Distributing Timing Signals in a High-EMI Environment

Introduction

Many applications for timing signals require that several different pieces of equipment, often separated by significant distances, be synchronized together. This is not a simple problem even in a relatively benign environment, but in many industrial applications, such as power substations, these signals must be distributed in a very difficult environment.

As will be seen, there are many factors which must be considered in such an application, but one of the most difficult is electromagnetic interference (EMI). EMI includes a variety of sources of interfering signals, ranging from dc and low-frequency (50 or 60 Hz) all the way up through the rf and microwave region. All of these signals have the potential to interfere in one way or another with the accurate and reliable distribution of timing signals.

This Application Note addresses this problem. It is broken into two sections. The first section is a general discussion which describes the characteristics of two different distribution techniques. The second section contains implementation guidelines, describing how to assemble a distribution system using products available from Arbiter Systems, Inc.

Part One — Discussion

Alternatives to Consider

Depending on the type of signals to be transmitted and the accuracy required, there are three different approaches which might be appropriate for any given situation. Sometimes, more than one approach may be used together to solve a complex problem.

Alternative #1: Fiber-Optic Distribution Systems

Properly-designed fiber-optic distribution systems offer the ultimate in rejection of EMI. They have several other key advantages, as well, but they have several disadvantages.

Advantages of Fiber-Optic Systems

First and foremost, if the supporting electronics are designed properly, fiber-optic systems are fundamentally insensitive to most EMI. Also important is the very wide bandwidth that a properly-designed fiber optic link can provide. This is important because it allows high-resolution timing signals to be transmitted accurately to distant locations.

For example, unmodulated (TTL or level-shift) IRIG-B is not generally thought of as a high-precision timing signal due to its low data rate of 100 bits per second. However, if this signal is generated accurately enough, it is capable of providing excellent precision; better, in fact, than the most accurate timing systems available. The ultimate example of this is that many of the most accurate timing systems use a one pulse per second (1 PPS) signal. If the edge speed is high (as it is with modern logic circuits), then the 1 PPS signal establishes an on-time mark within a few nanoseconds, plus the fundamental uncertainty of the timing source.

The key to maintaining this accuracy in distribution is high bandwidth; if a dc-coupled link will pass a 1 MHz square wave, for example, it is easy to show that it will also transmit a pulse with better than 500 nS precision. Fiber-optic links can deliver bandwidths measured in the megahertz range; unlike copper they require no bandwidth-limiting techniques for successful operation.

Properly-designed single-mode fiber-optic links are capable of transmitting high-resolution timing signals over distances of many kilometers. In this regard, they are generally superior to copper. However, as will be suggested later, at these distances the most cost-effective and reliable alternative is often a second satellite-controlled clock.

Disadvantages of Fiber-Optic Systems

Fiber-optic systems are expensive to install and maintain in comparison with copper-based systems. Despite significant improvements, fibers are still more delicate than copper wire to install. They require more expensive preparation than copper for termination, and the optical signal must in most cases be converted back to electrical at the receiving end. This requires active circuitry and a source of power, which adds to cost and complexity and degrades overall reliability.

Fiber-based systems are, for most practical purposes, point-to-point links. Complex networks with many taps can be built, but are quite expensive. Copper-based networks, on the other hand, easily lend themselves to multi-tap configurations.

Despite these cost disadvantages, fiber is the medium of choice when high-resolution timing signals must be transmitted over distances of approximately 20 meters to 2 kilometers. In this range, optimum cost-effectiveness is usually found using multimode fiber (such as 62.5/125 um type) and LED optical sources at either 820 or 1300 nanometers.

Delay in Fiber-Optic Systems

All transmission media delay signals propagated through them. For a length of two kilometers, both optical fibers and copper cable will have a delay around ten microseconds. For the case of the copper system described later, this delay is relatively small compared to the resolution limit of the modulated IRIG-B code and is therefore inconsequential. However, when using optical fiber to transmit high-resolution timing signals, this delay may no longer be insignificant.

A simple fiber-optic to logic-level adapter does not compensate for these delays. It simply reproduces at its electrical output a facsimile of the optical signal applied to it. A more complex circuit can be assembled which compensates for these delays by regenerating the timing signal with the required offset. Such a device, while technically feasible, is substantially more complex than a simple optical-to-electrical converter. As compensation, it can offer a variety of electrical outputs in addition to the applied signal. For example, from an unmodulated IRIG-B signal, a 10 MHz oscillator may be synchronized and 1 PPS extracted; from these, a variety of outputs may be created including both modulated and unmodulated IRIG-B, 1 PPS, and other pulse rates, fully synchronized, up to the oscillator frequency of 10 MPPS.

Alternative #2: Copper-Based Distribution Systems

The largest disadvantage of a copper-based system is that it is, effectively, a large antenna which will pick up interfering (EMI) signals over a wide range of frequencies. However, before dismissing copper as a transmission medium, it is important to consider its advantages. From this, you will see that there exist applications for which copper is the best overall solution.

Advantages of Copper-Based Systems

The largest advantage of copper is that a fully-passive, and therefore inexpensive and highly-reliable, network can be installed using copper wire. A wide variety of interconnection devices are available for copper wiring at economical prices. Copper-wire networks can easily be configured in complex topologies, in addition to point-to-point, including linear networks, branched networks, loop networks, and combinations. Any of these can provide a multitude of taps, providing signals to a variety of equipment in different locations.

The key to using copper wire to successfully distribute timing signals is to overcome copper's primary drawback, which is sensitivity to electromagnetic fields.

Designing a Successful Copper-Based Network

The most-commonly used timing signal is 1 kHz modulated IRIG-B. This signal can provide accuracy of 10 microseconds to one millisecond, depending on the circumstances. As it turns out, this level of performance is perfectly adequate for a majority of timing applications. Also, as it turns out, this signal is optimal for transmission over a copper-based network.

Fundamentally, copper has a very wide bandwidth. This is the source of many problems encountered when attempting to connect physically-separated locations together with copper cables. These problems may be due to high-frequency noise (radio transmissions, corona noise, etc.), which can appear on signal lines, degrading performance, or low-frequency and dc signals resulting from magnetic fields or ground-potential differences which cause circulating currents in ground loops. By proper system design, these problems can be overcome.

Overcoming High-Frequency Interference

High-frequency interference is circumvented by two techniques. The first is shielding and the second is filtering. Properly-shielded cables have substantial immunity to high-frequency signals. Further, when distributing an IRIG-B signal, which has a limited bandwidth (it can be transmitted in a 300 Hz — 3 kHz audio channel), the remaining high-frequency noise can easily be filtered from the distribution bus before the output signal is delivered to its destination. Such filtering does add some delay, and it slows down high-resolution timing signals; these are the primary limitations of a copper network with respect to such signals. However, a 10 kHz lowpass pole has a delay of only 16 microseconds, which approaches the resolution limit of the IRIG-B modulated signal. In addition, cable dielectric loss causes substantial attenuation of interfering high-frequency signals when transmitted over distances of several hundred meters, without adding much delay.

Overcoming Low-Frequency and DC Interference

Low-frequency and dc interference is suppressed using different techniques. It is common practice in the audio field to use balanced low-impedance lines to reject magnetic fields which can cause interference. With such lines, millivolt-level microphone signals can be transmitted with signal-to-interference ratio well in excess of 100 dB, over tens or even hundreds of meters, in the vicinity of thousands of watts of thyristor-controlled lighting. These lines are also shielded to reject high-frequency noise. Another example of the use of balanced, low-impedance lines is the local loop of a telephone network, which often covers distances of many kilometers.

Balanced, low-impedance lines are largely immune to low-frequency interference because the interfering signals appear in what is called common mode, that is, between the signal lines and ground, rather than across the two signal lines. By using devices which reject common-mode interference while passing the differential, normal-mode signal, high signal-to-noise ratio can be maintained in difficult environments.

While active (powered) electronic circuits can also be used, the oldest, most-common, and still most-reliable device to reject common-mode signals is the transformer. Millions are made every year to isolate audio signals, both high-fidelity and telephone-grade. It is also relatively easy to provide thousands of volts of isolation between the input (primary) and output (secondary) of a transformer, even in a relatively small and inexpensive device.

Overcoming Short-Duration Surges

High-voltage isolation is important when considering the effect of surges, which are momentary impulses, or bursts of impulses, caused by lightning or the breaking of nearby circuits carrying large currents. Such voltages, although short in duration (tens of nanoseconds through a few microseconds), can easily be thousands of volts in magnitude, particularly when built up over hundreds of meters of cable length. Excellent rejection of common-mode signals is only useful under such circumstances if adequate isolation is provided to prevent a direct discharge path from developing.

Surges can also cause normal-mode signals to appear, although usually of substantially smaller amplitudes, due to slight imbalances in the nominally-balanced system. These surges can be reduced by two methods: voltage clamping using metal-oxide varistors (MOVs) or silicon surge suppressors; and due to the short duration of the impulses, by low-pass filtering.

Other Possible Features of a Copper-Based System: Self Monitoring

In many applications for timing signal distribution, the equipment is located remotely. Monitoring and maintaining this equipment can become a significant challenge, very different from that faced in the laboratory. One feature which can be added to a copper distribution system is continuous real-time monitoring of distribution system health. Since the distribution network itself can be made fully passive, the likelihood of its failure is minimized. However, as with any system, failure is still possible. In addition, interruption of service due to physical damage to the distribution system (a cut cable, for example) is always a concern.

A copper network can be configured to monitor itself by sending a small dc current (10 mA or so) through the signal lines. Any break in the lines will cause the interruption of this current, which can easily be detected. By isolating the signal taps from this dc current, and by introducing the proper coupling networks into the system, the dc current can be forced to flow through every portion of the distribution bus, in series, to a terminating inductor at the far end of the bus, and then back along the same path through the return conductor. Any break can then be detected and reported.

A variation of this technique allows a form of “redundant ring” network to be built. In this variation, the “far end” of the network is brought back, physically, to the starting point. A special coupling network provides a return path for the dc monitor current, while providing a parallel driving point for the IRIG-B signal voltage. In this variation, the network will detect any break in the signal cable, while continuing to provide service to all taps!

Additional monitoring features can be added to detect faults such as a short circuit in the cable (which would, of course, pass the dc monitor current), and loss of the IRIG-B signal due to hardware failure at the source.

Copper-Based Distribution: Summary

In summary, by taking advantage of the characteristics of the modulated IRIG-B signal, a copper-based distribution system can be built which offers accuracy of approximately 100 microseconds and good rejection of interfering electromagnetic signals, while keeping costs to a minimum, including the costs for (1) acquisition or initial equipment costs; (2) installation or labor costs; and (3) reliability or maintenance costs. Such a system will be far simpler than a fiber-optic system, offer greater flexibility, and be more reliable. It can offer significant self-monitoring and redundancy features as well. Such a network is not, however, capable of transmitting signals with the resolution (bandwidth) which is possible with optical fiber.

Alternative #3: Multiple Satellite-Controlled Clocks

In some applications, the distance which must be covered, or number of signals which must be transmitted, increases the costs of the distribution system to the point where multiple satellite-controlled clocks may be a cost-effective alternative. In this scenario, the benefits are (1) a full-featured, complete satellite-controlled clock is available at all locations and (2) all locations are fully independent of each other. The disadvantages of this approach are few, primary of these being that (1) each additional clock can fail, and (2) the costs are not insignificant.

Summary: Fiber Optics vs. Copper

Three approaches have been described here. Each offers its own benefits and drawbacks. Table 1 is a summary of the three.

Depending on the application, a combination of methods may be appropriate. For example, a satellite-controlled clock can drive a copper-based IRIG-B distribution bus which provides medium-resolution signals to many devices over a kilometer or two of total bus length. The same clock can have a fiber-optic interface which drives several point-to-point links where high timing resolution is required, perhaps with a 1 PPS signal or a high-rate trigger, such as 1 MPPS. Thus, the majority of devices which require medium-resolution IRIG-B signals are driven with the optimum cost and reliability, while the high-performance capability of optical fiber is reserved specifically for the applications in which it provides important benefits.

Table 1. Summary of Advantages and Disadvantages

System	Advantages	Disadvantages
Optical Fiber	EMI Rejection High Resolution	Inflexible High Cost Reliability
Copper Wire	Flexibility Reliability Moderate Cost Self-Monitor Capability Redundancy Possible	Low Resolution Modulated IRIG Only
Multiple Clocks	Independent Redundant No EMI Issues Multiple Signals	High Cost Reliability

Part Two — Implementation Guidelines

Fiber-Optic Distribution System

Arbiter Systems, Inc. manufactures two products for distribution of timing signals via optical fiber. Option 20 for the Model 1088B GPS Satellite-Controlled Clock is a four-channel, configurable fiber-optic transmitter. It has four 820 nm LED optical sources with ST-compatible connectors, intended for use with multimode optical fiber of 50/125 or 62.5/125 um construction. Each channel of the Option 20 transmitter may be independently configured to any of the digital signals available from the Model 1088B mainframe. The Model 10881A Fiber-Optic to Logic Converter accepts the optical signal and converts it back to a 5V CMOS electrical signal.

The Model 1089A/B IRIG-B Controlled Clock, equipped with option 13 fiber-optic input, uses the same optical receiver as the Model 10881A logic converter, and the optical specifications which follow apply to it as well. The Model 1089A/B accepts either unmodulated IRIG-B or modified Manchester-encoded IRIG-B (per IEEE Standard P1344) at its fiber optic input, and provides many of the same functions as a GPS-controlled clock, including various output signals and interfaces.

Model 1089A slaves an internal oscillator to the IRIG-B signal received at the optical input. Internal adjustment is provided to advance the timing of the electrical outputs to compensate for delay in the optical fiber, from 0 to 100 microseconds (approximately 20 km of fiber). The Model 1089A has a 1-EIA unit rack-mountable package, similar to that of the Model 1088B, and will offer all of the same power input selections as the Model 1088B. An display and keyboard are also be included in the Model 1089B.

With the components used in these products, the following optical specifications apply:

Optical Power Output, 62.5/125 (50/125) um Fiber:
-15.0 (-18.8) dBm, minimum (25 deg. C)
-12.0 (-15.8) dBm, typical
-10.0 (-13.8) dBm, maximum (25 deg. C)

Optical Power Input for Logical “1” (+5V) Output:
-25.4 dBm, minimum (25 deg. C)
-9.2 dBm, maximum (overload limit)

Optical Power Budget, 62.5/125 (50/125) um Fiber:
10.4 (6.6) dB, minimum (25 deg. C)
9.2 (5.4) dB, minimum (0 - 55 deg. C)
13.4 (9.6) dB, typical

These numbers can be used to determine the maximum length of fiber that can be used to transmit timing signals. For example, using 62.5/125 um fiber having a specified loss of 2.8 dB/km typical, 3.5 dB/km maximum, a link could be built over a minimum distance of 2.6 km; typically, it would operate up to 4.7 km. These calculations do not include the effect of connector losses and splices. Allowances for these should be subtracted from the optical power budget prior to determination of the link length.

The Option 20 fiber-optic transmitter has a bandwidth compatible with all signals available in the Model 1088B. The Model 10881A receiver is limited to a maximum rate of 5 MPPS.

Taps and Splitters

Within limits, taps and splitters can be added to a fiber system, provided that the total optical loss does not exceed the optical power budget. For the transmitter and receiver used in the Option 20 and 10881A, a limited number of taps or splitters can be used, with a corresponding reduction of link length. For example, using a 1:2 splitter having a 1:1 splitting ratio (3 dB ideal loss) and 0.5 dB excess loss, for a total optical power loss of 3.5 dB, the fiber lengths in the example above would be reduced to 1.6 km (minimum) and 3.5 km (typical).

Sources of Supply for Optical Fiber, Connectors and Components

Arbiter Systems, Inc. does not supply optical fiber, connectors, termination kits, or splitters. These are available from a number of industry sources. Due to the fast growth of the fiber-optic industry, sources of supply are changing regularly. Should you have trouble identifying a source of supply for a particular component, Arbiter Systems will suggest one or more possible sources, if requested to do so.

Installation

The fiber-optic timing distribution system does not require any special tooling or techniques for installation compared with any other fiber application. However, installation and termination of fiber-optic cables does require skills and equipment different than those required to install copper wiring. If you are not familiar with these techniques, it may be advisable to subcontract the fiber installation and termination to a qualified contractor.

Copper IRIG-B Distribution System

Arbiter Systems, Inc. also manufactures several products which can be used to assemble a copper-based IRIG-B distribution system like that described in part one of this Application Note. Option 18 for the Model 1088B GPS Satellite-Controlled Clock provides an IRIG-B distribution bus output which is capable of driving 24 separate taps, loaded at 600 ohms or more, over a length of 500 meters of cable. Longer cable lengths, or more taps, may be used, depending on the loading and signal levels required.

Option 18 includes a built-in distribution system monitor, which continually checks for two conditions: the presence of an IRIG signal at the bus output terminals, and dc electrical continuity in the distribution bus cable. Any fault in the clock mainframe or Option 18 board which results in loss of IRIG drive, any bus short within approximately one kilometer of the clock (or more, depending on bus configuration and loading), and any electrical open circuit (a cut cable, for instance) will be detected and reported as a FAULT via the front-panel FAULT LED, the FAULT relay output, and RS-232.

Even in the presence of a break in the cable, service may be maintained at all taps, and the break detected and reported for maintenance, using the Model 10885A IRIG-B Distribution Redundant-Ring Adapter with a ring or loop-configured distribution bus (where the ‘far end’ of the bus is physically brought back to the start). This allows the system to offer a substantial degree of survivability with respect to broken cables, while nonetheless reporting the problem for corrective action. The Model 10885A also provides 3750 Vrms isolation from the return end of the bus to the clock mainframe, to prevent voltages induced in the bus loop from causing currents to flow in the distribution bus or its shield.

Three other products are offered for building an IRIG-B distribution system. The Model 10882A IRIG-B Distribution Tap, Model 10883A IRIG-B Distribution Terminator, and Model 10884A IRIG-B Distribution Splitter provide the functions needed to assemble a working system.

The Model 10882A tap is used to provide a decoupled, isolated output signal to your system loads. The source impedance of this tap is approximately 600 ohms, and it will provide an open-circuit signal level of 6.4 to 11 Vpp, depending on overall system loading and distance from the clock mainframe. Each tap provides 3750 Vrms isolation from the distribution bus to the load, as well as surge suppression and EMI filtering. The taps are capacitively-isolated from the dc bus monitoring current.

One Model 10883A terminator is located at the end of a linear distribution bus, and one at the end of each branch. This inductive terminator provides a high impedance to the IRIG-B signal while providing a return path for the dc loop current used for continuity monitoring.

The Model 10884A splitter is used to drive a branch from the main distribution bus, or to split a bus into two branches. It drives the two output branches in parallel as far as the IRIG-B signal is concerned, while they are connected in series for the dc loop monitoring current.

Bus Configurations

Using these three components, a linear or branched network can be assembled in any required configuration, while maintaining the ability of the Option 18 bus monitor to detect an open-circuit fault at any point along the bus or any branch. If the Model 10885A redundant-ring adapter is used to build a basic ring network, the Model 10883A terminator and Model 10884A splitter are not required. However, as shown in the accompanying figures, a complex system can be built using rings, branches, and linear segments in various combinations as needed to satisfy your requirements.

Determining Actual Signal Output Levels

The actual signal levels at the outputs of the various taps may be approximated with acceptable accuracy by treating the network as a resistive array. The source impedance of the Option 18 bus output is approximately 21 ohms. The recommended cable (Belden 8760 or equivalent, #18 AWG shielded twisted pair) has a resistance of 43 ohms per kilometer (13 ohms per thousand feet). The Model 10885A redundant-ring adapter has an effective series resistance to the ac signal of approximately 10 ohms. The Model 10884A splitter has an effective series resistance of less than one ohm.

Each Model 10882A tap places a load across the bus of approximately 580 ohms plus the load impedance it is driving; i.e. the tap acts like a 580-ohm resistor in series with the load, with which it forms a voltage divider. The Model 10883A terminator may be treated as an open circuit so far as the IRIG signal is concerned.

By using these numbers, along with the load impedances, in a suitable circuit-analysis program, or by solving the loop equations manually, the attenuation from the Option 18 bus output to the load at each tap may be determined. The open-circuit output level at the Option 18 bus output is nominally 11 volts peak-to-peak with a tolerance of ±5%; knowing this, along with the attenuation values, you can calculate the signal level at each tap.

Total DC Resistance Limit - Bus Monitor

There is a 500-ohm limit on the total dc resistance of the distribution system to ensure proper operation of the bus continuity monitor. This limit will not normally be a factor in system design. Still, loop dc resistance should be calculated for each system.

Since all of the components which pass dc current are effectively in series as far as the dc current is concerned, the resistances can simply be summed up. If the total is less than 500 ohms, proper operation is ensured.

The cable resistance is 43 ohms/km (13 ohms/Mft.) for the dc monitor current. The dc resistance of the Model 10885A redundant-ring adapter is 4 ohms. The dc resistance of each Model 10883A terminator and each Model 10884A splitter is 30 ohms. The number of taps has no effect on the system dc resistance.

The magnitude of the dc monitor current is 10 mA ±10% with a maximum dc open-circuit voltage of 8.5 volts. In the USA, NEC class-2 wiring is acceptable.

Detection of Short Circuits; Drive Capability

The Option 18 bus output is intended to drive a total ac load of 50 ohms or greater, although it will continue to operate without excessive signal distortion into any impedance. The bus monitor includes a circuit which detects the presence of the IRIG-B signal at the system output. The bus monitor is sensitive to both the waveshape of the signal at the bus output (it must look like a modulated IRIG-B signal), and the level of that signal.

If the load impedance drops below approximately 40 ohms, a drop in signal level will occur due to the 21-ohm source resistance of the bus driver. At this point, the output level will drop below the threshold required by the bus monitor, in turn causing a bus FAULT to be reported. Since in normal operation the system load exceeds 50 ohms, such a fault must be the result of a short circuit at some point along the bus.

Thus, the bus monitor function of the Option 18 IRIG-B distribution output is capable of detecting the three most likely types of system fault: failure of the IRIG-B drive signal at the source, an open circuit along the distribution bus, or a short of the distribution bus.

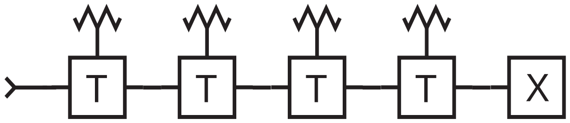
Installation

Installation of the IRIG-B distribution bus is straightforward for those experienced with the installation of control and communication wiring. No special tools are required. All of the components are terminated with pluggable, screw-type terminal blocks. A 3 mm (1/8") flat-bladed screwdriver, wire cutters and strippers are all that is required to terminate the cable.

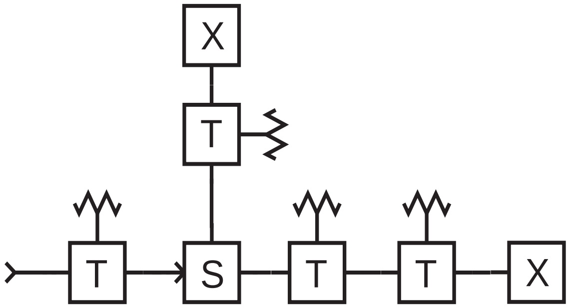
Summary

This Application Note has discussed the issues to be considered when assembling a system for accurate timing signal distribution in a high-EMI environment. It has described two basic methods which can be used in such systems, optical fiber and copper cable-based. The advantages and disadvantages of each have been described.

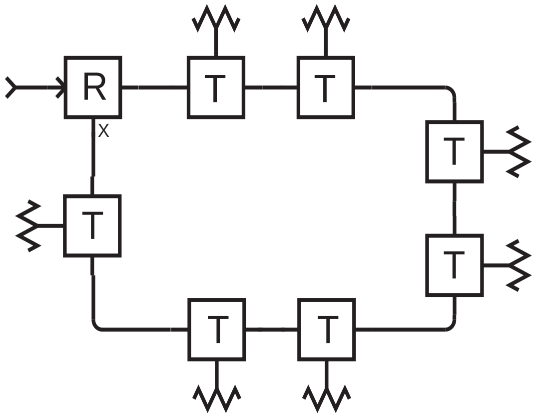
Products available from Arbiter Systems which are useful in constructing both types of systems have been described. Guidelines for implementing systems based on these products have been presented, and examples of system implementation discussed.



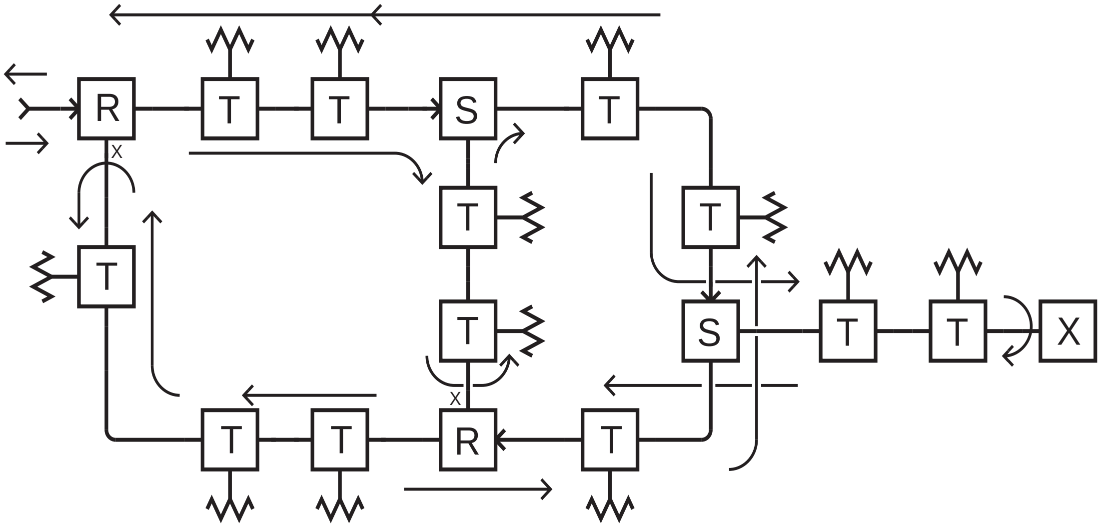
Linear Network

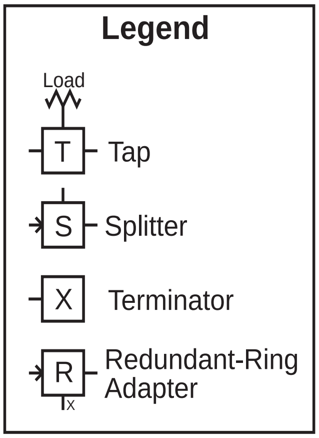


Branched Network



Redundant-Ring Network.
May also include one or more
(non-redundant) branches, if desired.





Complex network, showing multiple loops and branches. Arrows show direction of dc loop monitor current flow.

Bus Cable: Belden 8760 or equivalent; 18 AWG pair with foil-polyester shield and 20 AWG drain wire.

Fiber-Optic Configurations (Logic Signals)

Optical Fiber 62.5/125 µm