

Submitted for recognition as an American National Standard

Selection of Transmission Media

Foreword—It has been commonly accepted by most automotive RF engineers that a Class C Network at a transmission rate above 100 kilobits per second (kbps) will require either a fiber optic or a shielded cable for the transmission medium. Some communications engineers have proposed that transformer coupling to a twisted pair may be an acceptable alternative to a fiber optic or a shielded cable.

It has also been generally recognized that the EMI levels available in a vehicle to corrupt data transmission are very high and cannot be filtered out of the data. The employment of a fiber optic or a shielded cable for the transmission medium would also solve this EMI problem.

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1. Scope—This SAE Information Report studies the present transmission media axioms and takes a fresh look at the Class C transmission medium requirements and also the possibilities and limitations of using a twisted pair as the transmission medium.

The choice of transmission medium is a large determining factor in choosing a Class C scheme.

1.1 Background—The Vehicle Network for Multiplexing and Data Communications (Multiplex) Committee has defined three classes of vehicle data communication Networks:

- a. Class A—Low-Speed Body Wiring and Control Functions, i.e., Control of Exterior Lamps
- b. Class B—Data Communications, i.e., Sharing of Vehicle Parametric Data
- c. Class C—High-Speed Real-Time Control, i.e., High-Speed Link for Distributed Processing

1.2 Interrelationship of Classes A, B, and C—The Class B Network is intended to be a functional superset of the Class A Network. That is, the Class B Bus must be capable of communications that would perform all of the functions of a Class A Bus. This feature protects the use of the same bus for all Class A and Class B functions or an alternate configuration of both buses with a “gateway” device. In a similar manner, the Class C Bus is intended as a functional superset of the Class B Bus.

1.3 Electromagnetic Susceptibility (EMS) Considerations—Inherent with the high data rates of a Class C Bus is a higher probability of electromagnetic interference (EMI) corrupting data. There has been a lot of research on Class B Networks that use twisted pair operating at data rates below 50 kbps and methods have been found to overcome the communication problems (SAE J1850). But, it is commonly agreed that the corruption of serial data by EMI will be an issue if a twisted pair or any other kind of conventional wiring and connector design is used at the higher data rates. Also, if data communication requirements dictate transmission rates above 50 kbps, another technique may be required because 50 kbps is the practical upper limit of these Class B Networks (SAE J1850) that use twisted-pairs and conventional bus drivers.

1.4 Electromagnetic Interference (EMI) Considerations—A key concern is the generation of EMI when the Class C Vehicle Multiplexing Network is utilizing twisted pair for the transmission medium operating at data transmission rates above 50 kbps. It is because of this EMI concern that most automotive RF engineers commonly accept that either a fiber optic or a shielded cable will be required for the transmission medium at data rates above 100 kbps.

It is expected that the growth of data communications on vehicles, the issue of shielding cost requirements, and electromagnetic compatibility of copper-based systems, will drive future development. These factors and other, as yet undefined, needs for Class C communication will eventually drive the implementation of automotive fiber optic systems for higher data transfer rates.

2. References

2.1 Applicable Publications—The following publications form a part of this specification to the extent specified herein. Unless otherwise indicated, the latest issue of SAE publications shall apply.

2.1.1 SAE PUBLICATION—Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

SAE J1850—Class B Data Communications Network Interface

2.2 Other Publications

2.2.1 Henry W. Ott, Bell Laboratories, Noise Reduction Techniques in Electronic Systems, A Wiley-Interscience Publications. Second Edition, 1988.

2.2.2 CISPR/D/WG2 (Secretariat) 19, September 1989, International Electrotechnical Commission, International Special Committee on Radio Interference (CISPR), Subcommittee D: Interference Relating to Motor Vehicles and Internal Combustion Engines, Working Group 2, Test Limits and Methods of Measurement of Radio Disturbance from Vehicle Components and Modules: Conducted Emissions, 150 kHz to 108 MHz and Radiated Emissions, 150 kHz to 1000 MHz

2.2.3 A. L. Harmer, SPIE Vol. 468 Fibre Optics '84, pp. 174-185 (1984).

2.2.4 W. A. Rogers, D. R. Kimberlin, and R. A. Meade, Soc. Automotive Eng. 88, pp. 50-56 (1980).

2.2.5 M. W. Lowndes and E. V. Phillips, 4th Int. Conf. Automotive Electronics IEE Vol. 229, pp. 154-159, 1983.

2.2.6 P. G. Duesbury and R. S. Chana, 4th Int. Conf. Automotive Electronics IEE Vol. 229, pp. 160-164, 1983.

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- 2.2.7 K. Sekiguchi, Int. Fibre Optics and Commun. 3, pp. 56-60, 1982.
- 2.2.8 T. Sasayama, Hirayama, S. Oho, T. Shibata, A. Hasegawa, and Y. Minai, 4th Int. Conf. Automotive Electronics IEE Vol. 229, Nov. 1983.
- 2.2.9 K. Sasai, Sitev Conf., pp. i-ii, May 1983.
- 2.2.10 R. E. Steele and H. J. Schmitt, SPIE Vol. 840, Fiber Optic Systems for Mobile Platforms '87.
- 2.2.11 G. D. Miller, SPIE Vol. 989, Fiber Optic Systems for Mobile Platforms II '88, pp. 124-132 (1988).
- 2.2.12 D. A. Messuri, G. D. Miller, and R. E. Steele, A Fiber Optic Connection System Designed for Automotive Applications, Soc. Automotive Eng. #890202, Feb. '89.
- 2.2.13 T. W. Whitehead, Du Pont Electronics Private Communications (1989).
- 2.2.14 T. Sasayama and A. Hideki, SPIE Vol. 989, Fiber Optic Systems for Mobile Platforms 11, '88.
- 2.2.15 M. Kitazawa, Mitsubishi Rayon, Private Communications (1989).

3. Twisted Pair—A Twisted Pair is defined to be a transmission line consisting of two similar conductors that are insulated from each other and are twisted around each other to form a communication channel. The purpose for twisting the conductors around each other is to reduce the electric and magnetic field interaction with other conductors. In recent years there has been a lot of research on Class B Networks that use twisted pair operating at data rates below 50 kbps. At Class C data rates (>100 kbps) many new problems need development and attention.

3.1 Inherent Advantages/Disadvantages of Twisted Pair Networks—As the result of widespread Class B network development, a lot of research has been completed on the use of copper-based twisted pair for a transmission media. Class C development is an extension of that activity.

3.1.1 FAMILIARITY OF TWISTED PAIR NETWORKS—The desire to use twisted pair for the transmission medium of a Class C Network by the automotive industry is universal. This desire is twisted pair's biggest advantage. At lower data rates, the automotive wiring requirements for twisted pair and connector techniques are well known and developed. The failure modes such as shorts to ground and battery have been extensively studied. The use of proper techniques for termination have been developed. An effective I/O can be easily achieved by integrating the transmission hardware, used for driving the twisted pair, into an interface device that also contains the receiver and some external discrete filter components for EMI rejection. Bidirectional data transfer is easily obtainable using the same twisted pair for both reception and transmission. Statistical studies have provided data so that the reliability of a twisted pair network is known. The connector industry is currently developing insulation displacement type connectors so that in the future automated machines can be programmed to place bus connector drops as required, further reducing the cost of the wiring harness. Of course, at Class C data rates many of these and other factors such as the maintenance of twist uniformity and the harness interconnection requirements are likely to change. A large investment in research and development must be completed in order to demonstrate feasibility. The magnitude of the task could easily be underestimated even though this development is an extension of familiar work.

In most communications systems, the length of line is a large factor in determining the upper limit of data rates. However, line length in automotive networking is relatively small and does not play a major role, but the number of connectors and losses due to impedance mismatching at the connector is a concern. Perhaps developments in ribbon cabling techniques and insulation displacement connectors could improve this impedance matching situation.

- 3.1.2 RADIATED LINE LOSSES—The biggest problem to overcome is the fact that for data rates above 100 kbps, the radiated line losses are very high (2.2.1). These radiated line losses cause transmitter line driver problems and generate large amounts of EMI. The work at Class B data rates demonstrated that the transition rise time was responsible for most of the EMI. The present automotive quality of a twisted pair network medium does not exhibit good transmission line characteristics. Also the capacitance load to the output driver from the twisted pair was measured to be approximately 2000 pfd. At Class C data rates this capacitance loading, impedance mismatching at the connector, maintenance of twist uniformity, and drive symmetry match requirements between bus outputs make it very difficult, if not impossible, to design an output driver. The challenge will be to achieve a low enough output impedance to drive a twisted pair without incurring excessive losses or spectral distortion of the transitions especially for data rates above 1 Megabit per second (Mbps).
- 3.1.3 RECEIVER SUSCEPTIBILITY—The receiver is very susceptible to coupled (capacitive/inductive) and longitudinal noise interference (see 3.3.2 for details on longitudinal noise). At Class C data rates it is much more difficult to devise a filter that could eliminate the coupled line noise. The severity of this problem can be understood by realizing that the vehicle wiring harness appears to be resonant around 25 to 30 MHz which is approximately a quarter wavelength in length. Switching noise and spikes are broadband and excite the wiring harness to resonate at high levels. At Class B data rates this broadband noise is coupled into the circuit but is effectively eliminated by the filter. For Class C multiplexing the data rates required may be at 1 to 10 Mbps. This wire harness resonance is too close to the filter cutoff frequency for traditional filtering techniques to be very effective.
- 3.1.4 DRIVE PROBLEMS AND LINE LOSSES—The transmitter drive problem and line losses cause many experts to conclude that twisted pair and shielded twisted pair are not usable for data rates above 100 kbps. The filtering techniques for receiver susceptibility would also leave the network highly susceptible to data corruption and thus require very sophisticated error detection or reconstruction techniques.
- 3.2 Network Architecture Options**—The suitable topology configurations of twisted pair is a very strong advantage. It can accommodate any configuration from a Star, Tee, Bus, Ring, Daisy Chain, or various Hybrids. Many data encoding techniques have been employed with twisted pair as the transmission medium with a variety of I/O hardware configurations.
- 3.2.1 DATA ENCODING OF COMMUNICATION PROTOCOLS—The data encoding technique has a significant effect on the radiated EMI. To achieve the highest possible data rate it is important to choose a data encoding method that has the fewest transitions per bit with the maximum of time between transitions and is bit synchronized so that invalid bit testing can be effective. Invalid bit testing has proven to play a large role in providing data integrity in a high EMI environment. PWM, for example, has two transitions per bit with 1/3 bit times between transitions. NRZ has a maximum of one transition per bit but without the added overhead of synchronizing transitions is not suitable. Some of the disk drive encoding techniques such as Modified Frequency Modulation (MFM) or Run Length Limited (RLL) are synchronous with fewer than one transition per bit (see Table 1 for a comparison chart of a selection of encoding techniques). The variable column in the table describes an attribute whereby the transmission time for data byte is a variable quantity depending on the data value.

TABLE 1—COMPARISON OF DATA ENCODING TECHNIQUES

	Arbitrates	Compression	Synchronizing	Trans/Bit	Variable
PWM	Yes	Base	Yes	Two	No
VPWM	Yes	2 to 1	Yes	One	Yes
Manchester	Yes	1.5 to 1	Yes	1.5 Avg.	No
NRZ	Yes	3 to 1	No	One	No
MFM	Yes	3 to 1	Yes	0.75 Avg.	No
RLL	No	>6 to 1	Yes	<0.5 Avg.	Yes
Siefried	Yes	>8 to 1	Yes	<0.1	Yes
Arcnet	No	>16 to 1	Yes	<0.1	No

- 3.2.2 MRM ENCODING APPLIED TO VEHICLE MULTIPLEXING—A modulation technique developed during the latter 1960s called Modified Frequency Modulation (MFM) used in disk drives could be adapted to vehicle multiplexing. The advantage of using the MFM encoding technique is that it would be synchronous with an average of 0.75 transitions per bit. The encoding technique permits a transition rise time that can be maximized and wave shaped to significantly reduce EMI. Disk drives have a similar requirement where the modulation technique allows pulses to be recorded on a disk at maximum density. The diagram shown in Figure 1 demonstrates one way of applying MFM encoding technique to a communication data link.

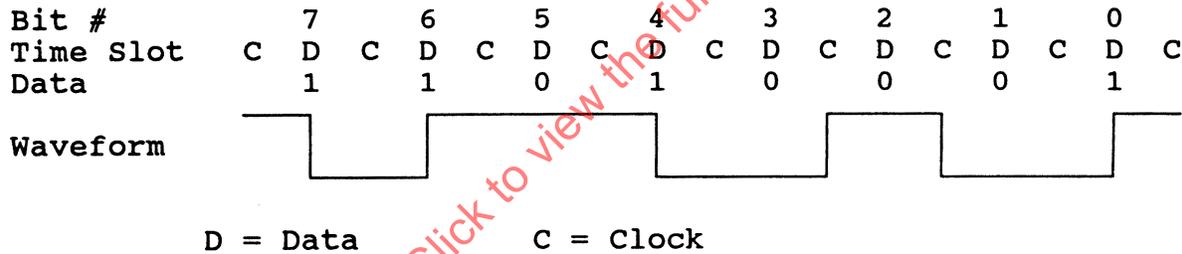


FIGURE 1—MFM ENCODED BYTE OF DATA

The rule for encoding simply causes a transition at the data time slot when the data at that time slot is a logic "1." A transition is also generated at the clock time slot when the data before and after that clock time slot was a logic "0" (or two "0's" in a row).

- 3.2.3 SIEFRIED ENCODING—The Siefried Patented Encoding Process may be especially useful for Class C Multiplexing. This data compression encoding technique is based on digitally varying the pulse width proportionally to the data byte value and then passing the modulated square wave signal through a narrow band filter to change the signal to a near sine wave. The high frequency content of the signal is limited and can be transmitted across ordinary twisted pair network medium. The Siefried technique generates a redundant negative portion of the waveform that is a mirror image of the positive. The data decode circuit should extract two identical values from both the positive and negative portion of the signal. If not, this inconsistency can be used for detection of data corruption due to EMI. The data is recovered by employing a zero crossing detector and converting the sine wave back into square waves. The encoding technique defines a minimum duration square wave that corresponds to a zero data value. All other data values increase the square wave duration proportionally to the data value. This variation should be small in proportion to the zero value square wave duration and easily converted to a near sine wave by the filter. Assume a square wave bias value of 256 μ s to illustrate the technique. In this example assume the data

varies the square wave by 128 one-half microsecond steps corresponding to an 8 bit byte of data values thus varying the square wave pulse width from 256 to 384 μ s. In this example one 8 bit byte of data was compressed into a single square wave, which duration varied from 256 to 384 μ s.

The Siefried Encoding Technique could be used in a medium access scheme that requires bit-by-bit arbitration but, as discussed, arbitration requires nonsymmetrical output drives. Token passing or time division multiplexing, on the other hand, would be a better choice for the medium access method. These access methods would take advantage of the Siefried Compression Encoding Technique and allow balanced current or transformer coupling to achieve the highest possible data rates. It would seem realistic that the equivalent of 500 kbps to 1 Mbps of the Siefried encoded data could be communicated across a Class C Network that uses only twisted pair for the network medium. However, there are a number of factors such as cost, resolution requirements and signal distortion that need to be proven. These factors will require a large investment in research and development to demonstrate feasibility.

3.2.4 ARCNET ENCODING—The Arcnet Encoding Technique is similar to Siefried except instead of digitally varying the pulse width proportionally to the data byte value the process digitally varies the sine wave amplitude proportionally to the data byte value. The technique is reported to generate a 16 to 1 data compression level by encoding the positive sine wave separately from the negative. An 8 to 1 data compression for both halves of the sine wave is achieved.

3.2.5 I/O HARDWARE CONFIGURATION—The driving difficulties are increased if we require an arbitration based protocol because an arbitration based I/O such as that used with SAE J1850 requires nonsymmetrical driving capabilities. The more difficult driving requirements of higher data rates are achievable if the transmitter could drive symmetrically both negatively and positively because better impedance matching is possible. Communications protocols such as Time Division Multiplexing, Master/Slave, or Token Pass may be a better choice than a bit-by-bit arbitration based protocol. A case can also be made for symmetrical driving by employing transformer coupling. However, the cost of transformer coupling may be an issue.

3.3 Key Concerns of Twisted Pair Networks—The EMI levels generated by a Class C Vehicle Multiplex Network and the susceptibility to externally generated EMI are the main concerns with utilizing twisted pair for transmission medium. A large factor in EMI levels is determined by both the data encoding methods and medium driving techniques.

3.3.1 COMPUTER SIMULATION OF EMI LEVELS—The EMI levels generated by a Class C Vehicle Multiplex Network has not been sufficiently studied or documented. A recent computer simulation was completed using Fourier Spectrum Modeling Technique. Appendix A details the method used for this EMI level modeling and the results of these studies are documented herein. The computer study predicts the EMI levels radiated by a single wire in a vehicle wiring harness and the effect of various data modulation methods. The four modulation techniques studied were PWM, VPWM, Manchester, and MFM. NRZ modulation would generate the same EMI levels as MFM and therefore was not simulated.

The first step in the computer simulation was to determine the worst case EMI levels for the four modulation methods studied. A constant 0.5 μ s transition rise time was simulated for all the modulation techniques and all permutations of data were considered in order to establish the worst case examples of EMI levels for each data encoding method. Figure 2 illustrates the resulting predicted worst case EMI levels for these four modulation techniques. The curve plotted for each modulation is the maximum level generated by the fundamental frequency and each harmonic. All simulated modulation examples were for 100 kbps data rates. Notice all the curves are parallel to each other and only a few dbV apart with Manchester Encoding being worse and MFM predicting the least EMI.

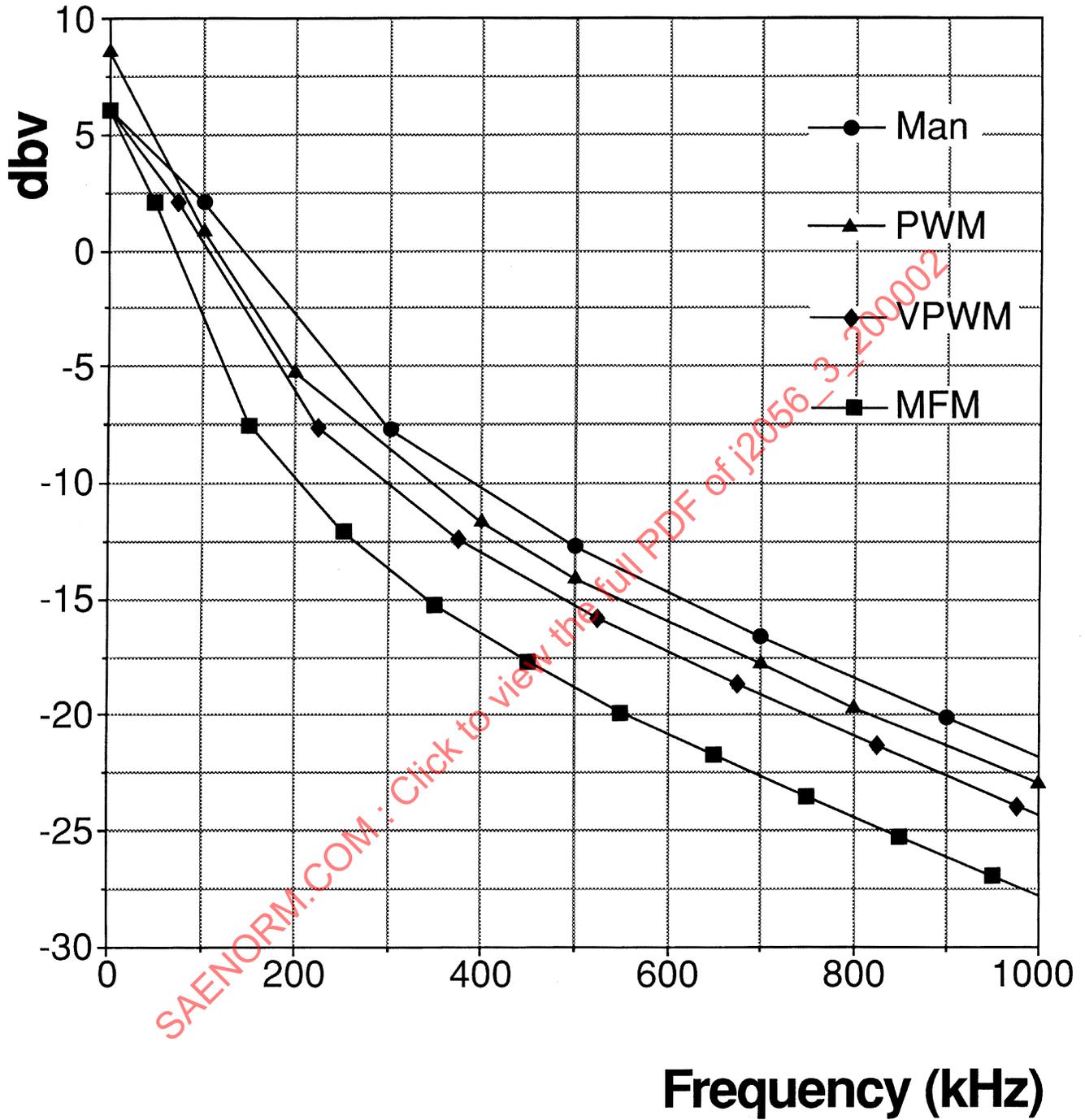


FIGURE 2—WORST CASE EMI LEVELS FOR PWM, VPWM, MANCHESTER, AND MFM

It is a well-known fact that the level of EMI generated by the harmonics is a function of the transition rise times. The second step in the computer simulation was to model these four examples using a variable transition rise time in order to reduce these harmonic EMI levels. The simulation was generated using a 25% factor of the minimum feature size (minimum pulse width) to determine the rise time. The resulting graph is illustrated by Figure 3 and clearly shows the effect of rise time on EMI levels predicted. As for the first simulation all modulation examples used the same data rates of 100 kbps. Take note that the EMI levels predicted for MFM are significantly less than the other modulation methods as would be expected because it has proportionally the longest rise time.

The third step in simulation is illustrated by Figure 4. The resulting graph is for MFM where the data rate was varied from 41.6 kbps to 125 kbps. The simulation was generated using the same 25% factor of the minimum feature size for the rise time. Take note that the break point at 500 kHz for the 125 kbps data rate is approximately -32 dBV.

The EMI level at the 500 kHz point has special significance. The computer study predicts the EMI levels radiated by a single wire in a vehicle wiring harness. A simulation was generated for VPWM at 10.4 kbps data rate and a 16 μ s rise time (see Figure 5). This simulation is of special significance because one implementation of SAE J1850 specifies this configuration and extensive vehicle verification tests show that it does not generate excessive EMI levels. Notice that the break point at 500 kHz is approximately -60 dBV.

CISPR/D/WG2 (Secretariat) 19 Sept 1989 Radiated Emissions Antenna & Probe Test Document (2.2.2) has been generally interpreted by most automotive RF engineers to specify a break point at 500 kHz of -60 dBV. Another way of demonstrating the validity of this is to compare the predicted levels illustrated by Figure 5 to the levels referenced by this CISPR document.

- 3.3.2 FOUR MEDIA DRIVING TECHNIQUES CONSIDERED—Since the computer model simulates a single wire, a twisted pair transmission medium would provide generated EMI cancellation. The amount of EMI cancellation obtained is dependent on the performance of the balancing effectiveness of the medium driving technique employed. Drivers integrated into a single device can be carefully designed to have balanced source impedances. The receivers can be designed to have high common mode rejection ratios. It should be possible to achieve up to 60 dB of EMI cancellation particularly at AM band frequencies.

The susceptibility to interference of the network is a different issue. The source of coupled line noise is as was previously discussed in 3.1.3. To gain a better understanding as to the source of the longitudinal noise, consider the simplified circuit diagram shown in Figure 6. The transmitter is referenced at a different ground point than the receiver. The noise source at each ground point is directly (not capacitively or inductively) coupled to that ground point and normally significantly different. Voltage V_G represents the difference in ground noise potential or longitudinal transient noise between these two ground points. The magnitude of V_G is usually very large (i.e., < 200 V). The frequency content of longitudinal transient noise can go as low as the audio range thus making traditional low pass filters ineffective. I_A and I_B represent the two currents that flow as a result of V_G into the differential receiver. If these two currents were of equal magnitude and phase they would then be cancelled across the load resistor R_L . This situation usually never exists as illustrated. I_A takes the path passing through R_S , and I_B takes the more direct route to R_L . The receiver amplifies the difference current across R_L thus making it susceptible to longitudinal noise.

- a. Voltage Drive 1/O: A computer simulation was completed of a PWM encoded 41.6 kbps signal, assuming a 2 μ s transition rise time. One implementation of SAE J1850 specifies this drive configuration and empirical tests have validated the EMI cancellation levels predicted by the study. The results of the simulation predict an approximately -37 dBV at the 500 kHz break point. This simulation can be interpreted to mean that in order to guarantee EMI-free operation greater than a modest 23 dBV of EMI cancellation must be achieved. If the same driving technique was used with MFM encoding, higher data rates would be achievable (see Figure 4), but operation at 100 kbps or 125 kbps would be within about 5 dBV of the PWM encoding 41.6 kbps signal. If required this 5 dBV improvement of EMI cancellation should be achievable.

The other point to consider with voltage drive I/O is the susceptibility to longitudinal noise. Figure 7 shows a simplified circuit diagram of the voltage drive I/O. Again the longitudinal noise currents do not cancel even though the source impedances R_S are balanced. I_A takes the path passing through Z_C , and I_B takes the more direct route to R_L . Z_C is of the same order of magnitude as R_S and, therefore, the longitudinal noise current match is poor.

- b. **Balanced Current I/O:** The balanced current I/O can also be integrated into a single device and can achieve EMI cancellation similar to voltage drive.

The main advantage of balanced current I/O is that it can be designed to achieve a significant improvement in balancing the two longitudinal noise currents particularly at audio frequencies. Figure 8 shows a simplified circuit diagram of the balanced current I/O. Even though I_A takes the path passing through Z_C , and I_B takes the more direct route to R_L both currents must pass through the constant current sources I_S . These current sources present a much higher impedance than Z_C and significantly improves the current matching of the longitudinal noise currents. It is claimed that this factor is responsible for as much as 40 dB improvement in susceptibility to vehicle longitudinal noise. The main concern in using balanced current I/O is that the sources and sink currents may be too low to allow the use of conventional automotive connectors.

- c. **Transformer Coupling:** Transformer coupling is also a very effective method for matching load impedance and generated EMI cancellation. Transformer coupling also plays an important role by isolating the ground connection at both ends of the transmission line and effectively blocking the longitudinal noise current. It is claimed that this factor can be responsible for a greater than 40 dB improvement in susceptibility to data corruption by longitudinal noise currents (2.2.1). The size, weight and cost of transformers are their major disadvantages. Also, transformer coupling places limitations on the allowable bit encoding techniques by requiring symmetrical waveforms.
- d. **Optical Coupling:** Optical coupling in theory can also be effective in blocking the longitudinal noise current. There are a number of technical concerns such as achieving proper bus termination with optical coupling but cost would be the main concern. A number of manufacturers make optical isolators, to an electrical medium, for computer interfacing. Also some hardware capable of driving a twisted pair medium at Class C data rates is available, but it is not known if any serious attempts have been made to develop this technology for a vehicle medium driver.

- 3.3.3 **MEDIUM DRIVING AND ENCODING TECHNIQUES CONCLUSIONS**—Integration into a single IC is important because this method can usually result in better matching between the positive and negative leads of the drivers and receivers. This balancing of the Bus + and Bus – I/O signal at the proper polarity in both amplitude and phase can be effectively used to cancel the EMI in the twisted pair transmission line. In order to achieve adequate levels of immunity to noise interference it is important to choose a medium driving and receiving technique that either cancels or blocks the longitudinal noise current.

Some encoding methods arbitrate more naturally than others if arbitration is required. This encoding factor affects cost and reliability of the network. Encoding selection is not the subject of this report and will depend on the final protocol selection (2.2.2). The choice of a proper data encoding technique with wave shaping the rise time to 25% of the minimum feature size (minimum pulse width) should allow twisted pair for the bus medium at data rates of 125 kbps without generating too much EMI. If it is possible to decode the data for larger percentages of rise times, a factor of four (500 kbps) increase in data rates establishes the approximate upper limit. The main concern is whether a 125 kbps data rate is high enough to accommodate Class C Multiplexing requirements without resorting to data compression techniques. If higher data rates are required, will consequent radiated EMI problems dictate data compression? If it is necessary to go to data compression, will the data integrity due to compression accuracy or EMI corruption be acceptable?

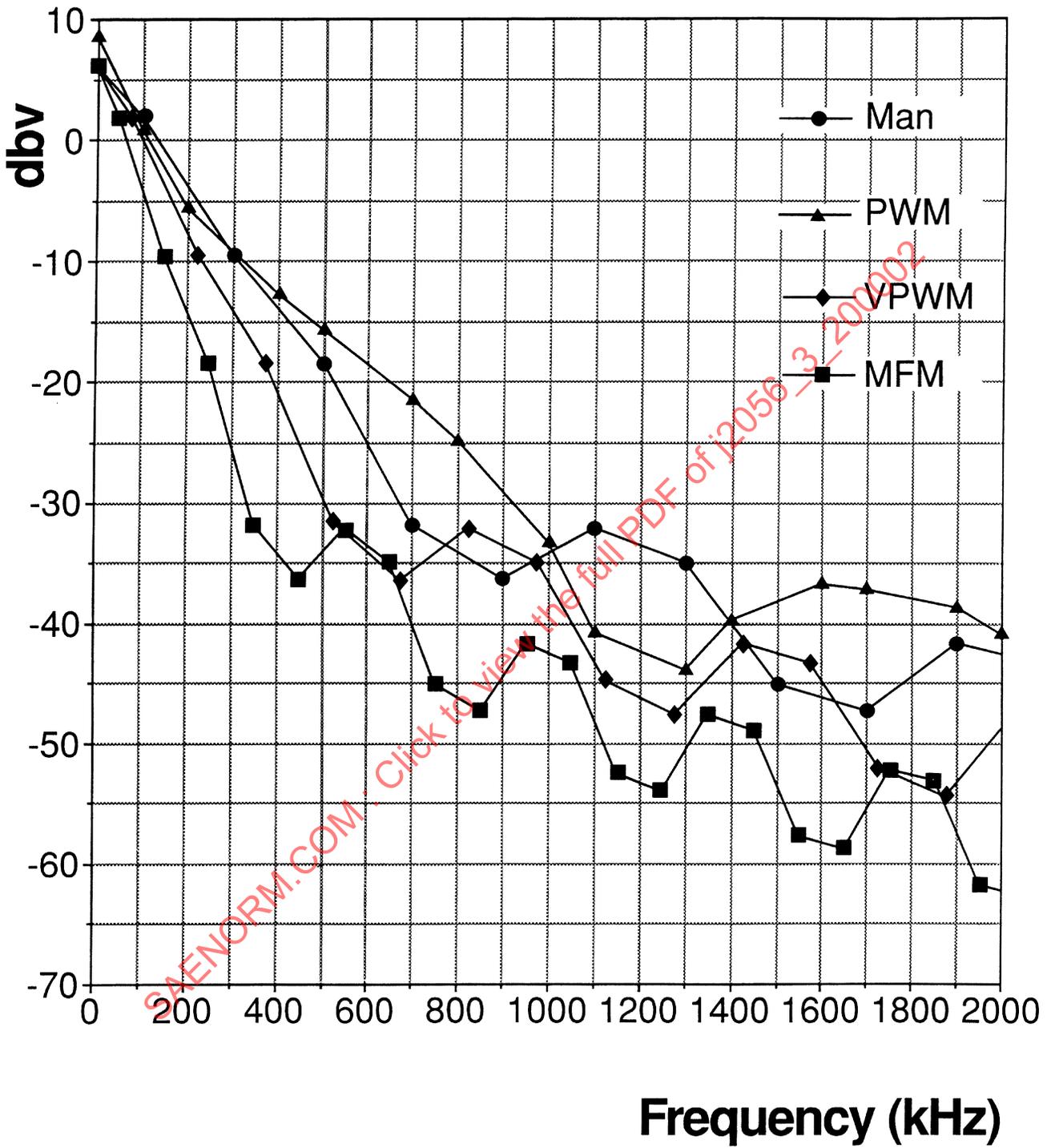


FIGURE 3—EMI LEVELS USING A 25% OF MINIMUM FEATURE TO ESTABLISH RISE TIME

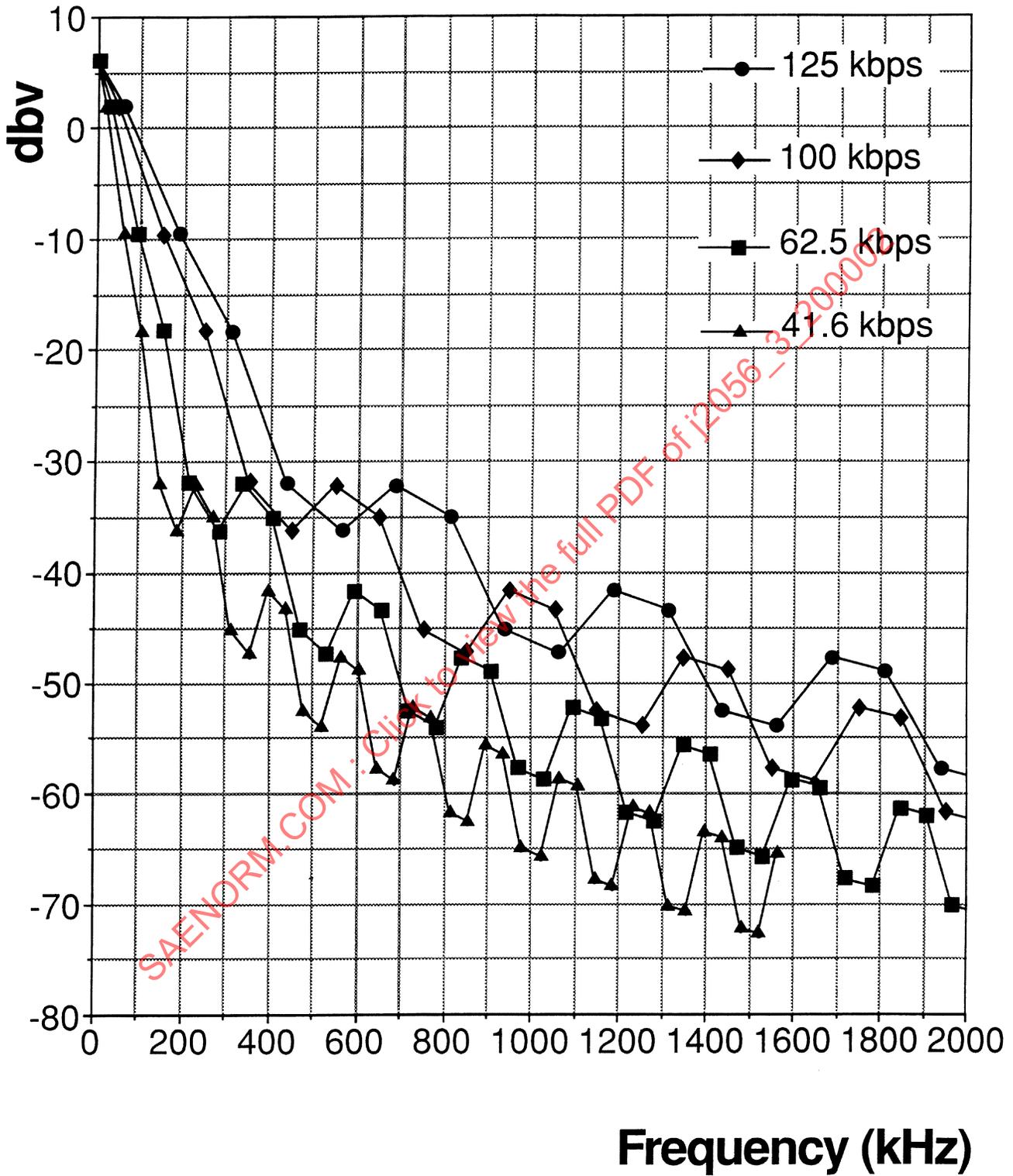


FIGURE 4—MFM FOR DATA RATES FROM 41.6 KBPS TO 125 KBPS

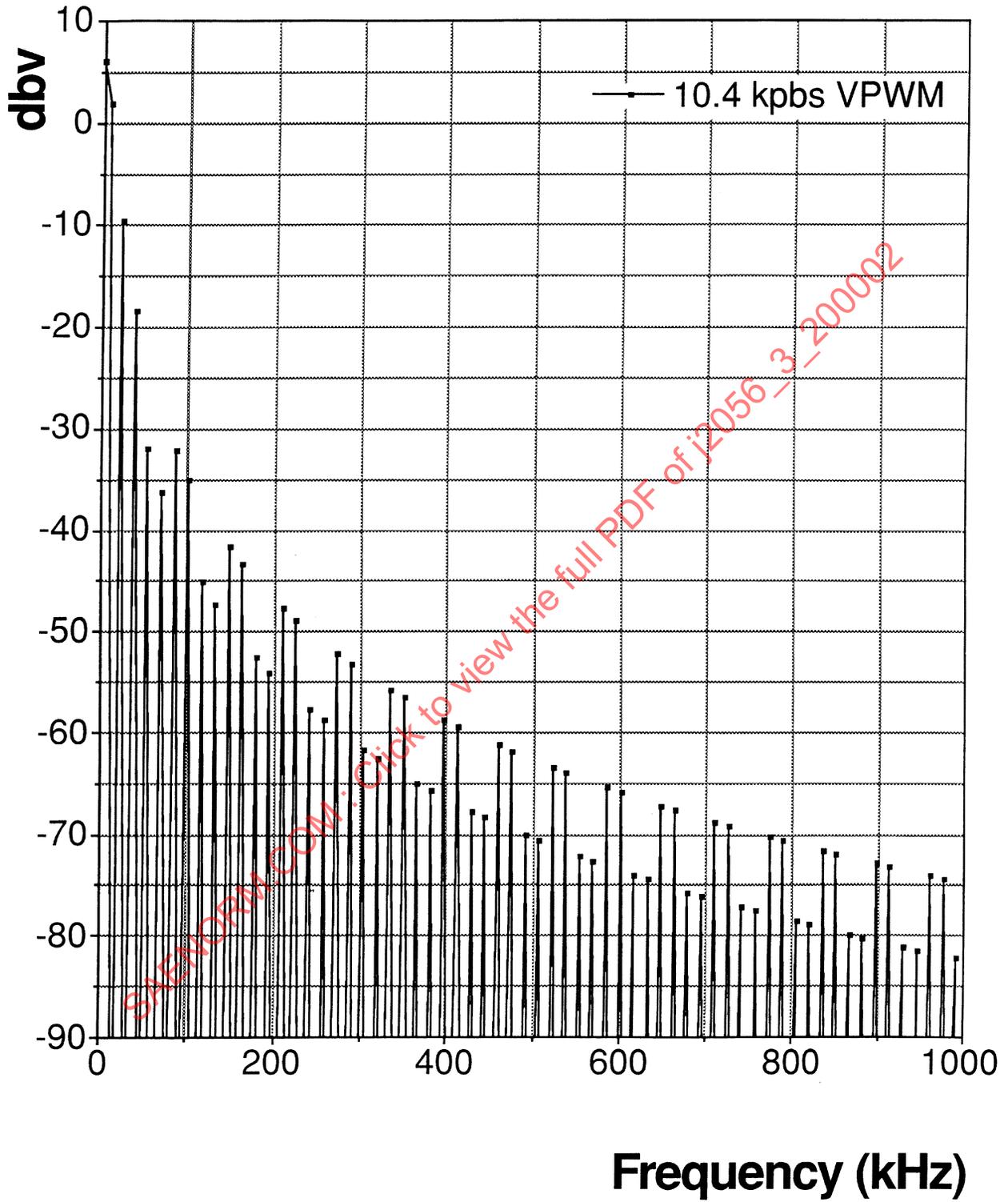


FIGURE 5—10.4 KBPS VPWM SIMULATION

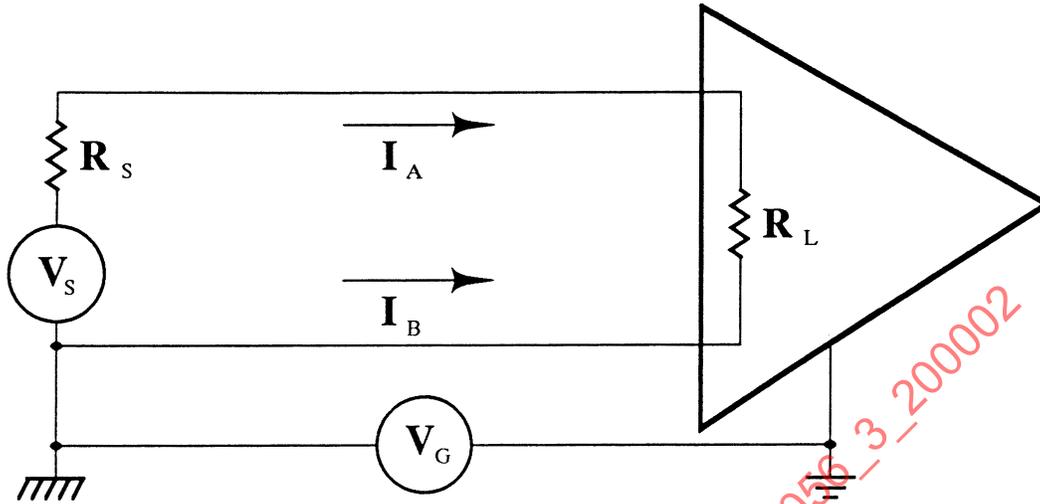


FIGURE 6—SIMPLIFIED CIRCUIT DIAGRAM OF DRIVER AND RECEIVER

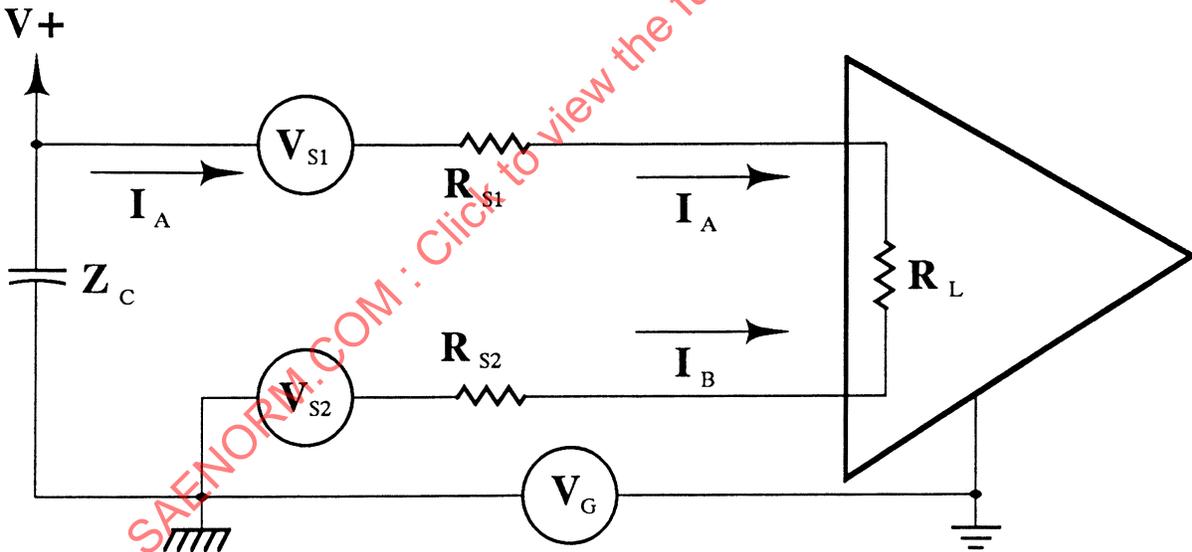


FIGURE 7—SIMPLIFIED CIRCUIT DIAGRAM OF VOLTAGE DRIVE I/O

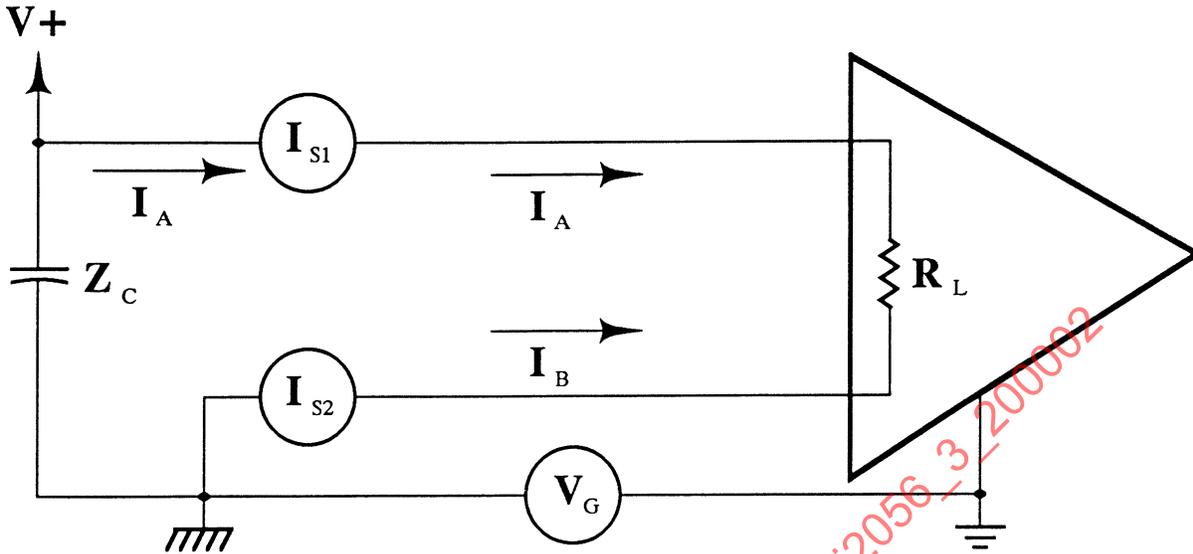


FIGURE 8—SIMPLIFIED CIRCUIT DIAGRAM OF BALANCED CURRENT I/O

4. **Shielded/Coaxial Cable**—There are two types of shielded cable considered in this report: shielded twisted pair and coaxial cable. Shielded twisted pair utilizes standard automotive connectors and sensors and has had some acceptance in automotive vehicle wiring but always in special cases. It has been used to shield sensitive sensors and low-level radio audio circuits. Coaxial cable requires special coaxial connectors such as those used for radio antenna cable and has never had wide acceptance in automotive wiring.

4.1 **Inherent Features of Shielded/Coaxial Cable Networks**—Shielded twisted pair for the transmission medium of a Class C Network does yield only about 15 dB of EMI and EMS improvements over twisted pair. This improvement is not significant because the shield must be broken at the ends where connection is made to the standard automotive connector or sensor and, unlike coaxial cable networks, allows the introduction of EMI noise. Shielded twisted pair does not offer any improvement in ability to drive and it is considered, along with the twisted pair, to be “not very useful” for data rates above 100 kbps (2.2.1).

On the other hand, whether triaxial or coaxial cable is used, it can be matched to a transmitter and is capable of being driven with data rates above 100 kbps. The disadvantage, of course, is considerably higher cost and the nonexistence of any automotive type connectors. Coaxial type cable in automotive circuits is considered unreliable because the shield must be maintained at the connector through all the environmental conditions, otherwise EMI can enter the system. In a practical sense, it is a source of EMI because the shield current and inner conductor currents are not always equal and, therefore, do not completely cancel. Shield grounding concerns present a whole series of issues such as number of ground connections, ground wire length, and shield distance from ground. Also, coaxial type cable is much more difficult to splice or tee tap.

4.2 **Network Architecture Options**—The topology configuration for shielded twisted pair and unshielded twisted pair can practically accommodate almost anything. The topology configuration for coaxial type cable is a different situation. Tee or other splices are not practical because they cause impedance mismatches, manufacturing difficulties, and increased cost. Coaxial cable is practically limited to accommodating only point-to-point or daisy chain type systems. The other alternative is to employ costly matching tee networks or active type repeaters.

The data drive I/O hardware configuration is similar to the unshielded twisted pair requirements. However, with coaxial cable there is not as severe an impedance mismatch problem. All communication protocols used by twisted pair can also be applicable with shielded twisted pair or coaxial type cable.

4.3 Key Concerns of Shielded/Coaxial Cable Networks—It is believed by most automotive wiring engineers that widespread use of shielded twisted pair or coaxial cable in automotive wire harnesses would require a development struggle much greater than the effort required to develop a fiber optic network medium. They believe that manufacturing and assembly issues along with maintenance and repair problems are nearly unsolvable. Shorts at the connector between the signal and shield are likely to plague harnesses causing the whole network to fail. The mechanic's maintenance procedure is likely to require costly harness replacements rather than the simpler repair technique used today.

5. Fiber Optic—Fiber optic systems saw their first widescale use in telecommunications and Local Area Networks (LANs). The reason for this was twofold; technical advantages and cost savings. Since then, fiber optic systems have gradually been replacing copper-based transmission systems like twisted pair and coaxial cable in aircraft, military use, factory automation, and others.

Applications of fiber optics to passenger cars started in the mid-sixties and were mostly for illumination and sensors (2.2.3). Over the past decade, several fiber optic multiplexing systems for experimental and test cars were described in the literature (2.2.4, 2.2.5, 2.2.6), and some isolated subsystems were implemented in low volume, high end cars (2.2.7, 2.2.8, 2.2.9).

As more electronic systems are added to control new functions in future vehicles, data transmission rates can be expected to increase above 150 kbps particularly in critical functions such as engine performance, antilock brakes, and other Class C functions. The effects of electromagnetic susceptibility and impedance variation on bit error rate are some potential data transmission reliability concerns with high-speed copper-based data links above 150 kbps. Experience has shown an even larger concern is that it can cause electromagnetic interference. A need exists today to re-evaluate and optimize the transmission medium for these higher data rates. A comprehensive approach to evaluate fiber optic system requirements in view of the distinct automotive needs was described in references (2.2.10, 2.2.11, and 2.2.12), and some of those criteria have been used in this report.

5.1 Inherent Features of Fiber Optic Systems—It is important to note at the outset that whatever advantages (or disadvantages) a fiber optic system has, compared to a copper multiplexed system, have been viewed mainly in terms of their relevance or significance to the automotive environment (2.2.12), as opposed to other applications, such as LANs, telecommunications, military use, factory automation, and others.

A fiber optic system could be designed for a glass fiber, a plastic fiber, or a combination of the two, depending on the application. The special needs of the automotive environment impose several requirements on any fiber optic system that is designed to operate in it. The main characteristics of an automotive fiber optic system are:

- a. Automotive networks normally require short (an average of 1.5 m) distances between nodes. This short distance means that an automotive system can tolerate higher signal attenuation than other fiber optic applications.
- b. There is a much higher ratio of connector to fiber use than is common in other applications, such as LANs or telecommunications; i.e., an optimized connector design will drive the system design.
- c. It is better adapted to high volume assembly and test than other fiber optic applications.
- d. The network can withstand a much harsher environment than most other fiber optic applications under temperature extremes, shock, vibration, corrosion, humidity, road salts, and other conditions.
- e. The wide use and acceptability of automotive networks are very sensitive functions of cost and serviceability.

At the present time plastic is preferred because one can achieve higher coupled power with the lowest cost fiber optic transmitters and receivers. This situation could change as glass-compatible connectors for use with larger diameters (e.g., greater than about 250 μm) become cost competitive with plastic-compatible connectors going forward, and as device manufacturers increase LED coupling efficiency. This technology is rapidly evolving, forcing designers to constantly review the glass versus plastic decision. Unless otherwise specified, the advantages and disadvantages listed as follows will apply to both glass and plastic fiber systems.

5.1.1 PRINCIPAL ADVANTAGES—The main practical consequence in the four following advantages over copper-based transmission media, particularly at the higher data rates, is the minimization or virtual elimination of bus shielding and impedance matching requirements. However, one still has to shield the emitter/receiver components like any other electrical box.

- a. EMI/RFI Immunity: Optical signals are immune to EM and RF interference. Thus, a fiber optic bus can be placed next to high voltage or radio receiver lines without distorting their outputs or being affected by them. This will become more important as dielectric materials replace metals for car bodies.
- b. Data Bus Termination Impedance Elimination: Bus termination and biasing networks are not required.
- c. Immunity From Cross-Talk: Optical signals, by their nature, do not radiate energy that interferes with electronic signals. Therefore, cross-talk between a fiber optic data line and other electronic signal lines is nonexistent.
- d. Ground Loop Elimination: In a copper-based system different ground locations present different impedance values to the same high frequency signal and thus give rise to a potential difference or noise at the receiver circuit. Since optical fibers do not conduct electrical current this "ground loop" is broken and the noise associated with it is eliminated.

5.1.2 GENERAL ADVANTAGES

- a. Data Rate or Bandwidth: Although a fiber optic system has bandwidths of several hundred MHz this advantage is irrelevant for Class C automotive applications at present because it is well beyond present defined Class C data rate requirements. However, as more and more video displays are designed into future cars the need for larger bandwidths will become more important and fiber optics will be the obvious choice.
- b. Weight and Space Savings: There is a sizeable weight reduction when several twisted pairs or coaxial cables are replaced by a single fiber optic cable, as is the case in telecommunications, but the weight difference is insignificant if a single 22 gauge twisted pair is replaced by a fiber optic cable. The same argument could be applied to cable sizes as well, but if shielding requirements are taken into consideration there will be overall space savings and increased design flexibility in a fiber optic system. Furthermore, fiber is easier to proliferate across different vehicle makes because of its immunity to routing-induced EMC problems. Copper-based systems sometimes have to be rerouted when placed into a different vehicle due to unanticipated interference problems.
- c. Long-Term Reliability: Present long-term experience in automotive fiber optic systems indicates that these systems will not be prone to connector erosion or conductor hardening over long periods of time, as is the case for copper-based systems. It is expected that recently developed low-cost fiber optic data transmission components will be reliable in automotive applications, based on their successful performance in laboratory tests (2.2.8, 2.2.9).
- d. Immunity from Short Circuits: Since fibers do not carry electrical current, shorts to ground are eliminated. The network signal cannot be shorted to power, ground, or other signal wires. This means that depending on network architecture the network cannot be disrupted by a short. Also, there is no need for transient suppression components for shorts to power or ElectroStatic Discharge (ESD).
- e. Data Integrity: It is anticipated that, because of the EMI immunity of optical signals, data integrity would be higher than in a copper-based system unless elaborate shielding is used in the latter. This needs to be explored further (see Section 4).

- f. **Lack of Familiarity:** One possible advantage to the use of fiber optics over the electrical alternatives is the respect it would be given due to the lack of familiarity. The high-speed electrical alternatives may be treated the same as their low frequency power and signal carrying cousins. The high frequency shield ground is not the same as any other ground. The shorting to ground of a high frequency ground could cause problems such as ground loops. A 6-in lead could mean the shield is not grounded. The practice of splicing or doubling at high frequencies is not acceptable. A wire at these frequencies is not just a wire anymore.

5.1.3 DISADVANTAGES

- a. **Sharp Bending Radii for Fibers:** Sharp bends have an inherent disadvantage in fibers compared to copper conductors. If the bend radius decreases below a critical value, which is related to the fiber radius, light transmission in the fiber is reduced. This effect is not a severe limitation but it implies that a routing-induced attenuation has to be anticipated as a system design parameter.
- b. **Unidirectional Transfer of Data:** This condition implies that one fiber is used to send data out from a transmitter and another fiber is used to receive incoming data. Thus a duplex cable is required instead of a coax or a twisted pair. With the advent of monolithic detector/transmitter devices (2.2.13), the need for a duplex cable could be eliminated and one fiber could be used.
- c. **Lack of Standards:** The intermittent use of fiber optic systems in automobiles, so far, has not called for standardization and vice versa. As fiber use gains more acceptance, this limitation will slowly disappear.
- d. **Lack of Automotive-Grade Connectors:** Most of the connectors on the market are designed for a glass fiber with applications for other than the automotive market. There are also connectors that are low cost, are not labor intensive, and require little training or skill to assemble, but most of these are not truly of automotive-grade. There are industry activities working to address this concern (2.2.12).
- e. **Availability of Reliable and Cost Effective Automotive Components:** This is probably the most important reason why fiber optics has not gained a wider automotive application. As mentioned earlier, a plastic system is believed to be more suitable for the automotive environment and at the heart of this system is the fiber. Although fibers and other components have been available for temperatures between -40°C and 85°C (passenger compartment) and fibers that operate, under the hood ($+125^{\circ}\text{C}$) are also currently available, fibers for the engine compartment ($+150^{\circ}\text{C}$) have not been available on a commercial basis let alone at a competitive price. Some recent developments (2.2.14) indicate that this is likely to change soon. Quite recently, prototype fibers with operating temperatures of 135°C (2.2.15) have been advertised. It is believed that a wider use of automotive fiber optic systems will spur more competition and drive the component price down. This could be accelerated if fiber optics is adopted as a standard for a transmission medium for Class C systems.

5.2 Network Architecture Options—There are a number of possible architectures that could be implemented in an automotive network. This report considers only the most likely candidate topologies the single and double ring, the active and passive star, and the linear tapped bus. All comparisons have been discussed on an equal basis. These five network architectures have been evaluated using cost, physical complexity, power moding, fault tolerance, expandability, serviceability, and latency as the seven criteria for comparison. The issues to evaluate the architectures are discussed in the following:

- a. **Cost:** Cost comparisons should include all necessary hardware, beginning with the input to the encoding and transmitter drive circuitry through the receiver and decoding circuitry. Total system cost, not just initial piece cost, will determine which network architecture will be selected for production. Initial cost will be the combination of the fiber ends, receiver transmitter pairs, and fiber length. Total cost will include assembly, warranty, and service costs. A relative comparison has been made to determine system advantage or disadvantage. With respect to cost, the best system will have the fewest components; one receiver transmitter pair per node and one fiber per node. Cost factors that can be readily quantified are fiber ends, receiver transmitter pairs, fiber length, and any other significant system components.

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1. Fiber ends: Due to the large number of fiber ends to finish in an automotive network, the number of fiber ends will be proportional to a significant part of the system cost and be inversely proportional to reliability. In other words the more mated ends, the more opportunities for a fault to occur.
 2. Receiver/transmitter pairs: Active devices are costly components. Minimizing receiver transmitter pairs will minimize cost and also result in improved system reliability.
 3. Fiber length: Although the amount of fiber per vehicle will be small, it still represents a cost factor that is easily quantified.
- b. Physical Complexity: Physical complexity is an issue that will impact the vehicle assembly plant operation. A physically complex system will be difficult to assemble reliably. This could add to assembly costs, dealer warranty cost, or owner maintenance cost. The best system will not have concentrations of complexity or have extra components such as fibers, nodes, or receiver transmitter pairs.
 - c. Power Moding: Power Moding is defined to be the selective control of node power consumption and its level of activity.
The electronic systems on the vehicle are not powered up at all times. Some systems may be purposely powered down during a portion of the time. Some systems will be maintained on for a time after the vehicle is turned off. Times such as ignition off, crank, or accessory operation require only a portion of the vehicle system to be operational to conserve battery charge. The network should allow for this reduced level of network operation. The best system would allow network operation with any combination of nodes powered.
 - d. Fault Tolerance: Continued network operation under a fault condition is desirable. The tolerance of a system to faults could impact the type of functions that could be included on the network. The more tolerant the network is to faults, the more critical functions that can be implemented on it. A fault tolerant system will continue to function with any single point fault.
 - e. Expandability: Expandability for vehicle variability, future vehicle improvements, and dealer installed options must be allowed for in the initial design. Easy network expansion and contraction is a desirable feature. The best system will be expandable without cost to the lesser system.
 - f. Serviceability: Second only to initial functionality, serviceability is a very important issue. The vehicle must be serviceable within the existing service network including local service stations. The best system will be self-diagnosing.
 - g. Latency: The time between data updates will impact the type of function performed on the network. Control applications will require rapid data exchange updates. The best system will have minimum transmission latency.

5.2.1 ACTIVE STAR—The active star network consists of a group of network nodes connected to the active star as shown in Figure 9. Each node consists of a receiver/transmitter (Rx/Tx) pair and a pair of optical fibers. The network also contains a central node that receives and retransmits all network communications. The central node contains an Rx/Tx pair for each network node and in its simplest form, an electrical bus. The active star is an electrical bus packaged in the central node and connected to the network nodes by point to point fiber optic links.

5.2.1.1 Advantages

- a. Cost: The active star allows the use of simple point-to-point fiber optic links which could minimize the cost/complexity of the electro-optical components and the optical connection system.

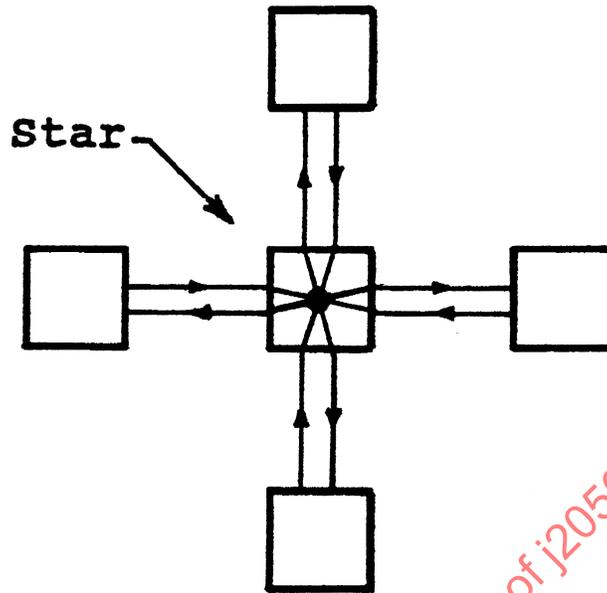


FIGURE 9—ACTIVE STAR

5.2.1.2 Disadvantages

- a. Cost: The active star requires an additional active node with its associated electrical content including a second Rx/Tx pair per node, power supply, and external electrical content (power and ground feeds).
- b. Complexity: The active star is more complex because of the added node and its associated electrical complexity with two fibers per node connecting to it.
- c. Power Moding: The star must be powered up at all times so that data can be exchanged on the network.
- d. Fault Tolerance: The central node offers many internal (electrical bus) and external (power and ground wiring) fault opportunities that could cause the complete network to be inoperative. A fiber fault will affect only a single node.
- e. Expandability: Expansion will be limited by the original hardware design and may require several design levels to minimize cost impact.
- f. Serviceability: Some fault identification is possible. A fault will be isolated to a specific spoke on the star or the central node.
- g. Latency: Central node retransmission will increase network latency. The added latency could be on the order of 140 ns.

5.2.2 PASSIVE STAR—The passive star network consists of a series of network nodes connected to the passive star as shown in Figure 10. Each node consists of an Rx/Tx pair and a pair of optical fibers. The network also contains a central element that acts like an optical splice and distributes the optical signal to all network nodes. The passive transmissive star contains a means to receive optical energy from any transmitting node and divide the optical energy evenly among the output fibers.

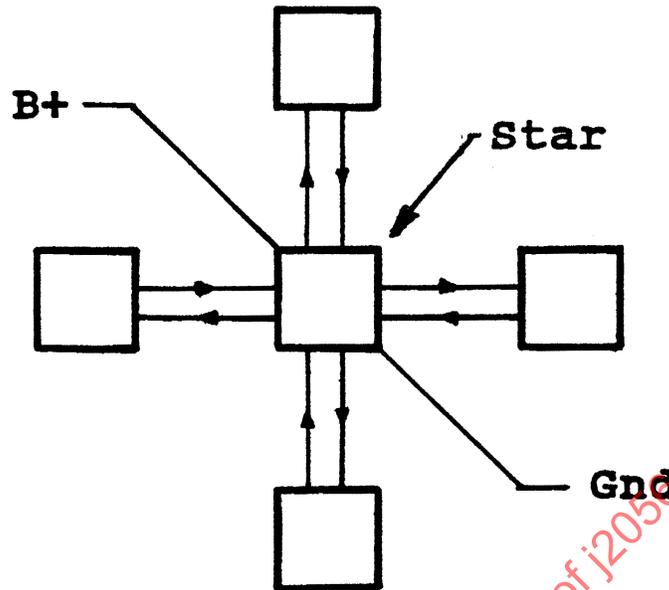


FIGURE 10—PASSIVE STAR

5.2.2.1 Advantages

- Cost: The passive star has a limited number of receiver/transmitter pairs and no electrical connections to the star.
- Power Moding: All nodes can be powered in any order or combination.
- Fault Tolerance: A fault will be limited to an individual node or its associated fibers. The star could be a single point fault, but because it is totally passive, its failure modes are limited to the physical design and with sufficient hardening this design should not be a problem.
- Latency: All nodes will monitor the data when it is transmitted with only the delay caused by fiber length.
- Serviceability: Some fault identification is possible since a fault will be isolated to a specific spoke or node on the network. The remainder of the network is still operational.

5.2.2.2 Disadvantages

- Cost: The passive star element will add cost to the network.
- Complexity: The passive star requires two fibers per node to route to the star.
- Expandability: It is limited by star port count and optical flux budget. Currently available devices limit the number of ports to seven.

5.2.3 SINGLE RING—The single ring network, illustrated in Figure 11, consists of an Rx/Tx pair and a single fiber for each node connected in series. Data is transferred around the ring through a continuous series of retransmissions by each node until it completes a circuit around the network. Each data message is received and retransmitted by each node. The amount of logic required depends on the particular technique used. The logic could be as simple as a series of shift registers through the capability to receive, decode, and retransmit a complete message.

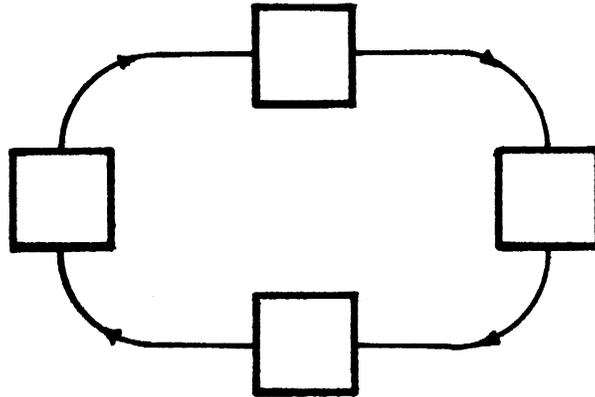


FIGURE 11—SINGLE RING

5.2.3.1 Advantages

- Cost: The single ring network contains the fewest fiber ends and requires no special hardware.
- Complexity: The complexity is minimized since there are no added nodes and the complexity is evenly distributed.
- Expandability: The single ring network is easily expanded by adding nodes into the ring.

5.2.3.2 Disadvantages

- Power Moding: All modules must be powered up for the network to operate.
- Fault Tolerance: A fault anywhere in the network will cause the network to be inoperative.
- Serviceability: Since any one fault causes the network to be inoperative, faults are not easily isolated.
- Latency: Each module must retransmit the data adding to the latency between the first and last node.

5.2.4 DOUBLE RING—The double ring or dual counter rotating ring, illustrated in Figure 12, consists of two single rings connected such that data flows in opposite directions. Data is passed around in two directions on two sets of fibers. Each node consists of two Rx/Tx pairs and two fibers, and some additional logic to allow for fault isolation and bypass. If a fault occurs in one or both rings, the nodes on either side of the fault wrap the data around the ring in the other direction on the second loop, as shown in Figure 13, completing the communication. Faulty nodes or fiber interconnects can be bypassed in this manner.

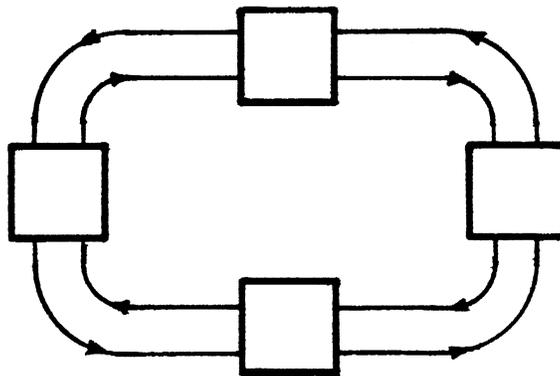


FIGURE 12—DOUBLE RING

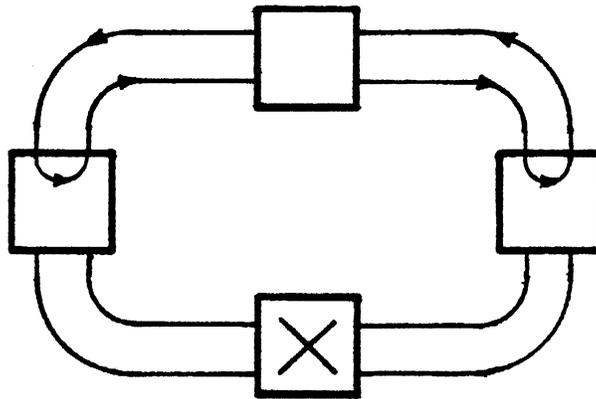


FIGURE 13—DOUBLE RING WITH FAULT

5.2.4.1 Advantages

- Fault Tolerance:** The double ring network is very tolerant of single faults (nodes or fiber interconnect). The remainder of the network continues to function.
- Expandability:** The network is easily expanded by inserting a node into the ring.
- Serviceability:** The network is capable of determining the location of a fault.

5.2.4.2 Disadvantages

- Cost:** The double ring network employs four Rx/Tx pairs, two fibers per node, and additional logic required for fault isolation and bypass will have significant cost impact.
- Complexity:** Complexity is evenly distributed, but each node requires four optical connections and two receiver/transmitter pairs.
- Power Moding:** One module could be powered down and the rest of the network will continue to function. For multiple modules to be powered down, they would have to be positioned in line on the ring, which would impact the physical complexity.
- Latency:** Each module must retransmit the data. This action adds to the latency between the first and last node.

5.2.5 **LINEAR TAPPED BUS**—The linear tapped bus can be implemented in many forms depending on the capability of the tap and the available optical flux budget. If the tap is assumed to be unidirectional, asymmetrical, and variable, the simplest configuration would consist of a single fiber that would route past each module twice as shown in Figure 14. The single fiber would be divided into a transmit leg and a receive leg. Each node has a launch tap on the transmit leg and a receive tap on the receive leg. The optical flux budget and the tap capabilities will determine the maximum number of nodes that can be handled passively. If a larger number of nodes is required, an active head end as shown in Figure 15 would be needed. Currently, with reasonably low-cost electro-optical devices and available tap technology, the maximum number of nodes that can be accomplished passively is ten.

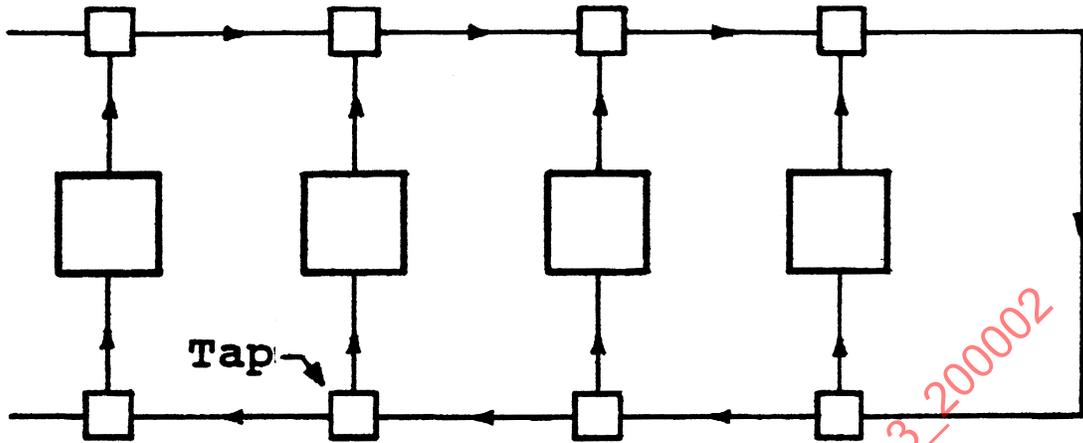


FIGURE 14—LINEAR TAPPED BUS

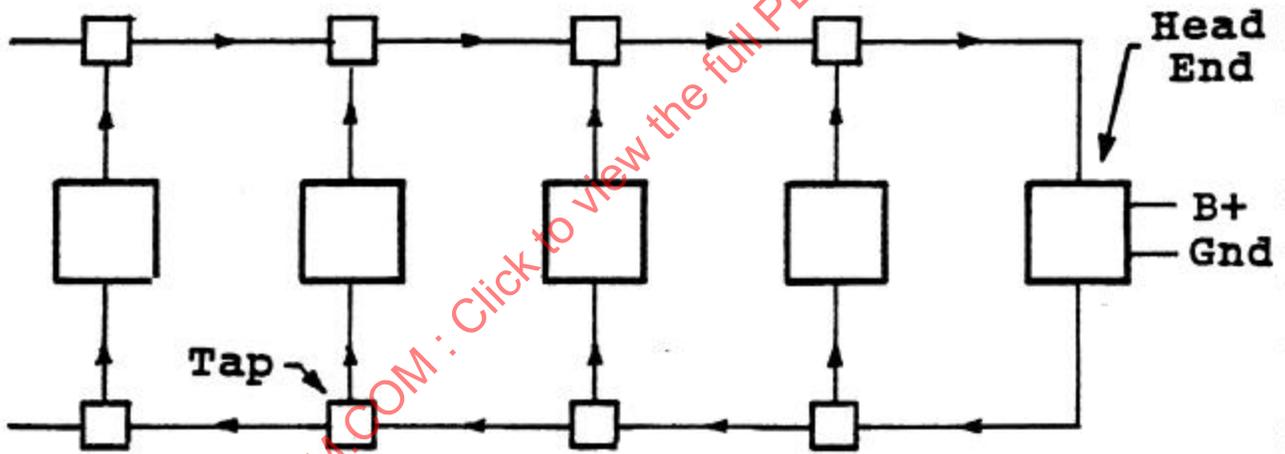


FIGURE 15—LINEAR TAPPED BUS WITH HEAD END

5.2.5.1 *Advantages*

- a. Power Moding: Passive implementation will allow all nodes to power mode independently.
- b. Latency: All nodes will see the data when it is transmitted with only the delay caused by fiber length unless a head end is required.

5.2.5.2 *Disadvantages*

- a. Cost: The linear tapped bus requires a large number of taps, two per node, and possible need for a head end node will increase the cost.
- b. Complexity: The packaging of taps and head end node will impact complexity.
- c. Power Moding: The head end node must be powered up continuously if required.
- d. Fault Tolerance: A fiber or tap fault will always cut off some portion of the network. The farther down the bus fiber the fault occurs, the more nodes that will be impacted until all nodes would be inoperative. A fault in the head end module or its power and ground feeds will incapacitate the whole network.
- e. Expandability: The expandability of the network will be limited by the tap characteristics and the original optical flux budget. The network would have to be designed and built with the capability for the addition of taps later. A tap could not be randomly applied anywhere within the network. It can only be applied where sufficient optical energy existed and where the downstream taps were designed to operate with the reduction in optical energy. Currently available taps and electro-optical devices limit the passive linear tapped bus to ten nodes.
- f. Serviceability: A number of conditions can cause the network to be inoperative making failure diagnosis difficult.
- g. Latency: The head end retransmission will add some latency.

5.2.6 NETWORK ARCHITECTURE CONCLUSIONS—Based on the assumptions made and the factors considered, the following conclusions about network architecture can be made:

- a. The single ring is inexpensive but lacks fault tolerance.
- b. The double ring is costly and complex.
- c. Both of the ring configurations have functional deficiencies in latency and power modes of operation.
- d. The active star is very costly, complex, and susceptible to single point faults.
- e. The linear tapped bus is costly with no offsetting benefits.
- f. The transmissive or passive star has the best tradeoffs and appears to have the most benefits, especially if the cost of the star with some expansion ports is reasonable.

5.3 **I/O Hardware Configuration**—The data encoding method, network topology, and protocol selected with a fiber optic transmission media has a pronounced impact on the I/O hardware configuration design.

5.3.1 TIME DIVISION MULTIPLEX (TDM)—Time division multiplex is the most commonly discussed method of data transmission for automotive applications. In TDM, the data is encoded in a series of amplitude modulated light pulses. The pulses are typically, but not necessarily, on/off pulses with light on being the dominant state for contention based systems.

5.3.2 FREQUENCY (WAVELENGTH) DIVISION MULTIPLEX—Frequency division multiplexing is typically used to extend the bandwidth of the fiber by allowing information to be transmitted at multiple wavelengths. Within the limitations of the fiber, the bandwidth can be a direct function of the number of wavelengths utilized.

FDM requires the use of filters at each receiver to select the appropriate wavelength for that node. The flux budget will be impacted since each node will utilize only the optical energy within its selected wavelength and discard all optical energy in the unwanted wavelengths. The energy in the unwanted wavelengths is lost.

Since the bandwidth of the fiber with a single wavelength is sufficient, FDM would probably not be cost effective.