CHAPTER 15

ENGINEERING DWDM SYSTEMS

15.1 INTRODUCTION

The design of DWDM systems requires the resolution of several issues. Excluding cost, several key parameters influence the design of a system and a network:

- Nominal center frequencies (wavelengths)
- Channel capacity
- Channel width
- Channel spacing or channel separation
- Channel bit rate and modulation
- Multichannel frequency stabilization
- Channel performance
- Channel dispersion
- Power launched
- Power received
- Optical amplification
- Fiber type used as the transmission medium
- Optical power budget
- Type of services supported
- Aggregate bandwidth management
- Protocol used to transport supported services

- Network management protocol
- Network reliability
- Network protection and survivability strategies
- Service protection
- Uninterrupted service offering network scalability and flexibility
- Wavelength management
- Interoperability
- Inter domain compatibility

15.2 ITU-T NOMINAL CENTER FREQUENCIES

For wavelength division multiplexing (WDM) system interoperability, the operating center frequency (wavelength) of channels must be the same at the transmitting and receiving ends. Presently, ITU-T recommends 81 channels (wavelengths) in the C-band starting from 1528.77 nm and incrementing in multiples of 50 GHz (or 0.39 nm).

Accordingly, starting with the first center frequency at 196.10 THz (or 1528.77 nm), and decrementing by 50 GHz (or incrementing by 0.39 nm), a table with all center frequencies (wavelengths) is constructed. These are the center frequencies (wavelengths) of the channels considered for recommendation by ITU-T G.692 (as of October 1998). Thus, the first of the 81 channels in the C-band is at a frequency of 196.10 GHz or a wavelength of 1528.77 nm, the second channel is at a frequency of 196.05 GHz or wavelength of 1529.16 nm, and so on; the last frequency is 192.10 GHz or a 1560.61 nm wavelength. However, as fiber technology evolves and optical components improve, more channels may be appended to this table. This may be expressed by the relationship:

$$F = 193.1 \pm m \times 0.1 \text{ THz}, \tag{15.1}$$

where 193.1 THz is a reference frequency and m is an integer. For a channel spacing of 100 GHz, the center frequencies of the channels are those that start with the first channel in the table and continue every other one. Similarly, for channel spacing of 200 or 400 GHz, one starts with the first center frequency (wavelength) and continues accordingly. Figure 15.1 illustrates a linear scale, calibrated in wavelength and frequency.

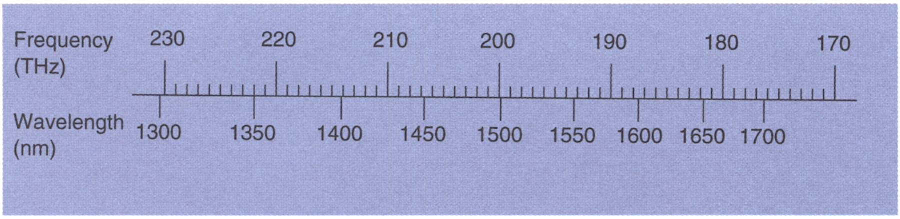

Figure 15.1 DWDM channels in frequency and wavelength in the spectrum defined by ITU-T.

Notice that frequency (not wavelength) is used as a reference. This is because certain materials emit specific well-known optical frequencies that can be used as accurate reference points. In addition, frequency remains constant, whereas wavelength is influenced by the refractive index of the material.

15.3 CHANNEL CAPACITY, WIDTH, AND SPACING

The number of channels, the channel selection (center frequency), and the frequency width of each channel, as well as the channel separation, are important parameters in dense wavelength division multiplexing (DWDM) system design. Channel center frequency and width determine the number of nonoverlapping channels in the spectrum. Channel width, wavelength, bit rate, type of fiber, and fiber length determine the amount of dispersion. To avoid interchannel interference, channel separation should allow for a frequency deviation (~2 GHz) due to frequency drifts in the laser, filter, and amplifier devices.

15.4 CHANNEL BIT RATE AND MODULATION

The bit rate of a channel and the modulation technique are parameters that determine the limits of channel width and channel separation, as well as channel performance [e.g., bit error rate (BER), cross-talk, etc.]. Dispersion and dispersion management, noise induced by amplifiers, and noise induced by other sources should be considered, since they affect the signal-to-noise ratio and thus the signal integrity.

15.5 WAVELENGTH MANAGEMENT

In DWDM systems where each wavelength is used as a separate channel, it is reasonable to consider the reliability of the transmitter, receiver, amplifier, and other active optical components on the optical path between transmitter and receiver. When, for example, a laser or photodetector ceases to perform, a fault is declared. However, for a fault to be declared, the fault must first be detected. This implies the need for an optical monitoring function, which in optical components is costly and nontrivial. Nevertheless, assuming that this function exists, there should be a capability to isolate the fault and restore service. In DWDM, if an optical component fails, one or more wavelengths will be affected. Thus, protection wavelengths should be allocated to replace the faulty ones.

Besides hard faults, there may be wavelength channels that perform below acceptable levels (e.g., BER $< 10^{-9}$). Monitoring optical signal performance in DWDM is more complex than merely distinguishing between good and bad. At any rate, when the signal degrades, it should be dynamically switched to a protection or standby wavelength that is known to perform better (this implies that the protection wavelength must also be continuously monitored for performance).

Either way, wavelength fault or signal degradation results in switching to another wavelength. In DWDM systems and networks, switching to another wavelength requires "wavelength management." However, the end-to-end path in DWDM traverses many nodes, hence consists of many sections (between nodes). If a wavelength changes in one section, the other sections on the path must be notified of the change; and if there are wavelength converters (or regenerators), they too must be tuned to the new wavelength.

In the case of an all-optical network, changing one wavelength to another becomes a multidimensional problem that needs further study. In certain cases, lack of available wavelengths, calls for the finding of another route to establish end-to-end connectivity. This means that the new route must not impact the budgeted optical power of the optical path.

Wavelength management is in its infancy, and depending on the network level, it is addressed in a simple deterministic manner (1:*N*, 1:1, 1+1, etc.). However, research is under way or in the proposal phase.

15.6 MULTICHANNEL FREQUENCY STABILIZATION

In DWDM, systems with optical filters experience filter detuning, or frequency offset from the center frequency. As detuning increases, interference with neighboring channels increases and so does the optical cross-talk. In addition, detuning increases insertion loss. Therefore, mechanisms that correct or compensate for detuning should be incorporated.

15.7 CHANNEL PERFORMANCE

The BER is a performance requirement that is specified by standards. DWDM systems should be designed so that signal integrity is maintained. The BER depends on interchannel interference, optical power level at the receiver with respect to the sensitivity of the receiver, modulation technique, and other noise sources (externally coupled noise, jitter, etc.).

15.8 CHANNEL DISPERSION

In DWDM systems, as wavelengths travel through fibers and various optical components (filters, amplifiers, etc.), dispersion or optical pulse widening occurs. Moreover, as light travels from one fiber to another (via connectors and splices), it is subject to further losses and dispersion. Depending on the number of channels, the frequency distribution of each channel around the center frequencies, the channel separation, the optical path length, and the dispersion characteristics of all devices in the path (including fiber(s) and connectors), the total dispersion of each channel should be calculated. As dispersion increases, so does cross-talk (which affects signal integrity) and received power (which impacts receiver sensitivity).

15.9 POWER LAUNCHED

In DWDM systems, the *maximum allowable power per channel* launched in the fiber, or the transmitted power, is the starting point of power calculations to assure that the optical signal at the receiver has enough power to be detected without errors (or within a BER objective, e.g., $<10^{-11}$). However, the maximum allowable power per channel cannot be arbitrary, because as explained, as coupled power increases so do the nonlinear phenomena.

15.10 OPTICAL AMPLIFICATION

In DWDM systems, optical signal losses should be carefully budgeted and optical amplification [erbium-doped fiber amplifiers (EDFA)] should be used as appropriate to restore the intensity of the optical signal (if needed). However, optical amplification introduces cumulative pulse widening and cost. Conversely, if EDFAs are to be used, the number of channels and the wavelength range (1.3 vs. 1.55 nm) should be considered because EDFAs operate best in the range of 1.55 nm.

15.11 FIBER TYPE AS THE TRANSMISSION MEDIUM

We have described a number of limitations encountered in optical transmission, including amplifier bandwidth, amplifier spontaneous emission, and linear effects such as fiber attenuation, chromatic dispersion, and polarization mode dispersion. In addition, nonlinear effects related to the refractive index and scattering degrade system performance in DWDM.

The contribution of the nonlinear effects to transmission is defined as the optical power density (power/effective area) times the length of the fiber. The *effective area* is the cross section of the light path in a fiber. Depending on the type of fiber, the effective area varies between 50 and 72 μm^2, the lower value corresponding to a dispersion-shifted fiber and the higher to a single-mode fiber. Clearly, the higher the optical power density and the longer the fiber, the greater the nonlinear contribution.

For a fixed length of fiber, the only variable that can be manipulated to lower the nonlinear contribution is optical power. However, if the optical power is lowered, the bit rate should be lowered to maintain transmission at the expected BER.

15.12 OPTICAL POWER BUDGET

The optical power budget in DWDM systems amounts to calculating all signal losses at every component in the optical path (couplers, filters, cross-connects, connectors, splices, mux/demux, fiber, optical patch panels, etc.) between transmitter and receiver. The main objective is to assure that the power of the optical signal at the receiver is greater than the sensitivity of the receiver.

Power gain and loss (in dB) are additive, and thus the power budget is a straightforward addition or subtraction calculation. One typically starts with the power of the optical signal to be launched into fiber, expressed as 0 dB. Then, for each loss item, the dB loss is subtracted from it, and for optical amplifiers the gain is added to it. The remainder is compared with the receiver sensitivity. Typically, a net power margin of several decibels is highly desirable.

$$\text{margin} = (\text{transmitter output power}) - (\text{receiver sensitivity}) - (\Sigma \text{ losses}) \text{ (dB)}. \qquad (15.2)$$

For example, the total loss in a cable is calculated by the sum

$$\text{all concatenated fiber segments, } \Sigma\alpha_n \cdot L + \alpha_s \cdot x + \alpha_c \cdot y \qquad (15.3)$$

where α_n is the loss coefficient, L is the length of the nth fiber segment, α_s is the mean splice loss, x is the number of splices, α_c is the mean loss of line connectors, and y is the number of connectors (see also Section 3.18.1).

The power budget, in addition, determines the fiber length between transmitter and receiver. This length, for a given transmitter output power, depends on the sensitivity of the receiver and on the bit rate. For example, for a transmitter output of 0 dBm, at OC-12 rate, and a receiver sensitivity of −35 dBm, the fiber length (for SMF) is determined to 64 km. For OC-48 and a receiver sensitivity of −29 dBm, the fiber length is determined to 51 km.

15.13 TYPES OF SERVICE SUPPORTED

Communications services are many: synchronous and asynchronous, real time and non–real time, low bandwidth and high bandwidth, circuit-switched and non-circuit-switched. A DWDM system is designed to support several services, thus adding to the complexity of the system and network design. One possibility is to put each different service type on a different wavelength. Another possibility is to packetize each service type and then multiplex packets and transport them over the same wavelength.

15.14 AGGREGATE BANDWIDTH MANAGEMENT

A typical node has many inputs. That is, it may be connected not only to other nodes but to terminals that may support different services, at a different bit rate, constant or variable. Thus, the node should be able to support a different level of quality of service for each type of service and an aggregate bandwidth that converges to the node. The hub, on the other hand, should be able to process the total bandwidth of all nodes connected to it. Consequently, the hub may be an advanced machine that recognizes all types of service supported by all nodes connected to it, provides bandwidth management functionality, and in many instances provides network management. In DWDM networks, the total aggregate bandwidth at the hub may be of an order exceeding terabits per second.

15.15 PROTOCOL USED TO TRANSPORT SUPPORTED SERVICES

The nodes and the hub must be able to process all protocols required by each service supported. Synchronous optical network/synchronous digital hierarchy (SONET/SDH), asynchronous transfer mode (ATM), frame relay, Internet Protocol (IP), video, telephony, signaling, and so on require different protocols. For example, telephony requires call processing (TR-08 or TR-303), whereas ATM requires call admission control (CAC) and quality-of-service warranties. Similarly, the priority of services varies; telephony has the highest priority, whereas certain packet-data services may have the lowest. Typically, all these communications protocols are transparent to many WDM networks on the optical layer: that is, the optical link between transmitter and receiver. However, the optical link layer must be compatible between the two terminating devices that must support and perform fault management, restoration, and survivability functionality.

15.16 PROTOCOL FOR NETWORK MANAGEMENT

The DWDM network communicates with the overall communications network. DWDM network health and billing information are communicated to a remote station from which the DWDM network is managed.

15.17 NETWORK RELIABILITY

The DWDM network processes many services and has a very large bandwidth throughput. As such, the reliability of the network is very important. Reliability is expressed in terms of quality of signal (BER), downtime (seconds per year without service), and traffic rerouting time (in seconds or milliseconds).

15.18 NETWORK AND SERVICE PROTECTION AND SURVIVABILITY STRATEGIES

Many high-speed and high-bandwidth systems have incorporated into their design strategies to provide uninterrupted service when one or more links or nodes fail. Protection strategies may be at the input level ($1+1$, $1{:}N$), at the service level, at the wavelength level (in DWDM systems), at the facility (fiber) level, and at the node level. The time from the instant a fault has been declared until switching to a protection channel, wavelength, facility, or until the rerouting of all traffic, is variously, prescribed in ITU-T and Bellcore recommendations (see also Chapter 16). In addition, the protection and the survivability strategies are service-type, system, and network-architecture dependent. In many systems/networks, they also depend on the transport protocol.

15.19 NETWORK SCALABILITY AND FLEXIBILITY

The network, as well as the network elements, must be scalable, to ensure that small incremental increases (in wavelength, hardware, and software) will accommodate increased bandwidth demand. In addition, network elements must be flexible enough to adapt to protocol upgrades and to offer new services as standards and market needs evolve. Network scalability and flexibility are highly desirable, and service providers place them at the top of the lists.

15.20 WAVELENGTH MANAGEMENT

The signal integrity on a wavelength assigned to a DWDM channel should be continuously monitored. Not only should interference due to optical noise be monitored, but also fault location and isolation of all components in the optical channel, transmitter, receiver, amplifiers, filters, and so on. When the signal quality of a channel is degraded, the wavelength management should be able to dynamically assign another wavelength. This means that DWDM systems must have optical devices with performance monitoring, (additional) wavelengths for protection, and protocols that support dynamic wavelength assignment.

15.21 INTEROPERABILITY AND INTERDOMAIN COMPATIBILITY

Interoperability assures seamless operation and data flow from one service provider network to another and interdomain compatibility assures seamless service between different service providers. Some networks have standard transport protocols and interfaces, while others are private or nonstandard. In addition, systems use wavelengths that, although compliant with ITU standards, belong to a subset of them. However, each system manufacturer uses a different subset, optimized for the particular application the system is designed for. Moreover, components used by one system manufacturer may not have the same frequency stability and line width as those of another system manufacturer, and the fiber from one network may not be exactly of the same type as that for another network on which it is to be installed. Therefore, when two dissimilar systems are connected, certain wavelengths (using wavelength converters) must be converted to others, and the signal level must be equalized to meet receiver requirements. In addition, the transport protocols must be identical; otherwise interoperability may be impossible. Finally, interoperability implies that issues of network management and survivability on the end-to-end optical path have been addressed and resolved.

ITU-T (G.872) specifies the following functionality in optical networks: transport, multiplexing, routing, supervision, and survivability of client signals. This optical network functionality, from a network level viewpoint, is predominantly processed in the photonic domain, the generic principles of which are defined in Recommendation G.805.

15.22 SINGLE-MODE POWER LOSS CALCULATIONS: AN EXAMPLE

The following is an approximate example of power loss calculations over an optical link.

Equipment manufacturer model	"APEX, Inc." model F145XYZ
Detector type	APD
Maximum receive signal	−15 dBm
Receiver sensitivity, P_R	−35 dBm at 10^{-9} BER
Bit rate	1 Gb/s
Transmitter wavelength	1310 (±20) nm
Total fiber span length	45 km
Fiber loss	0.35 dB/km

1. Transmitter output power	P_T	−8.0 dBm
2. Receiver sensitivity (at 10^{-9} BER)	P_R	−35.0 dBm
3. Total fiber system gain (system 1–system 2)	G	27 dB
4. Dispersion loss(at 10^{-9} BER)	P_D	1.0 dB
5. Miscellaneous losses (modal noise, connector reflections, etc.)	P_M	0.4 dB
6. Connector losses (4 at 1.0 dB each)	L_C	4.0 dB
7. Splice losses (9 at 0.2 dB each)	L_S	1.8 dB
8. Margin for future 4 repair splices	M_R	0.8 dB
9. Margin for WDM upgrades	M_{WDM}	3.0 dB
10. Maximum allowable fiber loss (items 3–9)	L	16.0 dB
11. Total loss due to fiber	L_F	15.75 dB
12. Receive signal level (items 1, 4–9, 11)	R	−34.75 dBm

It can thus be concluded that the received power level is within the receiver sensitivity (−35 dBm), although there is very little margin. Consequently, no amplification is required, no attenuator at the receiver is required, and total fiber loss (15.75 dB) is within the maximum allowable fiber loss (16.0 dB).

15.23 CHANNEL CALCULATIONS IN A NETWORK: THREE EXAMPLES

1. Consider a WDM system with N wavelengths over a wavelength range BW(λ) (in nm) that is supported by transmitters, filters, and receivers. In addition, consider that if the bit rate is B Gb/s, 2B GHz of bandwidth is needed for encoding (this determines the channel width). Moreover, if the channel bit rate is B Gb/s, for low cross-talk, a channel spacing of 6B GHz is required (as a rule of thumb). On the basis of the foregoing conditions, determine the conditions for using N channels in this network.

For a center frequency λ, and from the identity

$$\Delta f = \frac{c\Delta\lambda}{\lambda^2}, \tag{15.4}$$

the bandwidth range (in terms of frequency) is

$$\Delta f = \mathrm{BW}(f) = \frac{c\mathrm{BW}(\lambda)}{\lambda^2}. \tag{15.5}$$

Now, the bandwidth required over all N channels is

$$\mathrm{BW}_{\mathrm{req}} = 2\mathrm{B}N + 6\mathrm{B}(N-1). \tag{15.6}$$

Assuming that $\mathrm{BW}_{\mathrm{req}}$ is equal or less than BW(f), then

$$N = \frac{\mathrm{BW}_{\mathrm{req}} + 6\mathrm{B}}{8\mathrm{B}}. \tag{15.7}$$

Clearly, if $\mathrm{BW}_{\mathrm{req}}$ were greater than BW(f), the number of channels that can be accommodated is smaller.

2. For the preceding example, calculate the maximum number of channels that fit in Δf.

For a bandwidth Δf and for the same assumptions, the maximum number of channels is calculated by

$$N = \frac{\Delta f + 6\mathrm{B}}{8\mathrm{B}}. \tag{15.8}$$

3. For the preceding example, consider that the channel spacing is fixed to CS and that the channel width to CW. How many channels can fit in bandwidth Δf?

From

$$\Delta f = (\mathrm{CW})N + \mathrm{CS}(N-1) \tag{15.9}$$

one obtains

$$N = \frac{\Delta f + \mathrm{CS}}{\mathrm{CW} + \mathrm{CS}}. \tag{15.10}$$