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Fiber Optic Networks for Avionics Applications

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The purpose of this paper is twofold: 1) to present an optical network architecture appropriate for avionics applications and 2) to identify basic technology developments that enable a low cost, low weight, low volume and high reliability implementation of the architecture.

Introduction

Previous papers and presentations [1,2,3, 4] have identified the motivation of "fly-by-light" technology and also proposed various approaches to realization Key points covered in the previous works and considered applicable to this paper are:

1) The goal is a unified network wherein a common interconnect practice is used for a sensor network, a video network, a command and control network, a data flow network and a test and maintenance network. Shared use of communications and processing facilities reduces costs and simplifies maintenance.

2) Individual circuit boards within a module are interconnected with fiber optics in the same manner as one module is connected to another. Thus, there are no geographical constraints related to circuit board interconnections. Furthermore, optical-to-electrical conversions are minimized and high speed copper busses on backplanes are eliminated.

3) Digital signal processing modules are generic. Each circuit board is a Line Replaceable Modules (LRM). Functional differentiation arises from software configurations. An exception occurs for specialized processing as might occur for analog signals. In this case it might be possible to use analog-to-digital front ends to feed generic digital boards.

4) Source and sink fiber transmission links can be terminated directly on signal processing cards using highly integrated optical interface modules.

5) The physical network should be transparent to higher layer data protocols.

Communications Layers

This section provides an overview of the communications hierarchy from two points of view: physical connectivity (Figure 1) and protocol hierarchy (Figure 2).

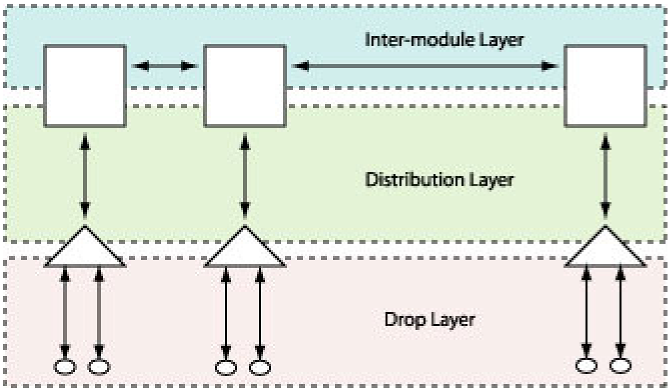

Figure 1 Connection Hierarchy

Any of these layers can utilize various forms of multiplexing depending on the bandwidth and nature of the traffic being carried. Analog signals and very high bandwidth signals imply the use of separate fibers or Wavelength Division Multiplexing (WDM). Low bandwidth signals, as needed for actuator control and collection of low rate sensors, are advantageously served by passive splitting and coupling (the triangles in Figure 1). Distribution of higher speed downstream digital data is advantageously served by signal regeneration from Vertical Cavity Surface Emitting Lasers (VCSELs). (A VCSEL merely replaces the passive splitter when the bandwidth and split ratio precludes use of purely passive solutions.)

Figure 2 depicts several protocol layers of interest. The most significant points illustrated in this diagram are:

1) Passive networking or WDM support all higher level protocols.
2) The form of active splitting described here only supports a Time Division Multiple Access (TDMA) protocol. Thus, other protocols use an adaptation layer to run on TDMA. Ethernet requires a very thin adaptation layer so it is shown as using TDMA directly.

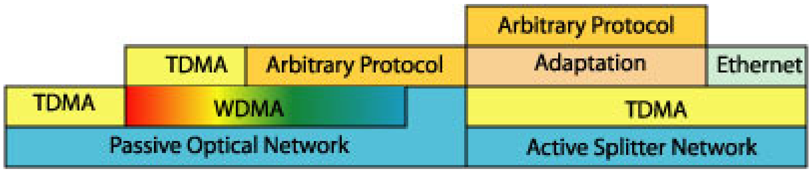

Figure 2 Protocol Hierarchy

Redundancy

Although not depicted in Figure 1, a dual redundant transmission and processing network is assumed for basic reliability. For particularly critical functions it might be desirable to utilize triple redundancy to increase the reliability and to simplify and speed up failure detection and recovery.

In general, when a processing function requires multiple circuit boards, redundancy is implemented by duplicating the multiple boards as a group as opposed to duplicating individual boards one at a time. This approach isolates failure detection to high level functional interfaces and simplifies internal interfaces between the boards themselves.

Inter-Module Communication

Communication between modules can be implemented in a variety of ways but a ring architecture appears to have the most promise. A ring provides mesh functionality without the complexity of mesh interconnections. Figure 3 depicts two versions of rings with redundant transmission links: Bi-directional and Uni-directional Rings. The bi-directional (reverse) ring is the most popular commercially available configuration because it maintains complete communication between all nodes when both fibers at a particular section are cut. Each node next to a cut loops its received data back to its source for propagation around the ring the reverse direction.

The uni-directional ring does not provide the same protection but if the dual transmission paths are physically separated (physical diversity) or are otherwise protected from single event failures, the uni-directional ring is attractive because it simplifies single failure recovery--particularly when momentary data losses are undesired. The uni-directional architecture is also readily adapted to triple redundancy.

a) Bi-directional Ring

b) Uni-directional Ring

Figure 3 Ring Architectures

The ring architectures shown in Figure 3 provide recovery for transmission link failures but not for equipment failures. Commercial SONET rings are typically implemented with dual hardware at each node for hardware failure protection. A Shunted Ring Network[4] shown in Figure 4 provides an alternative approach wherein a node failure is accommodated by the next node in the ring receiving the same input as the failed node.

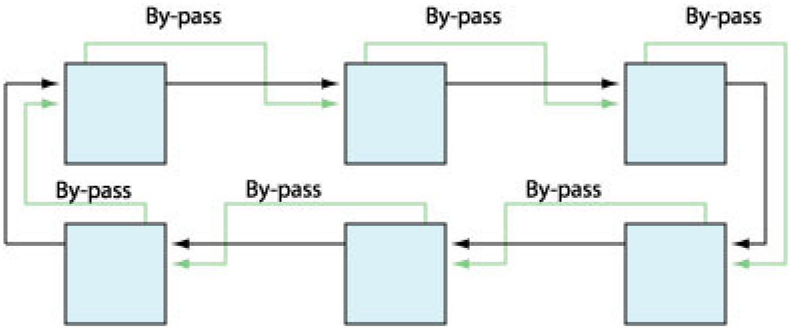

Figure 4 Shunted Ring Architecture (one direction of travel only)

Figure 5 depicts a transceiver for a shunted ring network. The optical signal on an incoming fiber is split using a 1x2 coupler. The signal is then sent to a photo-detector in the node and also to a photodiode of the next node via the bypass fiber. Note the totally passive bypass through the node (shown in green). Each node would have dual photodiodes (or receivers) receiving the primary and bypass signals. A means of comparing the signals in the fibers is employed, based on a pre-determined selection criteria (i.e. signal amplitude, power, wavelength etc.) in accordance with the network protocol and timing. If the quality of the signal in the primary fiber is deemed inadequate, the bias to the photodiode is switched off and applied to the bypass photodiode thus switching in the bypass fiber signal which is then sent to the signal conditioning electronics for re-transmission.

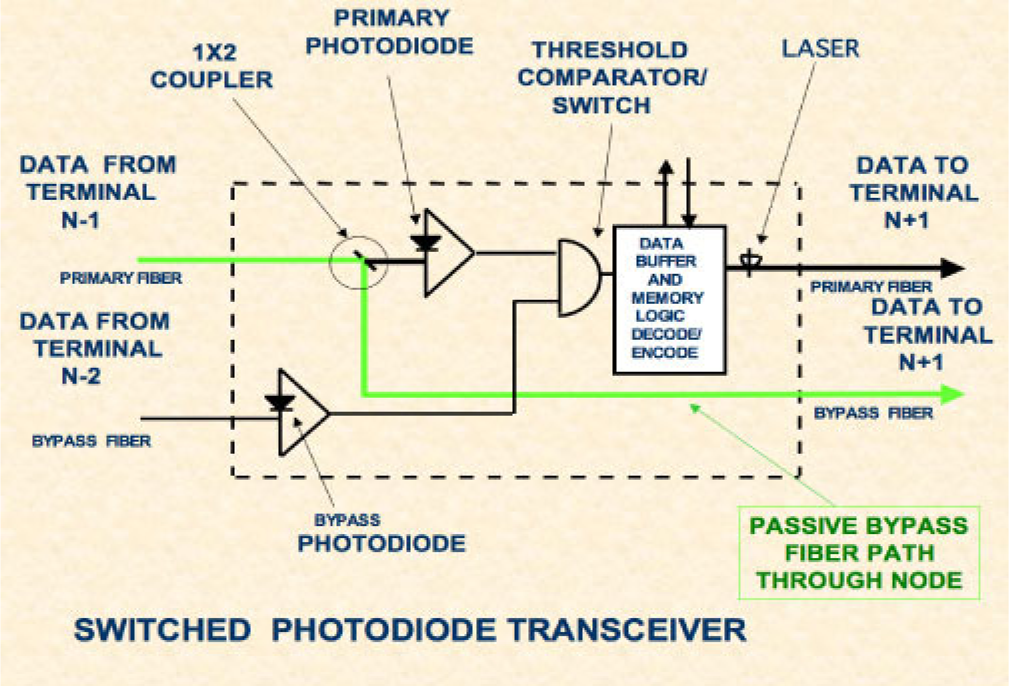

Figure 5 A Shunted Ring Transceiver

Wavelength Division Multiplexing

Wavelength Division Multiplexing (WDM) is a required technology when multiple signal types need to be accommodated or when the total bandwidth presented to the network exceeds the capacity of the available numbers of fibers. Again, a ring network is desirable wherein individual nodes within the ring can access individual wavelengths for reception and transmission. Figure 6 depicts an access module for WDM rings[1]. This module is specifically designed to provide interconnect between nodes within a rack and between racks. The Sum and Distribution paths are unidirectional. The Sum path collects all of the transmission wavelengths and the Distribution path distributes this optical composite to other nodes. The internal optical outputs of a node are combined with the incoming composite signal of the previous node and passed to the next node.

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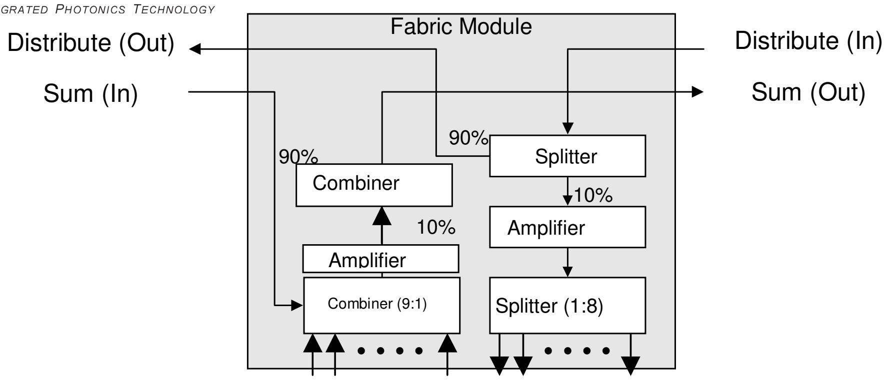
[1] The access module depicted is referred to as a fabric module in reference [1].



Characteristics

- Uses non-wavelength specific combiner to add eight local node wavelengths to system SUM signal
- Primary optical SUM path is passive
- Primary optical DISTRIBUTE path is passive
- Non-wavelength specific splitter delivers DISTRIBUTE signal to eight local nodes
- Fiber amplifier is used to increase power locally when necessary

Figure 6 Fabric Module Implementation [1]

Passive Optical Networking

This section highlights the operation, advantages and limitations of passive networking. In terms of reliability and cost, passive networking is the ideal solution. However, passive splitting becomes infeasible when the system gain (transmit power minus receiver threshold) is less than the sum of the losses between transmitter and receiver. These losses are generally dominated by the split ratio: the number of remote nodes driven by a single transmitter. If the data rate is low enough that receiver thresholds are low, high system gains can be achieved with moderate transmit powers so relatively large split ratios (e.g. 32 to 1) are possible. When the data rate delivered to individual nodes is high the system gain is too low to permit large split ratios. This section will provide definitive analyses to show the relationships between achievable split ratios, transmit power, receiver threshold and bandwidth.

Multiple protocols are possible for passive optical networking. The most common approach utilizes a Time Division Multiples (TDM) downstream and a Time Division Multiple Access (TDMA) protocol upstream (Figure 7). The TDM downstream signal contains synchronization, data, and upstream transmit control and is received by all nodes. The TDMA upstream protocol uses burst transmissions from each node that occur within time slots specified within the downstream signal. Guard bands around each upstream time slot ensure that two nodes do not interfere with each other.

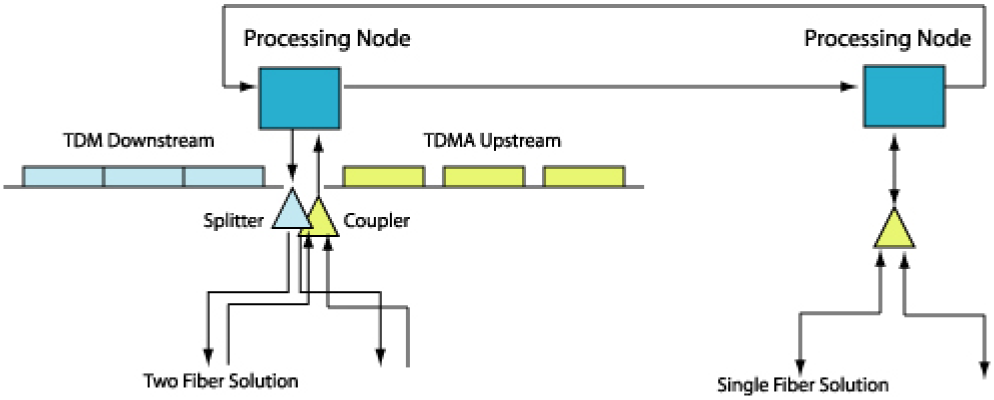


Figure 7 TDM/TDMA Protocol Through Passive Couplers and Splitters

Although any upper layer protocol can be carried on the physical transmission links, an Ethernet protocol is most useful. These systems are sometimes referred to as Ethernet over PON or EPON. As an example of the capacity of an EPON system, consider a raw data rate of 100 Mbps and 1500 byte Ethernet frames with 26 bytes of overhead. If eight bytes of margin are provided for time slot isolation, the number of time slots is $100(10)^6/(1534*8) = 8148$ slots/second. An individual time slot provides 1500*8 = 12 kbps of payload. Higher rates are implemented by assigning multiple slots to a channel.

Single Fiber v. Two Fiber

Figure 7 depicts two modes of operation: a two fiber solution. Because a splitter and a coupler are basically the same device a single fiber solution is readily available by combing both operations in a single device. Although not shown in Figure 7, the single fiber solution requires separation of the downstream and upstream signals at both terminal ends. The separation function is provided by optical circulators as shown in Figure 7a.

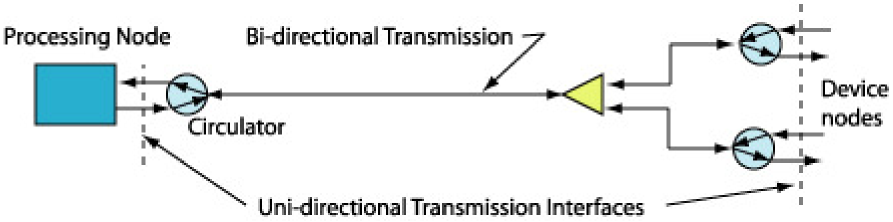


Figure 7a Circulator Usage for Signal Isolation at Terminal Endpoints

The main disadvantage of the need for circulators is the insertion loss of approximately .7 dB at each end of the link. Advantages of single-fiber usage, beyond the obvious, is the ability to infer transmit signal quality from the received signal quality (.e.g. attenuation in the path) and the ability to back off the transmit power (for eye safety) when no incoming signal is present. An additional disadvantage of single-fiber usage is difficulty that arises when an active device is needed at an intermediate point in the transmission path. A later section discusses the application of active splitters which are more easily accommodated in a two-fiber transmission plan.

Passive Optical Networking Capacity Analysis

This section determines the system limits of a PON wherein a single transmit signal is delivered to multiple receivers through signal power splitting. The basic analysis involves determining how many times the signal power can be divided and have adequate power delivered to each destination. Included in the analysis are connector losses and a loss margin. Transmission losses in optical fiber are considered negligible in the avionics application.

This analysis focuses on the downstream direction: form a central source to multiple destinations. The upstream problem is less restrictive because there is no significant amount of signal splitting in the upstream couplers. The analysis assumes separate fibers are used for downstream and upstream transmission. If a single fiber is to be used for both directions the loss of optical isolators needs to be included. (Optical isolators typically add a little over 1 dB of loss at each end.) Component parameters needed for the analysis are:

Optical transmitter launch power (in dBm): P_t
Optical receiver threshold power (in dBm): P_r
Data Rate at which the threshold is determined: R_r
Connector loss (in dB): L_c
Number of series connectors in the path: N_c
Excess Loss in a splitter (in dB): L_e
System margin (in dB): M_s
Total downstream data rate: R_d

A key factor in the system analysis is the power budget between the source and the destination referred to as the System Gain $G_s = P_t - P_r$. Because the receiver sensitivity is dependent on the data rate, R_r needs to be known to determine G_s at differing downstream data rates. For example, if the transmission rate is reduced by a factor of 2, the energy in a single bit doubles and thereby lowers the receiver threshold, and increases G_s, by 3 dB.

The basic relationship used to determine the maximum split ratio S_{max} is:

$$Gs(\text{at } R_r) + 10*\log_{10}(R_r/R_d) > N_c*L_c + 3*\log_2(S_{max}) + L_e + M_s$$

Table 1 lists maximum (binary) split ratios at differing downstream data rates R_d for three different values of G_s(at 1 GHz): 10, 15 and 20 dB. The parameter values assumed in the analysis are: $L_c = 0.5$ dB, $N_c = 4$, $L_e = 0.5$ dB and $M_s = 3$ dB. Note that the data rate delivered to each destination (assuming equal rates for all) is R_d/S_{max}.

Table 1 Maximum Split Ratios

Downstream Rate (MHz)	10 dB System Gain (1 GHz)	15 dB System Gain (1 GHz)	20 dB System Gain (1 GHz)
10	256	512	2048
20	128	256	1024
50	32	128	512
100	16	64	256
200	8	32	128
500	4	16	32
1000	2	8	16
2000	1	4	8

Table 1 reveals that significant split ratios can not be achieved at relatively high downstream rates unless G_s at 1 GHz is relatively high. Examples of commercially available transmitters and receivers with system gains at 1 GHz in the range of 15 dB are FTR-8519 devices from Finisar. (These devices are bidirectional so even better performance could be achieved with separate fibers.)

VCSEL Split Modules

Because VCSEL devices can be implemented in compact, low cost and relatively low power arrays they are naturally suited to replace passive splitters when the latter are unsuitable. Figure 8 depicts the basic functionality of a VCSEL in this application.

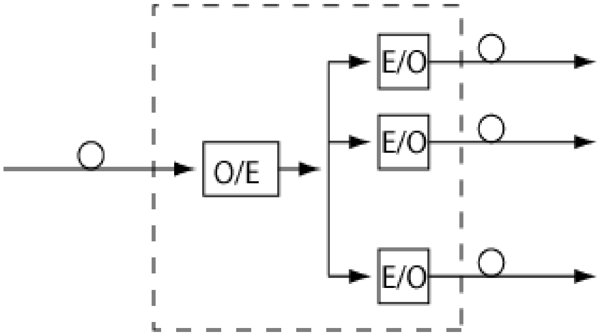


Figure 8 VCSEL Implemented Active Splitter

VCSEL Application to Sensors

A particularly useful application of VCSEL technology is illustrated in Figure 9 wherein a VCSEL array is implemented with each array element producing a separate wavelength of an optical signal. The individual sensor devices thereupon receive different wavelengths which are modulated according to the sensor environment. The separately modulated signals are combined by the passive coupler and delivered to the processing node which demultiplexes the incoming WDM signal and processes (demodulates) the individual sensor wavelengths to extract the sensor environment (e.g. temperature or position).

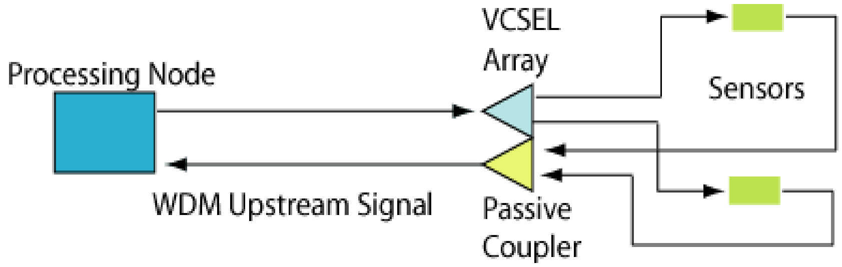


Figure 9 VCSEL Array and Passive Coupler Combination for Sensor Applications

The application described above assumes that the sensors are purely passive. The basic concept, however, can be extended to include an active actuator associated with the sensor. In this case, the actuator can be controlled by modulating (e.g. pulsing) the downstream signals with control information. The sensor returns its encoded environmental status with and without downstream encoding on the optical signal. Encoding of the downstream control information can be performed in the centralized node with each actuator responding to differing addresses or the VCSEL module can be enhanced to individually encode the control information onto a designated output. Although Figure 9 depicts the use of two-fiber transmission because it most easily supports active elements in the downstream direction it is possible to use single-fiber solutions with optical isolation where necessary.

A further extension of the above configuration is shown in Figure 10. In this configuration the end device (Remote Terminal) sends digital information back to the processing node by modulating (e.g. pulsing) the returning optical signal. A particularly attractive feature of this approach is that the WDM spacing is defined in the VCSEL array and not by individual sources in the end devices. Thus, wavelength separation is easier to maintain.

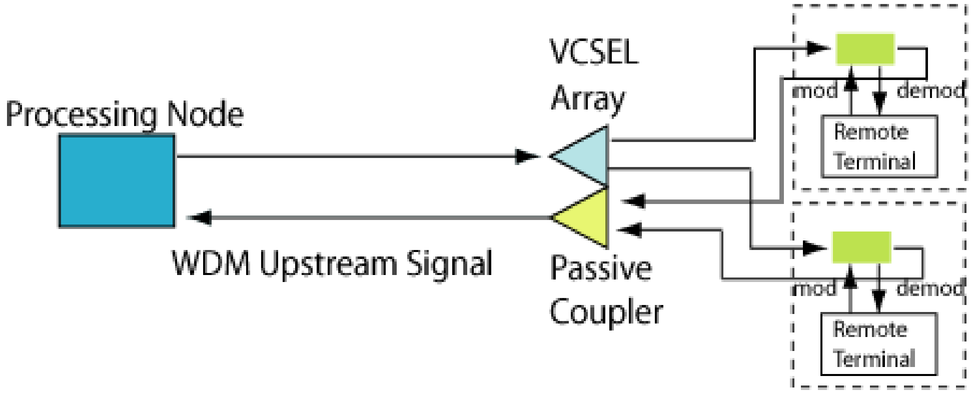


Figure 10 VCSEL Array and Passive Coupler Combination for Remote Terminal Applications

Glosssary

APON	ATM Passive Optical Network.
BPON	Broadband Passive Optical Network. (ATM transport standard G.983)
Directivity	Amount of coupling between two input ports of a coupler. Also referred to as isolation between input ports.
EPON	Ethernet Passive Optical Network. (1.2 Gbps for Internet Access)
Excess Loss	Energy loss from an input to an output in excess of the splitting loss.
ICP	Integrated Core Processing. Avionics platform wherein a collection of identical processing nodes are configured in software to perform avionics functions using wideband connections to other nodes or end devices.
FSAN	Full Service Access Network.
Insertion Loss	The sum of the splitting loss and the excess loss.
LRM	Line Replaceable Module
MEMS	Micro Electro-Mechanical System
MMIC	Monolithic Microwave Integrated Circuit.
OBIS	Optical Backplane Interconnect System. NAVAIR sponsored program with 1-Gbps optical interconnects between modules and a removable/replaceable optical backplane
Return Loss	The ratio (in dB) of the amount of energy coming out of an input port to the amount of energy entering the same port.
SCI	Scalable Coherent Interface. IEEE Std. 1596-1992
SCM	Sub Carrier Multiplexing. A frequency division multiplexing format wherein individual information bearing signals modulate separate RF carriers. The modulated carriers are summed using an RF power combiner and the resulting combined signal used to modulate an optical carrier for transmission on an optical fiber.
Splitting Loss	Ratio (in dB) of energy loss from an input port to an output port resulting from the designed amount of energy splitting.
System Gain	Difference between a transmitter output power and the input threshold of a receiver for a specified level of performance (maximum bit error rate).
TDM	Time Division Multiplexing. Multiple channel transmission wherein individual channels of communication are defined by a specific time slot within repetitive frames of transmission containing multiple time slots.
VCSEL	Vertical Cavity Surface Emitting Laser
VMS	Vehicle Management System

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