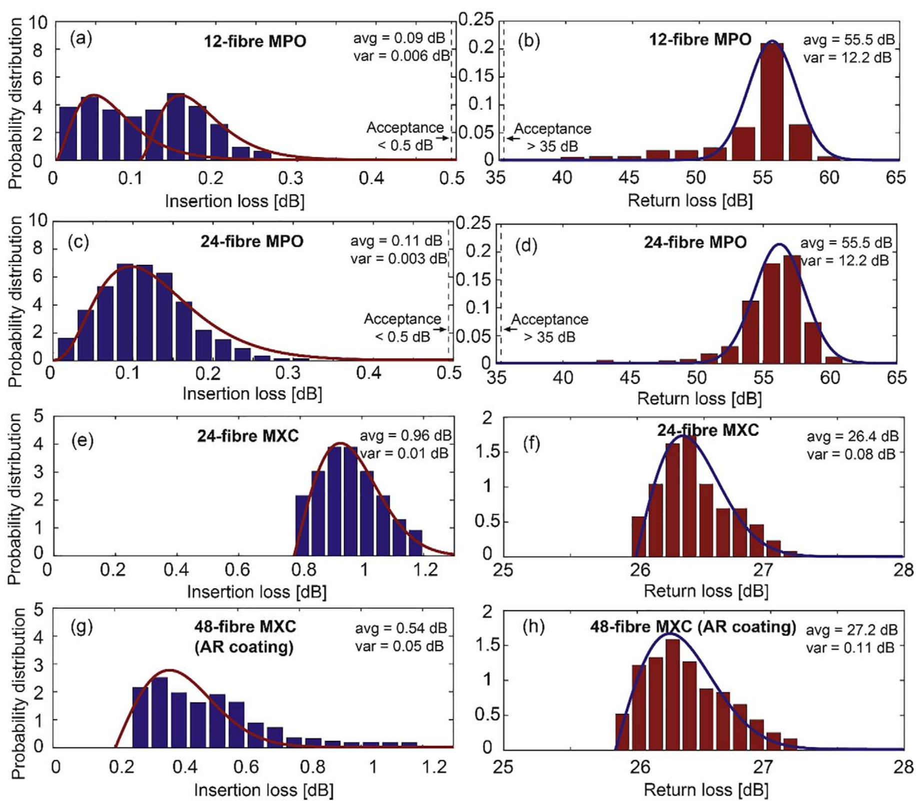

Fig. 5. Measured discrete probability distribution of multi-fibre connectors insertion loss and return loss for (a,b) 12-fibre MPO, (c,d) 24-fibre MPO, (e,f) 24-fibre MXC and (g,h) 48-fibre MXC.

dynamics, the above-mentioned analysis is crucial as it identifies any inconsistency that eventually affect links with tight power budget. For example in CERN structured fibre cabling which is widely implemented by single-fibre connectors, optical paths up to 15 km can be realized by connecting five individual links. Therefore, additional IL even as low as 0.1 dB at each connection can accumulate over the path and cause services disruption. The IL of multi-fibre connectors are equally important as they are extensively used in data centers for 10–40 Gb/s links. According to the IEEE 802.3b standard the 40 Gb/s channel can tolerate a maximum 1.5 dB loss over 150 m of MM-OM4 [37]. Assuming the standard 0.35 dB maximum connector IL and 0.5 dB propagation loss in 150 m of MM fibre, the channel will then have a small 0.3 dB loss margin which can get even narrower due to radiation induced losses. Therefore, regular performance measurement of procured connectors prevents the violation of these margins and subsequently system failure in early stages.

4. Conclusion

Five year evolution of CERN optical fibre cabling components was studied. The analysis of procured pre-terminated cables shows the increasing share of multi-fibre connectors and multi-fibre cable solutions.

This pattern is aligned with data centre segment which relays on increasing data rates by providing parallel optical paths. The analysis also shows blowing microduct is the major technique for installing non-terminated fibre cables. Moreover, it is clearly observed that the majority of conventional and microduct fibre cables are of single-mode type which is essential for interconnecting typical distances at CERN.

The analysis was extended to the optical performance of various connector types by obtaining the insertion loss and return loss probability distributions. The results show E2000 and LC connectors exhibit an insertion loss around 0.1 dB. Accordingly, they are set as standard CERN connectors in distribution points. In particular, E2000 takes advantage of an extremely low return loss thanks to the angled ferrule design. Multi-fibre connectors, despite exhibiting high return loss variance, have a low average insertion loss of 0.07 dB which is determining for data centers. Finally, the newly introduced expanded beam multi-fibre connectors showed a very stable return loss and acceptable 0.54 dB average insertion loss when manufactured with anti-reflection coating. Expanded beam connectors have not been widely used at CERN but they seem promising for future ultra-high density connectors.

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