

FIBER-OPTIC NETWORKS FOR TELEMETRY APPLICATIONS

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ABSTRACT

In this paper, we investigate high-capacity fiber-optic networks for real-time telemetry applications. The network topologies and related network components are analyzed for telemetry fiber-optic Local Area Network (LAN) and Metropolitan Area Network (MAN) as well as MAN internetworking with LANs. Two types of multiplexing techniques, namely, Wavelength Division Multiplexing and Time Division Multiplexing, are proposed to support real-time high-capacity telemetry applications, and the perspective of such networks is also considered. Finally, the optical modulation technique and the choice of optical devices are discussed, which are based on improving the reliability of fiber-optic LANs and MANs.

INTRODUCTION

Optical fibers have several important advantages over metallic wire and coaxial cables. For example, light weight improves the flexibility of field installation and maintenance; very large bandwidth (25,000 gigahertz) and low attenuation (0.2 dB/kilometer) offered by single-mode fibers greatly increase the transmission bit-rate and distance; Electromagnetic Interference (EMI)/Electromagnetic Pulse (EMP) immunity and no crosstalk (between fiber lines) significantly improve the communication reliability and quality. Moreover, no electromagnetic radiation from fiber lines can greatly enhance the security. On the contrary, even using well-shielded coaxial cables can only provide a few gigahertz (GHz) bandwidth, but the transmission distance is very short, for instance, it can only support 1 GHz signals to transmit about 0.1 kilometer (km). Moreover, if metallic cables are used,

the EMI/EMP and crosstalk would become serious problems which can dramatically degrade the system performance. As a result, fiber-optic-based Local Area Network (LAN) and Metropolitan Area Network (MAN) are very attractive to both military and special industry telemetry applications where real-time communications and high-speed, high-quality transmissions are required.

In this paper, we investigate the implementation of physical and data-link layers for high-capacity fiber-optic telemetry networks. Two types of multiplexing techniques are proposed, namely, Wavelength Division Multiplexing (WDM) and Time Division Multiplexing (TDM), they can provide the capability to support high-capacity, high-speed networks and real-time multiservice applications. The network architecture and related network components are analyzed for telemetry fiber-optic LAN (FO-LAN) and fiber-optic MAN (FO-MAN) as well as MAN internetworking with LANs. The applications of such networks are also discussed. Furthermore, the optical devices and optical modulation technique, which can be used for improving the reliability of FO-LANs and FO-MANs, are discussed. In Section 2, we briefly overview the conventional medium access control protocols. In Section 3, the multiplexing techniques are proposed for FO-LANs and FO-MANs. In Section 4, we analyze the network topologies and related network components. The optical modulation technique and the choice of optical devices are discussed in Section 5.

CONVENTIONAL MEDIUM ACCESS CONTROL PROTOCOLS

Several medium access control protocols have been developed for LANs in which many users are allowed to transmit messages to other stations through a common channel under the reasonable control by using various effective strategies [1]-[4]. The conventional medium access protocols can be classified into two categories. One is random access protocol such as ALOHA, carrier sense multiple access (CSMA), and CSMA with collision detection (CSMA/CD). The other is controlled access technique such as centralized scheme-polling and distributed controlled-access method-token passing [2]. The main purpose of using these protocols is to achieve bandwidth efficiency for multiple users sharing a common channel in the metallic cable LANs where the transmission bandwidth is usually restricted, whereas the bandwidth efficiency is not a main issue in fiber-optic networks because of the extremely-wide bandwidth offered by today's fibers. Thus, these protocols are suitable for low bit rates and bursty traffic. When the transmission speed becomes higher (e.g., in high-speed fiber-optic networks), however, the above access schemes are inadequate because the ratio of propagation delay over packet transmission time increases. Furthermore, the MAN applications make these protocols inefficient due to the large propagation delay to packet-length ratio [5]. Another main disadvantage of the above mentioned protocols is that only one of the users is permitted to send messages at any time in a network due to the mechanism of these protocols, so the

real-time and parallel communications can not be supported. However, for military telemetry applications such as launching vehicle bases for missiles and satellites as well as spacecrafts, and for some special telemetry applications such as telemetry in aircrafts and spacecrafts as well as in power stations, the networks are required to offer high-speed and parallel communications as well as real-time multimedia services. In order to meet these requirements, the feasible multiplexing techniques should be investigated for telemetry fiber-optic networks.

MULTIPLEXING TECHNIQUES FOR HIGH-CAPACITY FIBER-OPTIC TELEMETRY NETWORKS

For high-speed optical fiber networks, if the complex channel access control schemes are used, the complicated access procedures and data buffering must be executed very quickly to match such high-speed data transmission speeds [6]. Unfortunately, in the network nodes data throughput bottlenecks can be introduced by the implementation-related problems which in turn prevent these access schemes to use in very high-speed optical fiber networks. Usually, for very high-speed applications, the amount of processing which is required by channel access control protocols should be taken as minimal as possible at gigabit (Gb) level so as to greatly simplify the gigabit logic circuits. In this section, we discuss two types of feasible multiplexing techniques, i.e., WDM and TDM, for supporting multigigabit-per-second (Gb/s) fiber-optic telemetry networks.

Frequency Division Multiplexing (FDM) and TDM are the very mature multiplexing techniques in electrical communications, and they have been widely used for telemetry systems. One major advantage of TDM over FDM is that multiplexing cost per signal decreases as multiplexing speed increases. With the lowered cost and increased speed of digital electronics, TDM is more cost effective than FDM [7]. However, since FDM does not require various different users to be synchronized as in TDM case, the flexibility of FDM systems is improved. The cost of a FDM system is primarily dependent on the modulators, demodulators, and filters required to divide the transmission band [1], so FDM systems are still used in various telemetry networks including analog or digital transmission and combination of both because of the lower cost. However, the main impairment for electrical FDM systems is due to intermodulation effect and adjacent channel interference which heavily limit the total number of telemetry channels.

Employing TDM and WDM in fiber-optic networks are more attractive, because they have specific characteristics which distinguish themselves from the corresponding electrical versions. In the following, we deal with the design of fiber-optic TDM and WDM networks.

Fiber-Optic TDM Networks

TDM is a synchronous scheme which shares fiber bandwidth by all users transmitting messages at different time slots. Optical TDM can achieve much higher bit rates (e.g., 100 Gb/s) than electrical TDM, because optical processing removes the bottleneck at the electrooptic interfaces [8][9]. The block schematic of a star-coupler-based fiber telemetry network using optical TDM is shown in Figure 1. A centralized optical clock source located in the telemetry control station (TCS) generates a stream of very short optical pulses at the data rate $1/T$, then every bit of the low-speed electrical data which is sent by TCS or each telemetry terminal (TT) with identical data rate $1/T$ is optically sampled by the short optical clock pulses at the electrooptic modulator, and the sampled optical data is multiplexed into the correct time-slot assigned to the transmitter via fiber delay lines. Then the multiplexing signals are broadcast to all users by a passive star coupler. At the receiving end, the i th receiver correctly delays the clock signal by adequate amount and adds it to the incoming signal sequences. Since the correct addition of TDM signal and the delayed clock always results in the desired signal riding atop the clock signal, using a threshold detector can easily detect the signal at a receiver [8][9].

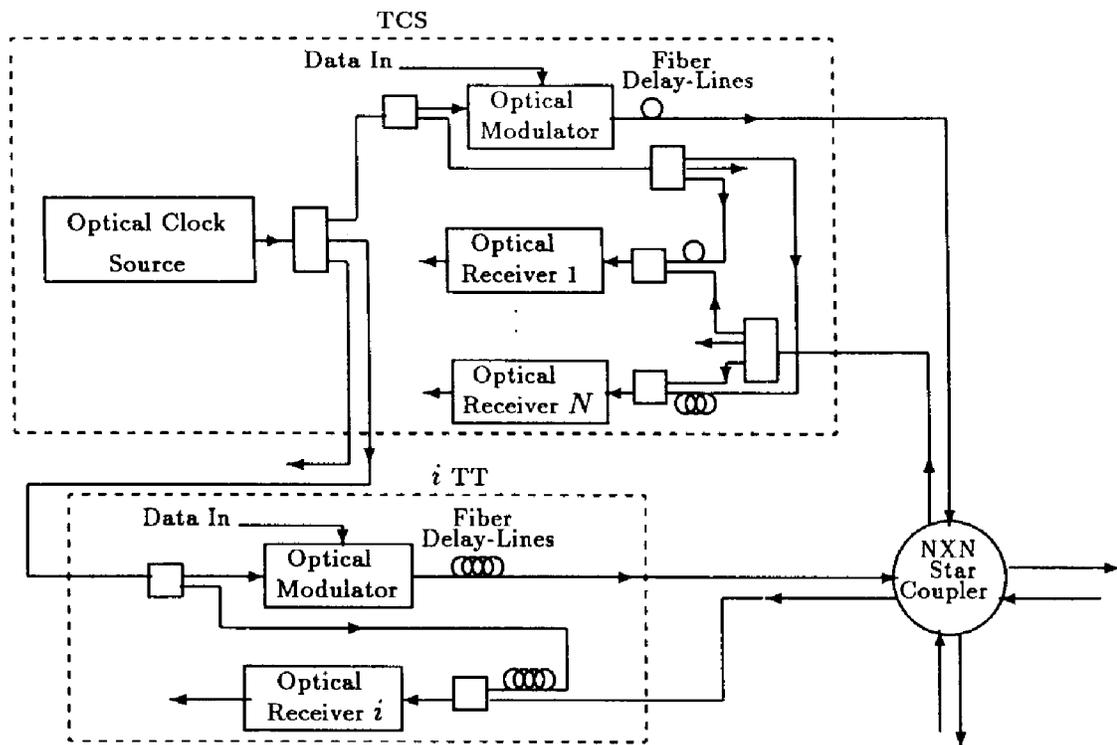


Figure 1: Block Schematic of a Star-Coupler-Based Fiber Telemetry Network Using Optical TDM

For telemetry applications, transmitter-based time slot assignment is more reasonable than that assigned to the desired receiver, because it permits TCS to easily receive messages from all TT and to feasibly broadcast the control information to all TTs. In this paper, the “telemetry terminals” are regarded as various sensor-based measuring instruments which contain analog to digital (A/D) converters and digital interfaces with the telemetry network unless otherwise specified, so the telemetry terminal-to-terminal communications are not required in general. In this way, the TDM signals which are sent by N TTs can be simultaneously separated and regenerated in a TCS via N parallel optical receivers, while only a single receiver is used in each TT. However, this scheme does not exclude the possibility of supporting communications between TTs if the variable or parallel time-slot decoders are adopted in TTs.

TDM can provide high traffic demands and does not suffer from cumulative delay compared with the above discussed medium access schemes, so fiber-optic TDM can offer ultra-high throughput up to 100 Gb/s, which permits to realize ultrafast telemetry networks. Currently, using digitized telemetry and related equipment have become a major trend. Standardized digital telemetry instruments are readily available now. Therefore, high-speed fiber-optic TDM networks are very promising to future telemetry applications. However, TDM suffers from the disadvantage that if a terminal has nothing to send as encountered in computer communications, its slot will be left idle, while other users may have packets waiting to be transmitted, so this scheme is inefficient for bursty traffic [3]. This problem is especially serious when most of terminals in a network is highly bursty, for which bandwidth is greatly wasted during the period of few active users transmitting. Moreover, requirements of variable bit-rate transmission and multimedia services can not be easily satisfied by TDM. As a result, TDM is suitable for fixed data-rate and continuous-type digitized telemetry. Moreover, the severe phase synchronization related to very short optical pulses limits the geographic distance to relatively short, so optical TDM is adequate to LANs.

Fiber-Optic WDM Networks

WDM is another practical solution for utilizing the enormous fiber bandwidth by users transmitting messages at different wavelengths. For example, when at a spacing of 1 GHz, 25,000 discrete channels could be in principle provided, while 2,500 channels could be realized at 10 GHz spacing. Here we distinguish WDM from optical FDM. The term WDM is used to indicate the case where channel spacing are large compared with their signal bandwidth (measured in wavelength units) and direct-detection technique is utilized [9]. Typically 1 nm (125 GHz) WDM bandwidth can support bit rates up to 2 Gb/s [10]. The bandwidth of fibers is most easily accessed in the wavelength or frequency domain rather than in the time domain. Although optical coherent FDM can offer more channels and higher receiver sensitivity than non-coherent WDM, the performance of optical

coherent FDM systems is impaired by laser phase noise, polarisation fluctuation, or local oscillator intensity noise, whereas none of these problems are present in WDM networks due to direct-detection and wider channel spacing [11]. In addition, frequency stability is a main problem in an optical FDM network while it is less severe in a WDM network where channel spacing is wider. Moreover, WDM networks have reached the stage of commercial availability. Therefore, considering the requirements on complexity, feasibility, and cost, WDM is more attractive to FO-LANs or FO-MANs than optical coherent FDM.

The block diagram of a typical star-coupler-based WDM network is shown in Figure 2. Such a network is composed of N fixed wavelength transmitters, wideband passive star coupler, one diffraction-grating wavelength demultiplexer for TCS and $N - 1$ fixed optical filters for all TTs, or N diffraction-grating wavelength demultiplexers. At each receiving node, the wavelength demultiplexer is followed by either a fixed or multiple fixed receivers which are required for different application purposes [12]-[14], while the wavelength filter is followed by a single receiver. Each node in the network transmits its messages on a unique wavelength, and the transmitted signals from all nodes are passively combined in a $N \times N$ transmissive star coupler. Then each of the wavelengths in the network is broadcast to all receiving nodes. This scheme can provide both point-to-multipoint broadcast connectivity and point-to-point transmission, so it can feasibly realize a high-capacity telemetry network where the TCS simultaneously receives all messages sent by $N - 1$ TTs due to a bank of $N - 1$ receivers used, and the command information from the TCS is easily broadcast to all TTs. If necessary, the TT-to-TT transmissions can also be offered by using multiple receivers in the corresponding TTs. Furthermore, video and voice transmissions can be feasibly supported in WDM networks. For further applications, in order to efficiently solve communications among many potential users in a telemetry network, the wavelength tunability for both transmitter and receiver is required. Several techniques can be used for this purpose [11][13]. The fast switching requirement implies the use of semiconductor laser devices. Multisection single-longitudinal mode lasers, e.g., distributed feedback and distributed Bragg reflector lasers, are main candidates. At each receiving node, a tunable optical filter is employed to select the desired wavelength and rejects the remaining ones. To realize it, one can use tunable fiber Fabry-Perot filters, tunable Mach-Zehnder filters, acoustooptic tunable filters, electrooptic tunable filters, and wavelength-selective filters based on DFB optical amplifiers. An alternative scheme is to use multichannel wavelength-switched optical transmitters and receivers with grating cavity/demultiplexer [15], which will be discussed in Section 5.

WDM has several important characteristics which distinguish itself from another multiplexing techniques [14]. It makes WDM networks very suitable for military and industry applications. Firstly, wavelength multiplexer/demultiplexer are totally passive devices containing no powered electronics, so the need for air-conditioned controlled-environmental vaults and remote power backup is eliminated and the cost is dramatically

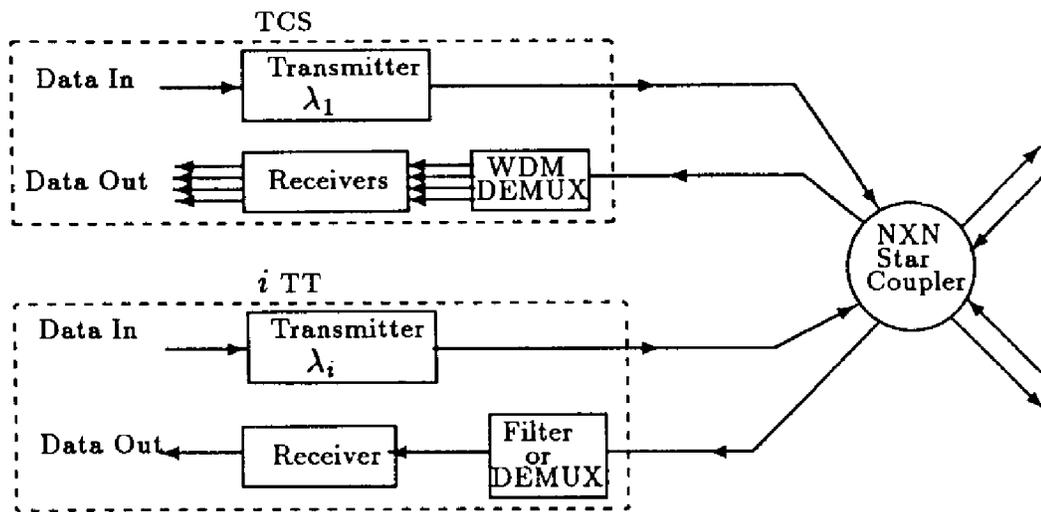


Figure 2: Block Diagram of a Typical Star-Coupler-Based WDM Telemetry Network

reduced compared with using the electronic multiplexing techniques. Moreover, the maintenance for WDM passive devices will be minimal. Consequently the problems associated with EMI/EMP and difficulty of field maintenance are effectively solved. Thus, WDM is very attractive to military and special industry telemetry application. Secondly, WDM channels are independent of each other and WDM channels are completely transparent to signal formats, data rates, multiplexing approaches, and protocols, so WDM networks can easily support such applications as multi-bit-rate or variable-bit-rate transmission, multimedia services, digital or/and analog telemetry instruments, and TDM or FDM system or combinations of both. Furthermore, it permits to use either different protocols or a single protocol in the WDM networks. The error detection, correction, and recovery schemes can be also allowed to easily use in WDM networks for the purpose of reliable communication. As a result, the network flexibility is greatly improved.

At the present time, due to the economic reason, analog telemetry instrument and system are still widely used, and in the near future they may be still used together with digital telemetry systems to achieve lower costs, especially for industry applications. Using WDM can implement cost-effective hybrid telemetry networks where analog and digital TTs, TDM systems (both electrical and optical), and FDM systems are used. Another advantages of WDM over optical TDM are that the upgrades and other changes in service demands can be easily provided because of WDM channel transparency, and no any node in WDM networks is required to process data at higher than the individual transmission rate. The characteristic of channel transparency can also allows the WDM network to be fully compatible with future telemetry standards. Therefore, based on these considerations, we propose to use WDM networks as the backbone of telemetry networks. Figure 3 illustrates the applications of fiber-optic WDM networks.

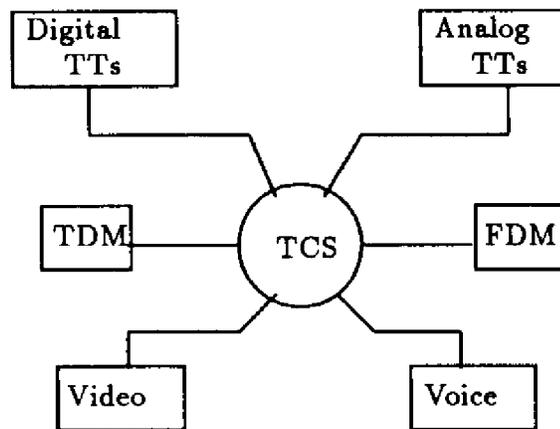


Figure 3: Applications of a WDM Telemetry Network

As encountered in TDM networks, if a network has a large number of highly bursty users, however, WDM scheme is inefficient to utilize optical bandwidth. On the other hand, today's state-of-the-art, grating-based WDM components can only accommodate up to 50 wavelengths [14], the further restriction on the number of available WDM channels (N) is due to channel spacing which limits N to a relatively lower value compared with optical coherent FDM. However, the distinguished feature of WDM technique is that the transmission bit rates or bandwidths supported by individual WDM channels are much higher (e.g., 2 Gb/s) than those by using conventional electrical FDM. In order to efficiently increase the capacity of a WDM network while maintaining less system complexity, subcarrier multiplexing (SCM) and TDM can be embedded in each node. SCM has the similar properties to WDM. For example, SCM is also transparent to data formats, data rates, and protocols, because individual SCM channels are independent. It is very flexible to integrate any new service in a SCM/WDM network by using new subcarrier. For the present applications, SCM/WDM is very efficient and attractive. This approach only needs one WDM optical transmitter and receiver per node instead of one WDM optical transmitter and receiver at each TT, and the signals can be easily multiplexed and demultiplexed by using commercially available optical and electronic components, so it can realize the cost-efficient broadband network for telemetry applications.

NETWORK TOPOLOGIES AND RELATED NETWORK COMPONENTS

The network topologies and related network components are of important topics which affect the design of telemetry networks. In this section, we focus on WDM-based fiber-optic networks.

For a passive network, the better network architecture is of passive star topology. The optical star coupler option is better than other options such as the passive bus, because stars have low excess loss and good coupling uniformity, and they are reasonably easy to

manufacture and are readily available [11][13]. For instance, a large $N \times N$ star can be built up by using either elemental directional 2×2 couplers or planar input waveguide array [9][16]. In a star network, the excess loss (in dB) grows only logarithmically and is relatively modest. On the contrary, for the tapped-bus topology, the number of stations is restricted due to the large accumulated excess loss of the couplers. In a tapped-bus network, the excess loss grows linearly with the number of taps and is much greater than that in the former case [9][11][16][17]. Therefore, fiber optic networks based on passive star-coupler physical topology are the most attractive candidate for FO-LANs and FO-MANs with a large number of users.

For telemetry FO-LANs or FO-MANs, we propose to use passive star-based topology shown in Figure 4a. Two kinds of optical components can be used for realizing this network architecture, they are dependent on the practical applications. For the common telemetry applications where all TTs only communicate with TCS or central computer (CC), and TT-to-TT communications are not required such as simple telemetry networks or telemetry in aircrafts and shuttles as well as spacecrafts, the single-star architecture is needed for FO-LANs and FO-MANs. Grating-based wavelength multi/demultiplexer can be used for this purpose as shown in Figure 4b. This approach can effectively reduce the number of physical fiber lines compared with using $N \times N$ optical star coupler, especially when all TTs are located in the small area and are relatively far from CC or TCS. However, if intelligent telemetry terminals are used and intercommunications with many users are required, a $N \times N$ optical star coupler would be used for connecting all N users.

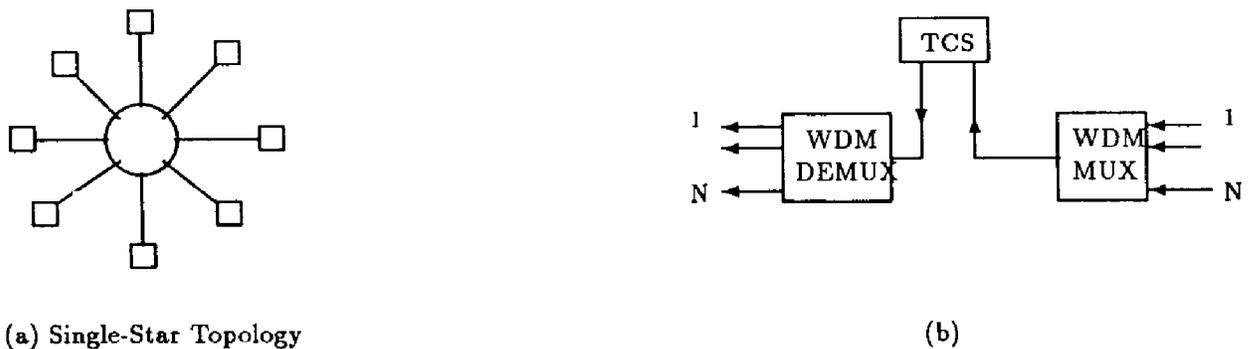
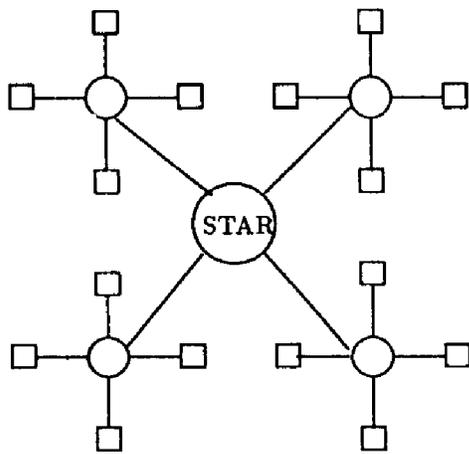
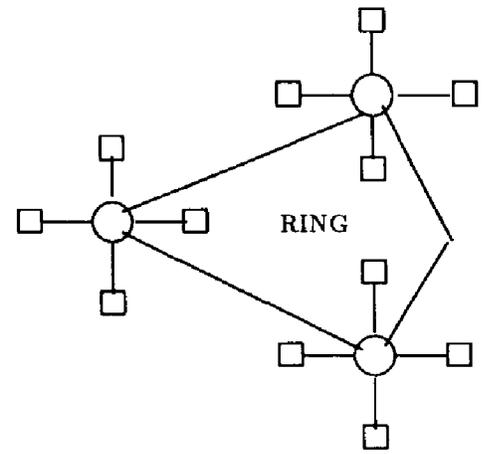


Figure 4: Single-Star Architecture and Simple Implementation

When several telemetry FO-LANs are required to internetwork with a FO-MAN or to interconnect with each other, and the MAN interconnections such as communications among multiple TCSs or CCs are required, the more complicated network architecture should be utilized. In order to efficiently solve these problems, we propose to use star-star topology for LANs or MANs interconnecting or MAN internetworking with LANs shown in Figure 5a, while to use star-ring topology for a few MANs interconnecting as shown in Figure 5b. The outer star is used for providing the connectivity within each separated



(a) Star-Star Topology



(b) Star-Ring Topology

Figure 5: Star-Star Topology and Star-Ring Topology

FO-LAN based on using star coupler or grating-based wavelength multi/demultiplexer as discussed in the above, while the inner star is to offer the interconnections of all LANs or MANs or MAN internetworking with LANs. If the number of MANs interconnected is quite small, and the geographic distances among MANs are significantly long, using a ring topology can feasibly connect MANs into a single ring network. To implement it, one can use directional couplers (both asymmetric and symmetric) as optical taps, then at each receiving node, diffraction-grating wavelength demultiplexer or optical filter is employed to separate the optical channels. Here we propose an alternative method to construct the ring topology, that is, using 2×1 couplers for transmitters access to a ring, then using a narrow-band wavelength filter based on an asymmetric semiconductor directional coupler in each receiving node. Compared to the former, our proposed structure is more adequate and reasonable. This transmitting-type bandpass wavelength filter has a bandwidth as narrow as 5.4 nm. with 1.3 mm device length at $1.5 \mu\text{m}$ centre wavelength region, and it is capable of electrically tuning the filter centre wavelength over the transmitting wavelength band [18]. Advantages of using this technique are that the complex processes such as grating fabrication is eliminated, the bandwidth and centre wavelength can be freely selected by controlling the compositions of the materials. Although employing ring topology results in higher accumulated excess loss than star topology, since the number of MANs interconnected is very small, the excess loss is not a major problem. By contrast, it can enhance to reduce the number of physical fiber lines and then increase the flexibility of network maintenance for long-distance transmissions. The perspective of high-capacity WDM telemetry networks is illustrated in Figure 6.

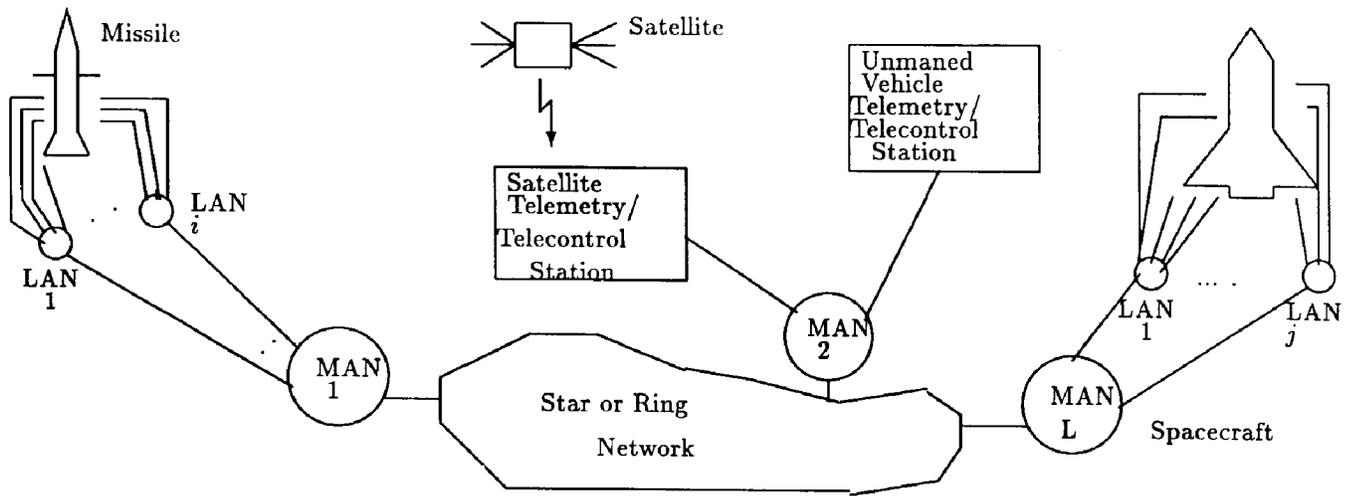


Figure 6: High-Capacity WDM Telemetry Networks

OPTICAL MODULATION TECHNIQUE AND CHOICE OF OPTICAL DEVICES

Since optical fiber transmission systems using intensity modulation and direct-detection are modeled as positive systems, only optical power-on and -off states are used in such systems. For asynchronous or packet message transmission, the lack of optical negative component make the reliable distinction between active and silent states of a network or between data logic 0 and no message state at the optical receiver very difficult. To eliminate it, the adequate modulation technique should be employed in such optical fiber transmission systems. We propose an reliable modulation scheme called the Partial Trilevel Coding for military telemetry applications to achieve high reliability while maintaining less system complexity. The basic principle of Partial Trilevel Coding is that, the logic 1 and logic 0 of data signals are represented by high-level (P_h) and low-level (P_l) optical power signals, respectively, whereas optical power-off signal denotes the “No-Message” state as shown in Figure 7. Three output states can be easily obtained from two threshold detectors at the receiver. The low-threshold one is utilized to identify the states of the corresponding optical transmitter and to regenerate the transmitting control signal; the high-threshold detector is used for the signal detection once if the receiver is in the “Message” state, so this technique efficiently solves the problem associated with no message and logic 0 states as well as logic 1 state.

For military applications, the high reliability is specifically required, and the work environment is very severe, which imposes restrictions on the choice of optical devices. WDM/optical TDM fiber-optic networks need to use laser diodes as optical sources due to the demands on high output power and high modulation bandwidth as well as narrow spectral width. Recently, high-reliability, high-power, single mode laser diodes have been fabricated [19], and the reliability test has shown that an average lifetime of these lasers is

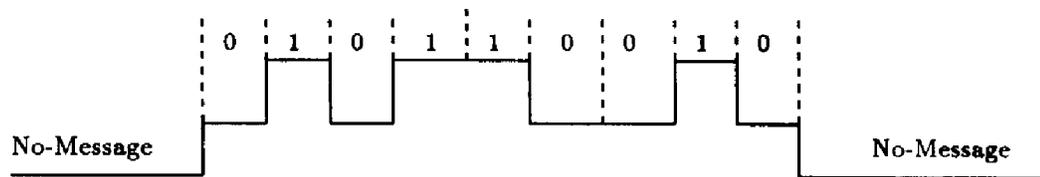


Figure 7: Partial Trilevel Coding

greater than 20000 hours at 50°C at an operating power of 100 mW CW while 100000 hours lifetime can be achieved at 25°C. Such laser diodes have modulation bandwidth larger than 2 GHz in the 820-860 nm wavelength range, so they can meet the requirements of military FO-LANs applications such as aircrafts, shuttles, spacecrafts, and various local area telemetry stations. Furthermore, using short wavelength near 0.85 μm is very attractive, because it allows to use the more mature GaAlAs transmitter and silicon receiver which are more reliable and less expensive. Although optical receivers using the avalanche photodiode (APD) can achieve higher receiver sensitivity than that using pin photodetector due to its internal avalanche gain, unfortunately the APD requires a high voltage bias supply (typically 100-300 V) which must be adjusted to track the temperature dependence of the APD gain, then it increases the receiver complexity and reduces the system reliability. Moreover, the impulsive noise can be induced in the multiplied signals by changing the high voltage bias of an APD (through the power supply of APDs), because the strong EMI/EMP sources usually exist in the military environment. On the contrary, using a pin photodetector can solve these problems, so pin photodetectors are more suitable for military applications. In addition, since multimode optical fibers have better mechanical property and are more feasible to maintain than single-mode fibers, they are suitable for various military FO-LANs where the transmission distances are usually less than 1 km, especially for aircraft/shuttle/spacecraft applications which are limited to ~ 100 m. Thus the optical power loss caused by multimode fibers can not place restrictions on the system performance. Moreover, the grating devices typically feature multimode fibers, whereas grating components using single-mode fiber arrays usually suffer higher loss due to small core diameter of single-mode fibers [14]. However, FO-MANs require to use single-mode fiber, because its very low attenuation makes the transmission distance extend for several tens of kilometers while the power loss still keeps in relatively low values.

In order to realize wavelength tunability in transmitting or/and receiving ends, wavelength-tunable lasers and tunable filters/receivers are required. According to the requirements of high reliability, multichannel grating cavity laser transmitters and grating demultiplexer receivers, which can offer up to 50 separate channels in the 1.3 to 1.6 μm wavelength range and can achieve switching time as low as a few nanoseconds [15], are more suitable for telemetry applications. A key feature of these multichannel components is their use of

an environmentally stable passive wavelength-space multiplexer such as a lens combined with a diffraction grating. The high wavelength stability coupled with the relatively wide channel spacing enabled by the wide wavelength switching range of the components allows channel transmitting and receiving wavelength bands to be presented during component manufacture. The components do not require adjustment or fine tuning in use. However, the continuously tunable lasers and amplifiers suffer from transient drift of wavelength when wavelength is switched [15].

CONCLUSIONS

High-capacity fiber-optic networks are proposed for real-time telemetry applications in this paper. We investigate two types of feasible multiplexing techniques - WDM and TDM to implement such networks. Since WDM technique has several important advantages, it makes WDM very attractive to various telemetry fiber-optic networks. Moreover, WDM networks are fully compatible with future telemetry standards to be developed, due to the characteristic of channel transparency. Then We analyze the topologies of telemetry networks. The single-star architecture is suitable for FO-LANs and FO-MANs. The star-star topology is useful for LANs or MANs interconnecting or MAN internetworking with LANs. If the number of MANs is small, and the distances among them are long, using the star-ring topology is more reasonable. The related network components are also discussed. In order to improve the reliability of FO-LANs and FO-MANs, we propose an efficient modulation technique called the Partial Trilevel Coding. The reasonable choice of optical devices are also discussed to meet the requirements for military telemetry applications.

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