Characteristics of CWDM:

Roots, Current Status & Future Opportunities

Abstract

Coarse wavelength division multiplexing (CWDM) is a multi-protocol transport technology showing significant market growth due to its low cost attributes and design simplicity. CWDM represents a perfect economic and technology match throughout the metro access and metro core marketplace. It provides outstanding connection from dense wavelength division multiplexing (DWDM) in the long-haul network through to the business or residential user. It delivers multiple wavelengths through an optical fiber at a fraction of the cost and complexity of DWDM systems. This paper addresses the characteristics of CWDM from its early days of use through to the current marketplace and on into its potential impact.

1 Roots of CWDM

1.1 Definition of Coarse Wavelength Division Multiplexing

Coarse wavelength division multiplexing is a form of wavelength division multiplexing that has wider spacings between the wavelengths used than Dense WDM. Also, unlike other forms of WDM, it uses a far broader photonic band spectrum than other such systems, which often are confined to one or two bands. Up to 18 wavelengths can be sent using some schemes of CWDM. CWDM can be used over multimode and single-mode fibers although signal distances are generally shorter than DWDM. The costs of deploying CWDM are significantly lower than DWDM.

1.2 Early Generation of WDM Technologies & Applications

CWDM technologies have been in use since the early 1980s, long before the general acceptance of WDM into the telecom network. Initial deployments involved multiple wavelengths with 25 nm spacings in the 850 nm window over multimode fiber local area networks (LANs). Applications included multi-channel video distribution and bi-directional, latency sensitive telemetry and control information transmitted over a single optical fiber. [1]

The market for CWDM applications through the mid-to-late-1990s continued to consist of 850 nm multimode LAN applications, aided by new Vertical Cavity Surface Emitting Laser (VCSEL) and thin-film filter technologies to reduce cost and increase packaging density. [3]

Interestingly, the term CWDM itself did not come into industry usage until 1996 or thereabouts. In fact, the term "coarse" was contrasted with "dense" in defining WDM and was not used until after DWDM had come into the nomenclature. In its early stages, CWDM did not have specific standards and there was initial confusion in some regard to its meaning and application.

This was to change in the late 1990s, when CWDM became a subject of interest within the IEEE 802.3 High Speed Study Group for solving dispersion and loss problems for 10 Gigabit Ethernet LANs and some 10xGbE WAN applications. [5,6] For the 10 GbE LAN applications, four wavelengths in the 850 nm or 1310 nm windows were proposed to extend the life of the installed base of multimode fiber in building and campus environments. To differentiate between the two LAN windows, the 802.3 High Speed Study Group referred to the 850 nm wavelengths as CWDM and the 1310 nm wavelengths as Wide WDM (WWDM). As we note later in this paper, both terms may be combined into the CWDM nomenclature.

	Coarse WDM (includes WWDM)	**WDM**	**DWDM** (includes ultra dense WDM)
Channel Spacings	Large, from 1.6 nm (200 GHz) to 25 nm	1310 nm lasers used in conjunction with 1550 nm lasers	Small, 200 GHz and less
Number of bands used	O,E,S,C and L	O and C	C and L
Cost per channel	Low	Low	High
Number of channels delivered	17-18 at most	2	Hundreds of channels possible
Best Application	Short-haul, Metro	PON	Long-haul

Figure 1 Types of Wavelength Division Multiplexing

WDM is also used in carrier access network applications such as Passive Optical Networks (PONs). [2,7,8] However, this form of wavelength division multiplexing comprises simple band splitters for multiplexing upstream and downstream traffic into the 1310 nm and 1550 nm windows. Figure 1 summarizes the types of wavelength division multiplexing.

1.2.1 Early WDM Presence in the Metro Market

When introduced in the early-to-mid-1990s, WDM in the form of DWDM was used mainly in the long-haul space. The primary application was to help long-distance (known as inter-exchange) carriers deal with fiber exhaust between cities.

This began to change in the late 1990s as WDM products also began to help alleviate congestion in the metro and regional areas. However, the metro area had an entirely different set of requirements: the distances were shorter; more fiber was available; in addition to SONET/SDH, more protocols such as Gigabit Ethernet and Fibre Channel needed to be supported; the amounts of information were often smaller; and the ability to pay for bandwidth was much less. Given these characteristics, carriers and enterprises requested transmission means quite different from the densely packed, extraordinarily precise, high bandwidth DWDM technologies so helpful to long-distance transmission.

Since the long-haul market had been the paradigm, carriers in the metro space sought a more relaxed, far less expensive form of DWDM. The concepts of “wavelength banding” or “hierarchical WDM” [4] and “more coarsely spaced wavelengths” [9] emerged as technology solutions.

To further reduce metro product costs, expensive dispersion compensators normally used in long-haul networks could be removed due to the shorter distances required. However, expensive EDFAs were still required. These refinements led to coining of the term “Metro DWDM.” While there were refinements, there was a general failure on the part of providers of long-haul DWDM to provide economic packaging for the metro space. While metro DWDM was an attempt to respond to some of these different variables, it still had many of the undesirable characteristics of the products engineered for the inter-exchange market.

CWDM began to emerge as an obvious alternative. However, the CWDM product which had been developed for short-distance LAN applications needed to be re-engineered to provide a range of wavelengths more suited to transmission distance requirements of metro applications. As shown in Figure 2, some lesser-known wavelength bands are used in CWDM for metro applications. These included the Original (1310 nm), Extended, Short & Long, or more simply, the O, E, S & L bands. These bands can potentially be used to provide 10x more bandwidth than the C-band or 10x wider wavelength spacing for the same bandwidth. The latter option was a logical solution to the metro WDM technology and cost issues.

As evident from Figure 2, five of the CWDM wavelengths fall within the E-Band. This band is normally not used on standard G.652 type fiber due to the water peak. The loss due to the water peak is typically 0.5 dB/km, which is not large. However, the maximum loss can be 2 dB/km or greater. Carriers are not willing to take the risk that purchased equipment may not operate on some or all of their metro G.652 type fiber. Consequently, the first products to implement and deploy CWDM in metro applications focused on the O, S, C & L bands only.

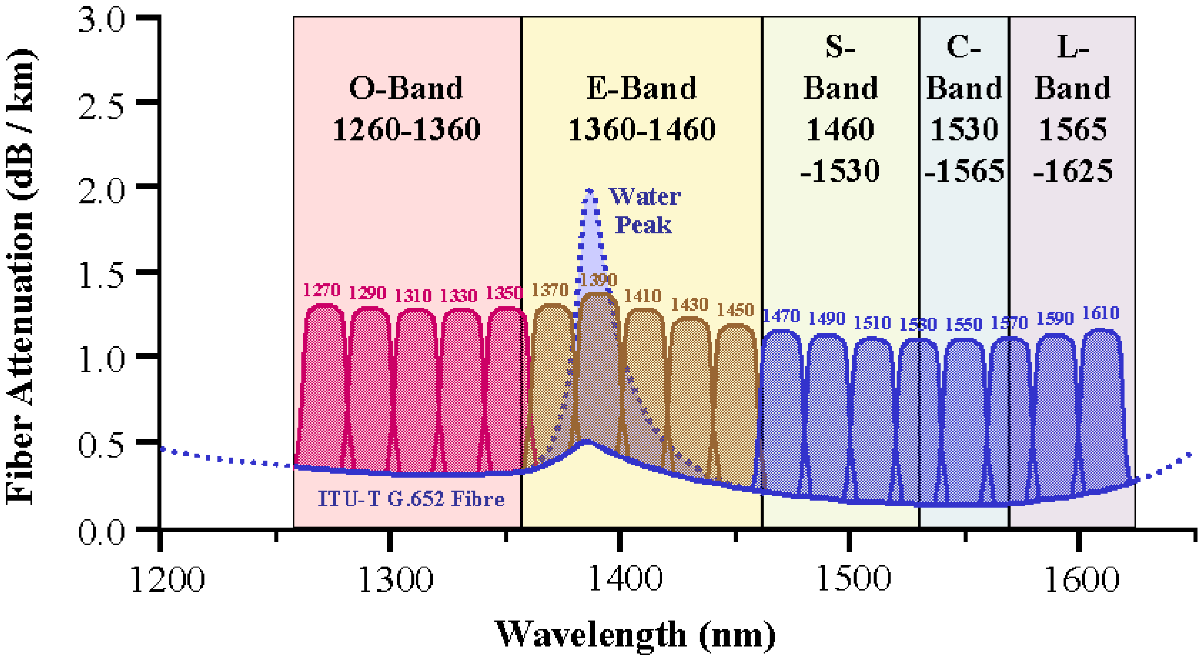

Figure 2 Metro CWDM Wavelength Grid as specified by ITU-T G.694.2

1.2.2 ITU CWDM Wavelength Grid

Metro CWDM technologies now comprise optical filters and uncooled lasers with 20 nm spacings. There are 18 wavelengths currently specified with nominal wavelengths ranging from 1270 nm to 1610 nm inclusive. Figure 2 shows a mapping of the ITU-T G.694.2 CWDM wavelength grid. A typical attenuation curve for the installed base of ITU-T G.652 fiber is also shown. The mapping of CWDM wavelengths onto the fiber attenuation curve has been done for greater clarity and to highlight the higher loss incurred by some wavelengths.

As evident from Figure 2, five of the CWDM wavelengths fall within the E-Band. This band is normally not used on standard G.652 type fiber due to the water peak.

1.2.3 10 GbE and Similar Standards

The 10GbE standard supports several Physical Layer (PHY) Media Dependent sub-layer options in the O-Band. Of particular relevance is 10GbaseLX-4 WWDM PHY. This standard, geared to the 1310 nm window, resulted from the CWDM LAN studies undertaken in the mid-to-late 1990s. Initially, there was proposed a 10GbaseSX-4 CWDM option for the 850 nm window and there are proprietary products available that implement this option.

The 10GbaseLX-4 standard is very similar to the ITU CWDM standard, except that it uses 24.5 nm spacing between wavelengths and is differentiated by the term Wide WDM. This standard originated to allow the installed base of optical fiber cabling in buildings and campuses to be used for 10GbE. It is therefore intended for both multimode and single-mode fiber, for which excessive dispersion would be a problem at 10 Gbit/s serial line rates. Instead, 4 wavelength channels or “lanes” in the O-Band are defined (listed below), each at a rate of 3.125 Gbit/s. Transmission distances are specified to 10 km but some commercial WWDM devices can reach up to 20 km.

Lane 0	1269.0-1282.4 nm	(1275.7 nm nominal)
Lane 1	1293.5-1306.9 nm	(1300.2 nm nominal)
Lane 2	1318.0-1331.4 nm	(1324.7 nm nominal)
Lane 3	1342.5-1355.9 nm	(1349.2 nm nominal)

In January 2002, the Optical Internetworking Forum (OIF) commenced the specification of a Very Short Reach (VSR) Level 5 interface for Intra Office and client interconnects at OC-768 (40 Gbit/s) rates. Several options are planned, including 4 x 10 Gbit/s CWDM over single-mode fiber in the O-Band (1310 nm) [10]. The IEEE 10GbaseLX-4 wavelength plan is proposed for this.

1.2.4 CWDM & WWDM Standards Convergence

Submissions have been made to the ITU for the IEEE 10GbaseLX-4 and OIF VSR-5 wavelength plan to be adopted for the ITU CWDM standard. One option could mean replacing the existing five wavelengths spaced 20 nm apart in the O-Band (as defined by ITU-T G.694.2) with four wavelengths spaced 24.5 nm apart (as defined by IEEE 10GbaseLX-4). This would result in 17 rather than 18 CWDM wavelengths.

Convergence of the Metro CWDM and LAN WWDM standards would further reduce component and systems costs. Apart from the loss of one CWDM channel, there do not appear to be any negative aspects associated with a single convergent CWDM standard.

2 Current Status of CWDM

2.1 CWDM System Components

2.1.1 Fiber

For metro fiber network upgrades and Greenfield applications, the opportunity now exists to install the latest ITU-T G.652.C fiber technology, which substantially eliminates the water peak at 1383 nm and thus releases the E-Band for further capacity expansion. OFS championed the development of low loss fiber, which overcame the water peak problem, and now both OFS and Corning supply fiber that conforms to the G.652.C standard. .

Legacy Dispersion Shifted Fiber (DSF or DS fiber) which cannot be used with DWDM in the C-Band due to 4-wave mixing problems can now be reused with the new Metro CWDM technologies. This may prevent the unnecessary tearing-up of an entire section of DS fiber cable that was once installed to support future 40Gbit/s TDM systems.

2.1.2 Lasers

Direct Modulated CWDM Lasers

Direct Modulated CWDM Lasers with bit rates up to 2.5 Gbit/s are optimized for low cost. Their design is based on tried and proven DFB technology. The DFB technology has the benefits of a narrow line-width with highly suppressed side-modes, thus providing similar low dispersion performance to direct modulated DWDM lasers. As a result, CWDM lasers are capable of transmitting 2.5 Gbit/s over distances of 80 km on ITU G.652 fiber. The low cost, small power and reduced space benefits of CWDM laser transmitters result from their uncooled design. This means that they do not have bulky heat sinks, control circuits and Thermo-Electric Coolers (TECs) coupled close to the laser chip, which saves electrical power and space. A typical optical output of 1 mW (0dBm) is achieved with low cost CWDM lasers.

Vertical Cavity Surface Emitting Lasers (VCSELs)

VCSELs are now manufactured in volume for GbE and 10 GbE WWDM LAN applications with 850 nm / 1310 nm and single-mode/multimode options. As mentioned earlier, the OIF VSR-5 study group is now specifying 4 x 10 Gbit/s O-Band CWDM lasers that can be used for VSR LANs and Central Office (CO) interconnects. These CWDM devices will most likely be based on low cost 1310 nm VCSELs.

Long Wave (1500-1610 nm) VCSELs (LW-VCSELs) have now been developed for single-mode fiber and WDM applications [11]. Both fixed wavelength and tunable variants using integrated MEMS technologies have been demonstrated. Transmission distances of 80 km have been achieved at 2.5 Gbit/s with small power penalty and 10 Gbit/s units are expected soon. Wavelengths suitable for CWDM and 100 GHz DWDM have been achieved.

CWDM vs DWDM Laser Technology Comparison

The dominant factor that differentiates CWDM transmitter costs from DWDM transmitter costs is the WDM channel spacings. The channel spacing determines how far the associated laser that lights the channel can drift from the nominal wavelength due to manufacturing tolerances, temperature range and modulation current. This is illustrated in Figure 3 for a 1550nm CWDM filter and multiple 200GHz spaced DWDM filters and representative DFB laser wavelengths in the C-Band.

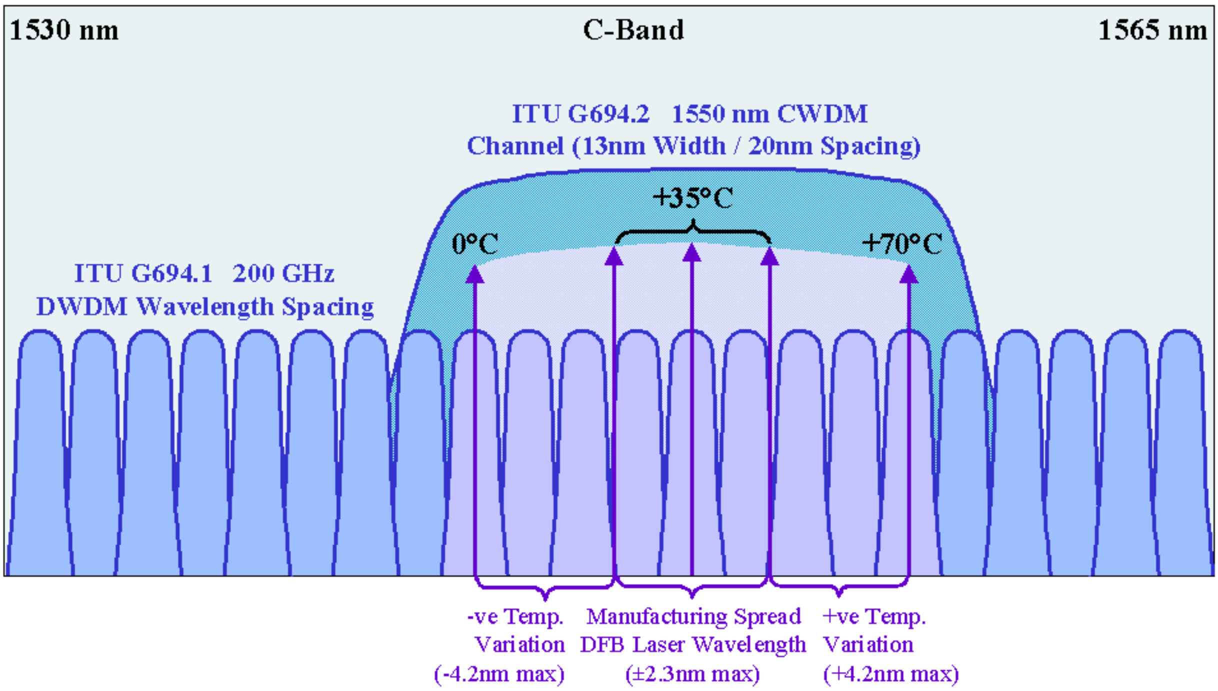

Figure 3 CWDM vs DWDM - Manufacturing and Temperature Tolerances

The following summarize the differences between DWDM and CWDM transmitters:

- The volume occupied by a DWDM laser transmitter is about eight times the volume of a coaxial CWDM laser transmitter.
- The power consumed by a DWDM transmitter is about 20 times the power consumed by a CWDM transmitter. For a 16-channel WDM system, the CWDM transmitters consume approximately four watts, while the same functionality in a DWDM system can consume over 80 watts.
- Due to the above issues, packaging a DWDM laser transmitter is more expensive than an uncooled CWDM laser transmitter. As a result, DWDM transmitter components are typically four to five times the cost of their CWDM counterparts.

2.1.3 Receivers

The receivers used in multi-channel CWDM systems are essentially the same as those used in DWDM systems. In contrast to standard single protocol receivers, they often require larger bandwidths that can capture all the specified bit-rates and protocols.. The front ends of these receivers use wavelength agnostic PIN or Avalanche Photodiode detectors (APDs) that cover the entire ITU CWDM band. It is the CWDM filters that provide the wavelength selectivity. The benefit of the PIN detectors is a lower cost, simpler receiving design. The benefit of the APD detectors is a 9-10 dB improvement in receiver sensitivity.

2.1.4 Filters

CWDM Filters

CWDM filters are implemented using thin-film filter (TFF) technology. They are available as discrete single-channel filter devices and as integrated multiplexer/demultiplexer devices with typically four or eight wavelength ports. Various configurations of these devices can be used to implement a multi-channel optical add/drop multiplexer product. CWDM filters can be specified for uni-directional transmission on two-fiber networks or for bi-directional transmission on single-fiber networks. The latter option has the advantages of lower first-in cost for leased-fiber applications and reduced fiber count for fiber exhaust applications. Due to the thin film processes and materials used, the thermal stability of the CWDM filter center wavelength is excellent - typically resulting in less than 0.002 nm/°C drift.

CWDM vs. DWDM Filters

CWDM filters are inherently less expensive to make than DWDM filters due to the fewer number of layers in the filter design. Typically there are over 100 layers required for a 200 GHz filter design as used in metro DWDM products, where there are only 50 layers in a 20 nm filter used in Metro CWDM products. The result is shorter manufacturing time, less materials and higher manufacturing yields for CWDM filters. As a result, CWDM filter costs are generally less than 50 percent of the cost of comparable DWDM filters. [12]

2.1.5 Optical Add Drop Multiplexers, Repeaters and Amplifiers

Figure 4 illustrates a linear (bus) network comprising an 8-wavelength CWDM mux/demux filter at the head-end or central office and four OADM filters distributed among remote customer nodes spaced 15 km apart. The total network size is 60 km, which in this example is loss limited - assuming an APD, 1 dB OADM insertion loss (express & add/drop), 4 dB mux/demux insertion loss, and 0.4 dB/km fiber + splice loss at the 1470 nm and/or 1610 nm wavelengths.

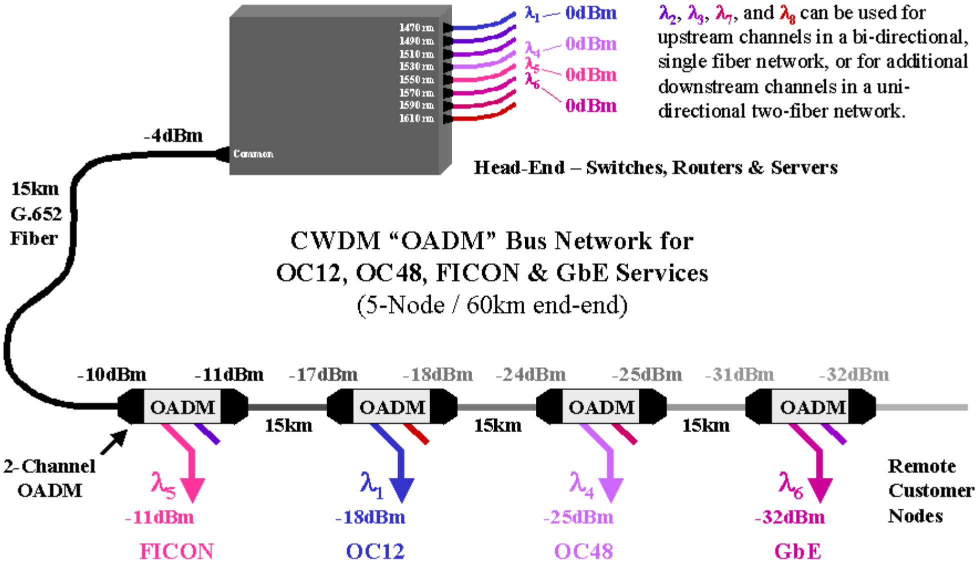

Figure 4 Example Network of 2-Channel OADMs and an 8-Channel Mux/Demux

For 2.488 Gbit/s OC-48/STM-16 applications, this OADM network is also approaching the 80 km dispersion limit of many direct modulated CWDM lasers. This is due to chromatic dispersion of the modulated 1610 nm wavelength in standard G.652 fiber. Such fiber is optimized for zero dispersion at 1310 nm and thus causes significant dispersion at 1610 nm.

As shown in Figure 4, calculating the maximum size of the downstream segment of an unamplified CWDM bus network requires simple math—not dissimilar to the tap-loss calculations used for the coaxial segment of an HFC network. The flip side to this is that unamplified CWDM networks are intrinsically small in size and thus confined to metro-access applications having a small number of customer nodes.

Expansion of CWDM networks to greater distances and/or more nodes than shown in Figure 4 requires an insertion of either a repeater or amplifier. Repeaters can provide either 2R or 3R regeneration (reshaping and retiming) while amplifiers provide 1R (amplitude) regeneration. While single wavelength or multiple wavelength repeaters certainly are options for larger metro network applications, a Semiconductor Optical Amplifier (SOA) is an alternative lower-cost solution for smaller or lower capacity CWDM metro networks having a large number of nodes. There is expected to be available in 2003, a range of small low cost SOAs that together cover the O,E,S,C & L bands. .

Multi-wavelength 3R repeaters can be enhanced to include full OEO add/drop multiplexing (ADM) features normally found in major optical switching centers, thus creating a regenerative OADM (or R-OADM). Multiple R-OADMs can be connected to form a large, regenerative CWDM network, which may be configured as a bus or ring. When configured as a ring, full logical mesh connectivity and multiple (BLSR & UPSR) protection options are possible. This is referred to as a “true ring” topology, as against the looped bus topology used by many all-optical OADM and PON networks.

Regenerative OADMs enable more flexible network solutions that provide the multi-protocol transparency and low latency of WDM and the network design simplicity of SONET & SDH (TDM). New TDM technologies, such as Next Generation SONET (NG-SONET) will have an important part to play above the CWDM layer by enabling smaller (sub-lambda) channel granularities and hence greater bandwidth efficiency. However, NG-SONET imposes greater processing overheads, latency, power consumption and cost when it tries to compete head on with the multi-protocol simplicity of regenerative CWDM networks.

CWDM-based R-OADMs with 10 Gbit/s capacity per optical fiber today (40 Gbit/s in the future) offer functional and economic advantages compared to conventional CWDM-based OADMs and OC-192 NG-SONET based ADMs in metro-access and metro-core networks.

2.2 Product Related Benefits

The smaller size and lower power consumption of CWDM vs. DWDM components translates into smaller CWDM multiplexer dimensions, fewer or lower consumption power supplies and reduced thermal management equipment to remove the heat that both the transmitters and power supplies generate. These differences are graphically illustrated in Figure 5 using data from representative 16 wavelength DWDM and CWDM components as discussed in the previous section.

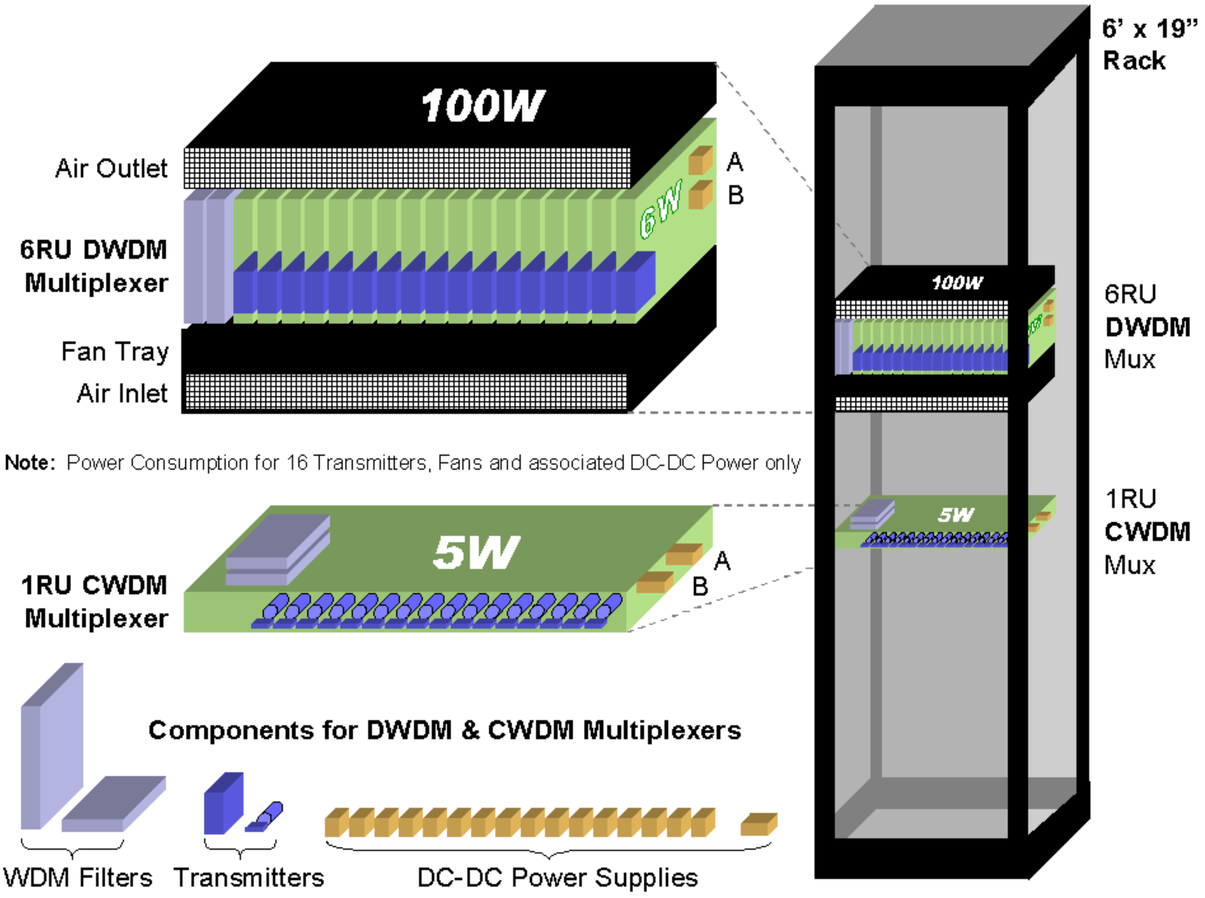

Figure 5 Representative DWDM vs CWDM Products – Space & Power Differences

The multiplexer architectures shown in Figure 5 are based only on the most significant component differences between 200 GHz WDM and CWDM technologies, being thin film filters and directly modulated DFB laser transmitters. In both cases, pigtailed lasers are assumed.

The representative product space and power differences are significant - but of little surprise to equipment manufacturers who have experience in both DWDM and CWDM product developments. As shown in Figure 5, the combination of fiber management and power (heat) density drive the DWDM products towards a large chassis with many vertical card types. In contrast, the low power density of the CWDM technologies permits a low-profile chassis with fewer module types or even a single motherboard in the case of a commercial grade product.

The additional space requirements of DWDM products result in considerable extra cost - especially in co-location situations where the space is leased from another carrier. Additional space is also required for larger AC-DC power supplies and/or backup batteries which are a major consideration in the operation of telecom equipment. In addition to the power supply and thermal management requirements and associated capex costs of DWDM systems, opex costs also increase due to the power and air-conditioning load. Due to all of these considerations, the life-cycle cost of a DWDM solution compared to a CWDM solution is greater than the basic component cost comparison would indicate.

3 Future Opportunities

CWDM has the potential to operate efficiently and economically throughout the metro core and metro access all the way to the customer premises. The ability to provide multiplex wavelengths at a reasonable cost should resonate well throughout the carrier community, which has simply been unable to justify the large costs associated with DWDM when matched to the frugal requirements of the local exchange.

3.1 Fiber to the Building

Building equipment rooms are popular locations for co-locating carrier metro-access equipment and private enterprise LAN/WAN gateway equipment. Enterprise customers and carriers both require that fiber-to-the-building networks support multiple services (eg, OC-n, FICON and GbE) and multiple path protection options.

Metro CWDM networks are ideal for these applications since space is at a premium in equipment rooms and high-power-consuming equipment is not desirable where there is inadequate air conditioning. The low capex and opex cost benefits of CWDM are essential for justifying new higher bandwidth services that the enterprise customers demand but are often reluctant to pay a premium for. Examples include GbE LAN extension, ESCON and FICON (Fibre Channel), Storage Area Networks (SANs) as well as existing broadband services transported via ATM or packet over SONET.

3.2 Remote Terminals

Due to the low cost, power and space benefits of CWDM, this is an ideal “pair-gain” technology for installing in Outside Plant applications close to the customer.

In contrast to NG-SONET upgrades, a regenerative CWDM network provides a cost-effective “no fork-lift upgrade” solution for adding a new OC-12 to OC-48 backhaul for the new broadband DSL services, without affecting an existing OC-1 or OC-3 ring previously installed for basic POTS services.

3.3 Inter-Office (CO-CO)

The emergence of carrier-grade Metro CWDM products, which conform to the ITU-T G.694.2 wavelength grid, has changed the economics of providing a WDM overlay. CWDM requires considerably less equipment space and power and offers typically 8x pair-gain on existing ITU-T G.652 and G.653 (DSF) fiber infrastructure. At a conservative 20 percent yearly growth rate, one may get another 10 years life out of the installed fiber base. At a very optimistic 50 percent yearly growth rate, this equates to another five years of fiber life. Furthermore, for situations where DS fiber is widely deployed (eg Japan), CWDM enables a much greater return on investment of this fiber infrastructure than was previously thought possible.

Regenerative CWDM products that support longer transmission distances (at least 160 km) and “true ring” capabilities (such as full logical-mesh connectivity) are therefore ideal for inter-connecting COs within the metro-core network.

3.4 Future Mass Produced Components and Systems

Significant manufacturing cost reductions in CWDM components and systems are anticipated over the next 2-3 years due to automated manufacturing processes and increased component integration. TFF filter costs are projected to drop by a factor of three during this time. LW-VCSEL transmitter and APD receiver arrays with integral thin film mux/demux filters are likely to be developed for multi-channel point-point Metro CWDM applications. This will further reduce the cost per channel. As evidence of this trend, 10 GbE CWDM VCSEL transceivers and mux/demux filters are already available with this level of integration and associated mass production cost benefits.

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5 About RBN

RBN is a designer and developer of optical transport and switching products for the access and metro markets. RBN has identified and addresses a key issue—an imbalance between carrier revenues and costs. RBN addresses the issue by designing and developing products that enable carriers to offer lower cost broadband services. Designed for simplicity and flexibility of use, small form factor, low power usage and low cost of ownership the company pushes the boundaries of optical networking closer to the end user.

RBN was the first to market with a reconfigurable optical add/drop multiplexer that is outside plant hardened for use in the central office, enterprise environments and remote terminals. More specifically the platform can be used in a variety of applications including fiber pair gain, SONET upgrade avoiding truckrolls, Digital Loop Carrier (DLC) network upgrade and integration of new services into existing infrastructure

The company’s flagship product, the RBNi 8200, uses the simplicity and low-cost features of CWDM and is multi-protocol enabling the integration to transport voice, video and data.

RBN’s business model is to market and distribute its product through leading communications manufactures and solution providers.

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