CHAPTER 8

Measurement Signal Transmission

Chapter Outline

8.1 Introduction

There is often a necessity in many measurement systems to transmit measurement signals over quite large distances from the point of measurement to the place where the signals are recorded and/or used in a process control system. The need to separate the processing/recording parts of a measurement system from the point of measurement can arise for several reasons. One major reason for the separation is the environment around the point of measurement, which is often hostile toward one or more components in the rest of the measurement system. Extremes of temperature, humidity, weather, or fumes are typical examples of environments at the point of measurement that are too hostile for other measurement system components. Remoteness of the point of measurement can be another reason for transmitting measured signals to another point. We often meet this problem in environmental and weather monitoring systems. One example is water quality measurement in rivers, where sensors may actually be anchored in the river. In this sort of situation, no mains powered by electricity supply is available. While it is possible to use battery or solar power for the sensors themselves, main power is normally needed for the necessary signal processing. Furthermore, there

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are usually no buildings available to protect the signal processing elements from the environment. For these reasons, transmission of the measurements to another point is necessary.

We will therefore devote this chapter to a study of the various ways in which measurement data can be transmitted. We will see that the need to transmit measurement signals over what can sometimes be large distances creates several problems that we will investigate. We will discover in the following pages that, of the many difficulties associated with long-distance signal transmission, contamination of the measurement signal by noise is the most serious. Many sources of noise exist in industrial environments, such as radiated electromagnetic fields from electrical machinery and power cables, induced electromagnetic fields through wiring loops, and spikes (large transient voltages) that sometimes occur on the mains AC power supply. Our investigation into signal transmission techniques will show us that signals can be transmitted electrically, pneumatically, optically, or by radio telemetry, in either analog or digital format. We will also discover that optical data transmission can be further divided into fiber optic transmission and optical wireless transmission, according to whether a fiber optic cable or just a plain air path is used as the transmission medium.

8.2 Electrical Transmission

The simplest method of electrical transmission is to transmit the measurement signal as a varying analog voltage. However, this mode of transmission often causes the measurement signal to become corrupted by noise. To avoid such corruption, the signal can be transmitted as a varying current instead of a varying voltage. An alternative solution is to transmit the signal by superimposing it on an AC carrier system. All of these methods are discussed below.

8.2.1 Transmission as Varying Voltages

As most signals already exist in an electrical form as varying analog voltages, the simplest mode of transmission is to maintain the signals in the same form. However, electrical transmission suffers problems of signal attenuation, and also exposes signals to corruption through induced noise. Therefore, special measures have to be taken to overcome these problems.

Because the output signal levels from many types of measurement transducer are very low, *signal amplification* prior to transmission is essential if a reasonable signal-to-noise ratio is to be obtained after transmission. Amplification at the input to the transmission system is also required to compensate for the attenuation of the signal that results from the resistance of the signal wires.

It is also usually necessary to provide *shielding* for the signal wires. Shielding consists of surrounding the signal wires in a cable with a metal shield that is connected to earth. This provides a high degree of noise protection, especially against capacitive-induced noise due to the proximity of signal wires to high-current power conductors. A full discussion on noise sources and the procedures followed to prevent the corruption of measurement voltage signals can be found in Chapter 3.

8.2.2 Current Loop Transmission

The signal attenuation effect of conductor resistances can be minimized if varying voltage signals are transmitted as varying current signals. This technique, which also provides high immunity to induced noise, is known as current loop transmission and uses currents in the range between 4 and 20 mA[1] to represent the voltage level of the analog signal. It requires a voltage-to-current converter of the form shown in Figure 8.1, which is commonly known as a *4–20 mA current loop interface*. Two voltage-controlled current sources are used, one providing a constant 4 mA output that is used as the power supply current and the other providing a variable 0–16 mA output that is scaled and proportional to the input voltage level. The net output current therefore varies between 4 and 20 mA, corresponding to analog signal levels between zero and the maximum value. The use of a positive, nonzero current level to represent a zero value of the transmitted signal enables transmission faults to be readily identified. If the transmitted current is zero, this automatically indicates the presence of a transmission fault, since the minimum value of current that represents a proper signal is 4 mA.

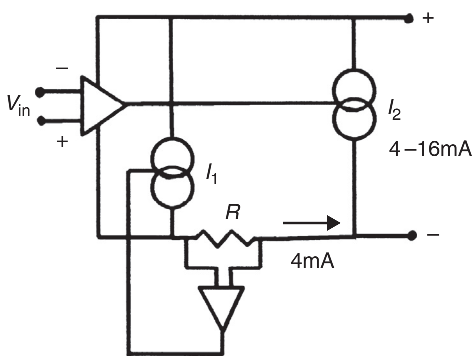

Figure 8.1
Voltage-to-current converter (current loop interface).

[1] The 4–20 mA standard was agreed in 1972, prior to which a variety of different current ranges were used for signal transmission.

Current-to-voltage conversion is usually required at the termination of the transmission line to change the transmitted currents back to voltages. An operational amplifier, connected as shown in Figure 8.2, is suitable for this purpose. The output voltage V is simply related to the input current I by $V = IR$.

The advent of intelligent devices has also led to the development of a modified current loop interface known as the *extended 4–20 mA current interface protocol*. This provides for the transmission of command/status information and the device power supply in analog form on the signal wires. In this extended protocol, signals in the range of 3.8–20.5 mA are regarded as "normal" measurement signals, thus allowing for under and over range from the 4–20 mA measurement signal standard. The current bands immediately outside this in the range of 3.6–3.8 mA and 20.5–21.0 mA are used for the conveyance of commands to the sensor/transmitter and the receipt of status information from it. This means that, if the signal wires are also used to carry the power supply to the sensor/transmitter, the power supply current must be limited to 3.5 mA or less to avoid the possibility of it being interpreted as a measurement signal or fault indicator. Signals greater than 21 mA (and less than 3.6 mA if the signal wires are not carrying a power supply) are normally taken to indicate either a short circuit or an open circuit in the signal wiring.

8.2.3 Transmission Using an AC Carrier

Another solution to the problem of noise corruption in low-level DC voltage signals is to transfer the signal onto an AC carrier system before transmission and extract it from the carrier at the end of the transmission line. Both amplitude modulation (AM) and frequency modulation (FM) can be used for this.

AM consists of translating the varying voltage signal into variations in the amplitude of a carrier sine wave at a frequency of several kiloHertz. An AC bridge circuit is commonly

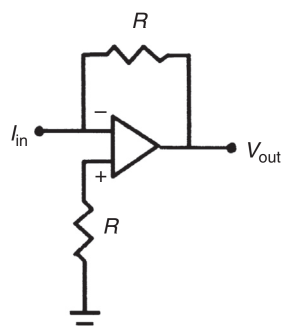

Figure 8.2
Current-to-voltage converter.

used for this, as part of the system for transducing the outputs of sensor that have a varying resistance (R), capacitance (C), or inductance (L) form of output. Referring back to Eqns (7.14) and (7.15) in Chapter 7, for a sinusoidal bridge excitation voltage of $V_s = V\sin(\omega t)$, the output can be represented by $V_o = FV\sin(\omega t)$. V_o is a sinusoidal voltage at the same frequency as the bridge excitation frequency and its amplitude FV represents the magnitude of the sensor input (R, C, or L) to the bridge. For example, in the case of Eqn (6.15):

$$FV = \left(\frac{L_u}{L_1 + L_u} - \frac{R_3}{R_2 + R_3}\right)V$$

After shifting the DC signal onto a high frequency AC carrier, a high pass filter can be applied to the AM signal. This successfully rejects noise in the form of low-frequency drift voltages and mains interference. At the end of the transmission line, demodulation is carried out to extract the measurement signal from the carrier.

FM achieves even better noise rejection than AM and involves translating variations in an analog voltage signal into frequency variations in a high-frequency carrier signal. A suitable voltage-to-frequency conversion circuit is shown in Figure 8.3, in which the analog voltage signal input is integrated and applied to the input of a comparator that is preset to a certain threshold voltage level. When this threshold level is reached, the comparator generates an output pulse that resets the integrator and is also applied to a monostable. This causes the frequency f of the output pulse train to be proportional to the amplitude of the input analog voltage.

At the end of the transmission line, the FM signal is usually converted back to an analog voltage by a frequency-to-voltage converter. A suitable conversion circuit is shown in Figure 8.4, in which the input pulse train is applied to an integrator that charges up for a specified time. The charge on the integrator decays through a leakage resistor, and a balance voltage is established between the input charge on the integrator and the decaying charge at the output. This output balance voltage is proportional to the input pulse train at frequency f.

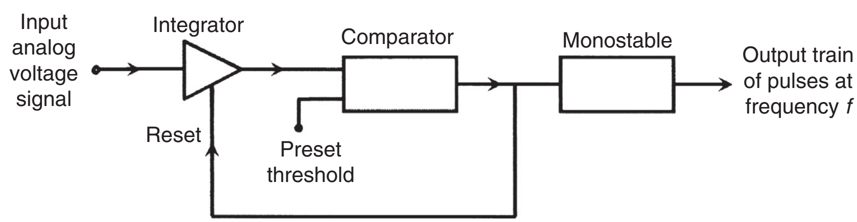

Figure 8.3
Voltage-to-frequency converter.

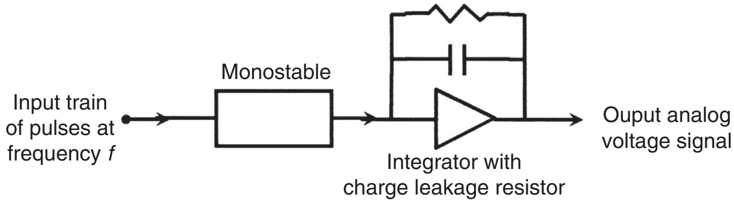

Figure 8.4
Frequency-to-voltage converter.

8.3 Pneumatic Transmission

In recent years, pneumatic transmission tends to have been replaced by other alternatives in most new implementations of instrumentation systems, although many examples can still be found in operation in the process industries. Pneumatic transmission consists of transmitting analog signals as a varying pneumatic pressure level that is usually in the range of 3–15 psi. (Imperial units are still commonly used in process industries, though the equivalent range in SI units is 207–1034 mbar, which is often rounded to 200–1000 mbar in metric systems.) A few systems also use alternative ranges of 3–27 psi or 6–48 psi. Frequently, the initial signal is in the form of a varying voltage level that is converted into a corresponding pneumatic pressure. However, in some examples of pneumatic transmission, the signal is in varying current form to start with, and a current-to-pressure converter is used to convert the 4–20 mA current signals into pneumatic signals prior to transmission. Pneumatic transmission has the advantage of being intrinsically safe, and it provides similar levels of noise immunity to current loop transmission. However, one disadvantage of using air as the transmission medium is that transmission speed is much slower than electrical or optical transmission. A further potential source of error would arise if there were a pressure gradient along the transmission tube. This would introduce a measurement error because air pressure changes with temperature.

Pneumatic transmission is found particularly in pneumatic control systems where sensors or actuators or both are pneumatic. Typical pneumatic sensors are the pressure thermometer (see Chapter 14) and the motion-sensing nozzle flapper (see Chapter 19), and a typical actuator is a pneumatic cylinder that converts pressure into linear motion. A pneumatic amplifier is often used to amplify the pneumatic signal to a suitable level for transmission.

8.4 Fiber Optic Transmission

Light has a number of advantages over electricity as a medium for transmitting information. For example, it is intrinsically safe, and noise corruption of signals by neighboring electromagnetic fields is almost eliminated. The most common form of optical transmission consists of transmitting light along a fiber optic cable, although wireless transmission also exists as described in Section 8.5.

Apart from noise reduction, optical signal attenuation along a fiber optic link is much less than electric signal attenuation along an equivalent length of metal conductor. However, there is an associated cost penalty because of the higher cost of a fiber optic system compared with the cost of metal conductors. In short fiber optic links, cost is dominated by the terminating transducers that are needed to transform electrical signals into optical ones and vice versa. However, as the length of the link increases, the cost of the fiber optic cable itself becomes more significant.

Fiber optic cables are used for signal transmission in three distinct ways. First, relatively short fiber optic cables are used as part of various instruments to transmit light from conventional sensors to a more convenient location for processing, often in situations where space is very short at the point of measurement. Second, longer fiber optic cables are used to connect remote instruments to controllers in instrumentation networks. Third, even longer links are used for data transmission systems in telephone and computer networks. These three application classes have different requirements and tend to use different types of fiber optic cable.

Signals are normally transmitted along a fiber optic cable in the digital format, although analog transmission is sometimes used. If there is a requirement to transmit more than one signal, it is more economical to multiplex the signals onto a single cable rather than transmit the signals separately on multiple cables. *Multiplexing* involves switching the analog signals in turn, in a synchronized sequential manner, into an analog-to-digital converter that outputs onto the transmission line. At the other end of the transmission line, a digital-to-analog converter transforms the digital signal back into analog form and it is then switched in turn onto separate analog signal lines.

8.4.1 Principles of Fiber Optics

The central part of a fiber optic system is a light transmitting cable containing at least one, but more often a bundle, of glass or plastic fibers. This is terminated at each end by a transducer, as shown in Figure 8.5. At the input end, the transducer converts the signal from the electrical form in which most signals originate into light. At the output end, the

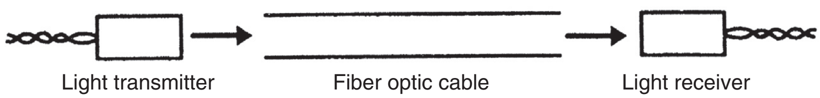

Figure 8.5
Fiber optic cables and transducers.

transducer converts the transmitted light back into an electrical form suitable for use by data recording, manipulation, and display systems. These two transducers are often known as the transmitter and receiver, respectively.

Fiber optic cable consists of an inner cylindrical core surrounded by a cylindrical cladding and a protective jacket, as shown in Figure 8.6. The jacket consists of several layers of polymer material and serves to protect the core from mechanical shocks that might affect its optical or physical properties. The refractive index of the inner core is greater than that of the surrounding cladding material, and the relationship between the two refractive indices affects the transmission characteristics of light along the cable. The amount of attenuation of light as it travels along the cable varies with the wavelength of the light transmitted. This characteristic is very nonlinear and a graph of attenuation against wavelength shows a number of peaks and troughs. The position of these peaks and troughs varies according to the material used for the fibers. It should be noted that fiber manufacturers rarely mention these nonlinear attenuation characteristics and quote the value of attenuation that occurs at the most favorable wavelength.

Two forms of cable exist, known as single mode and multimode. Single-mode cables (sometimes known as monomode cables) have a small diameter core, typically 6 μm, whereas multimode cables have a much larger core, typically between 50 and 200 μm in diameter. Both glass and plastic in different combinations are used in various forms of cable. One option is to use different types of glass fiber for both the core and the cladding. A second, and cheaper, option is to have a glass fiber core and a plastic cladding. This has the additional advantage of being less brittle than the all-glass version. Finally, all-plastic cables also exist, where two types of plastic fiber with different refractive indices are used. This is the cheapest form of all but it has the disadvantage of having high attenuation characteristics, making it unsuitable for transmission of light over medium to large distances.

Protection is normally given to the cable by enclosing it in the same types of insulating and armoring materials that are used for copper cables. This protects the cable against

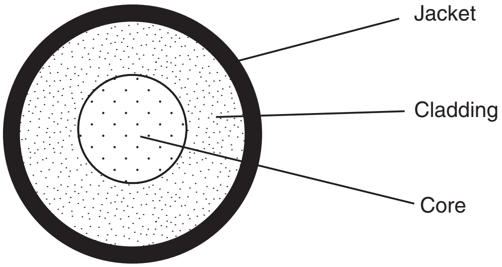

Figure 8.6
Cross section through the fiber optic cable.

various hostile operating environments and also against mechanical damage. When suitably protected, fiber optic cables can even withstand being engulfed in flames.

The *fiber optic transmitter* is responsible for converting the electric signal from a measurement sensor into light and transferring this into the fiber optic cable. It is theoretically possible to encode the measurement signal by modulating either the intensity, frequency, phase, or polarization of the light injected into the cable, but light intensity modulation has now achieved a dominant position in most fiber optic transmission systems. Either laser diodes or light emitting diodes (LEDs) can be used as the light source in the transmitter. Laser diodes generate coherent light of a higher power than the incoherent light produced by LEDs. However, laser diodes are more complex, more expensive, and less reliable than LEDs. Also the relationship between the input current and the light output is more linear for LEDs. Hence, the latter are preferred in most applications.

The characteristics of the light source chosen for the transmitter must closely match the attenuation characteristics of the light path through the cable and the spectral response of the receiving transducer. This is because the proportion of the power from the light source that is coupled into the fiber optic cable is more important than the absolute output power of the emitted light. This proportion is maximized by making purpose-designed transmitters that have a spherical lens incorporated into the chip during manufacture. This produces an approximately parallel beam of light into the cable with a typical diameter of 400 μm.

The proportion of light entering the fiber optic cable is also governed by the quality of the end face of the cable and the way it is bonded to the transmitter. A good end face can be produced by either polishing or cleaving. Polishing involves grinding the fiber end down with progressively finer polishing compounds until a surface of the required quality is obtained. Attachment to the transmitter is then normally achieved by gluing. This is a time-consuming process but uses cheap materials. Cleaving makes use of special kits that nick the fiber, breaks it very cleanly by applying mechanical force and then attach it to the transmitter by crimping. This is a much faster method but cleaving kits are quite expensive. Both methods produce good results.

A further factor that affects the proportion of light transmitted into the optic fibers in the cable is the transmitter alignment. It is very important to achieve proper alignment of the transmitter with the center of the cable. The effect of misalignment depends on the relative diameters of the beam and the core of the cable. Figure 8.7 shows the effect on the proportion of power transmitted into the cable for the cases of (1) cable core diameter > beam diameter, (2) cable core diameter = beam diameter, and (3) cable core diameter < beam diameter. This shows that some degree of misalignment can be tolerated except where the beam and cable core diameters are equal. The cost of

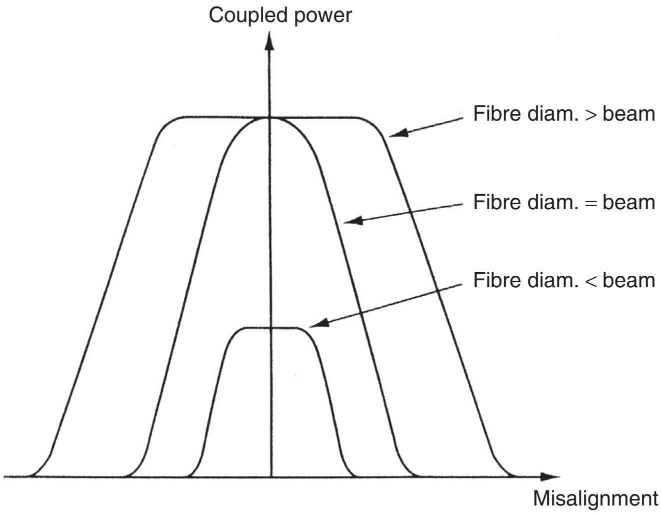

Figure 8.7
Effect of transmitter alignment on light power transmitted.

producing exact alignment of the transmitter and cable is very high, as it requires the light source to be exactly aligned in its housing, the fiber to be exactly aligned in its connector, and the housing to be exactly aligned with the connector. Therefore, great cost savings can be achieved wherever some misalignment can be tolerated in the specification for the cable.

The *fiber optic receiver* is the device that converts the optical signal back into the electrical form. It is usually either a PIN diode or a phototransistor. Phototransistors have good sensitivity but only have a low bandwidth. On the other hand, PIN diodes have a much higher bandwidth but a lower sensitivity. If both high bandwidth and high sensitivity are required, then special avalanche photodiodes are used, but at a severe cost penalty. The same considerations about losses at the interface between the cable and receiver apply as for the transmitter, and both polishing and cleaving are used to prepare the fiber ends.

The output voltages from the receiver are very small and amplification is always necessary. The system is very prone to noise corruption at this point. However, the development of receivers that incorporate an amplifier is finding great success in reducing the scale of this noise problem.

8.4.2 Transmission Characteristics

Single-mode cables have very simple transmission characteristics because the core has a very small diameter and light can only travel in a straight line down it. On the other hand, multimode cables have quite complicated transmission characteristics because of the relatively large diameter of the core.

While the transmitter is designed to maximize the amount of light that enters the cable in a direction that is parallel to its length, some light will inevitably enter multimode cables at other angles. Light that enters a multimode cable at any angle other than normal to the end face will be refracted in the core. It will then travel in a straight line until it meets the boundary between the core and cladding materials. At this boundary, some of the light will be reflected back into the core and some will be refracted in the cladding.

For materials of refractive indices n_1 and n_2 as shown in Figure 8.8, light entering from the external medium with refractive index n_0 at an angle α_0 will be refracted at an angle α_1 in the core and, when it meets the core−cladding boundary, part will be reflected at an angle β_1 back into the core and part will be refracted at an angle β_2 in the cladding. α_1 and α_0 are related by Snell's law according to:

$$n_0 \sin\alpha_0 = n_1 \sin\alpha_1 \tag{8.1}$$

Similarly, β_1 and β_2 are related by:

$$n_1 \sin\beta_1 = n_2 \sin\beta_2 \tag{8.2}$$

Light that enters the cladding is lost and contributes to the attenuation of the transmitted signal in the cable. However, observation of Eqn (8.1) shows how this loss can be prevented. If $\beta_2 = 90°$, then the refracted ray will travel along the boundary between the core and cladding and if $\beta_2 > 90°$, all of the beam will be reflected back into the core. The case where $\beta_2 = 90°$, corresponding to incident light at an angle α_c, is therefore the

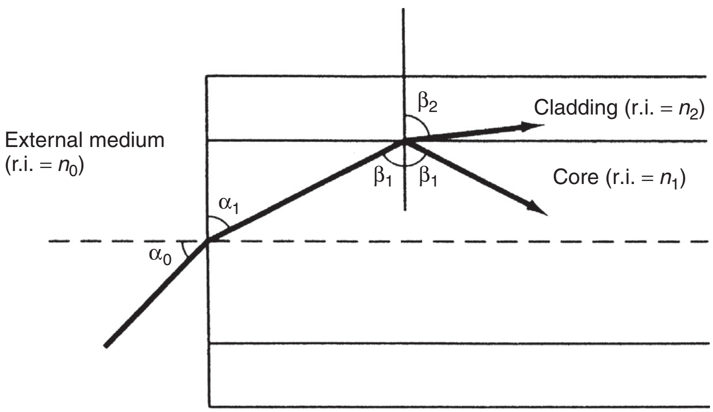

Figure 8.8
Transmission of light through cable.

critical angle for total internal reflection to occur at the core–cladding boundary. The condition for this is that $\sin\beta_2 = 1$.

Setting $\sin\beta_2 = 1$ in Eqn (8.1):

$$\frac{n_1 \sin\beta_1}{n_2} = 1.$$

Thus:

$$\sin\beta_1 = n_2/n_1$$

Inspection of Figure 8.8 shows that $\cos\alpha_1 = \sin\beta_1$.

Hence:

$$\sin\alpha_1 = \sqrt{1 - \cos^2\alpha_1} = \sqrt{1 - \sin^2\beta_1} = \sqrt{1 - (n_2/n_1)^2}$$

From Eqn (8.1):

$$\sin\alpha_c = \sin\alpha_0 = \frac{n_1}{n_0}\sin\alpha_1.$$

Thus:

$$\sin\alpha_c = \frac{n_1}{n_0}\sqrt{1 - \left(\frac{n_2}{n_1}\right)^2}$$

Therefore, provided that the angle of incidence of the light into the cable is greater than the critical angle given by $\theta = \sin^{-1}\alpha_c$, all of the light will be internally reflected at the core–cladding boundary. Further reflections will occur as the light passes down the fibers and it will thus travel in a zigzag fashion to the end of the cable.

While attenuation has been minimized, there is a remaining problem that the transmission time of the parts of the beam which travel in this zigzag manner will be greater than light which enters the fiber at 90° to the face and so travels in a straight line to the other end. In practice, the incident light rays to the cable will be spread over the range given by $\sin^{-1}\alpha_c < \theta < 90°$ and so the transmission times of these separate parts of the beam will be distributed over a corresponding range. These differential delay characteristics of the light beam are known as modal dispersion. The practical effect is that a step change in light intensity at the input end of the cable will be received over a finite period of time at the output. Multimode cables where this happens are known as *step-index* cables.

It is possible to largely overcome this latter problem in multimode cables by using cables made solely from glass fibers in which the refractive index changes gradually over the cross section of the core rather than abruptly at the core/cladding interface as in the step index cable discussed so far. This special type of cable is known as a *graded index* cable and it progressively bends light incident at less than 90° to its end face rather than reflecting it off the core/cladding boundary. Although the parts of the beam away from the center of the cable travel further, they also travel faster than the beam passing straight down the center of the cable because the refractive index is lower away from the center. Hence, all parts of the beam are subject to approximately the same propagation delay. In consequence, a step change in light intensity at the input produces an approximate step change of light intensity at the output. The alternative solution is to use a single-mode cable. This usually propagates light in a single mode only, which means that time dispersion of the signal is almost eliminated.

8.4.3 Multiplexing Schemes

Various types of multiplexing schemes are available. It is outside the scope of text to discuss these in detail, and interested readers are recommended to consult a specialist text in fiber optic transmission. It is sufficient to note here that wavelength division multiplexing is used predominantly in fiber optic transmission systems. This uses a multiplexer in the transmitter to merge the different input signals together, and a demultiplexer in the receiver to separate out the separate signals again. A different modulated frequency is used to transmit each signal. Since a single optic fiber is capable of propagating in excess of 100 different wavelengths without cross interference, multiplexing allows more than 100 separate distributed sensors to be addressed. Wavelength division multiplexing systems normally use a single-mode cable of 9 μm diameter, although there are also examples of usage of 50 or 62.5 μm diameter multimode cable.

8.5 Optical Wireless Telemetry (Open Air Path Transmission)

Wireless telemetry allows signal transmission to take place without laying down a physical link in the form of electrical or fiber optic cable. This can be achieved using either radio or light waves to carry the transmitted signal across a plain air path between a transmitter and a receiver.

Optical wireless transmission was first developed in the early 1980s. It consists of a light source (usually infrared) transmitting encoded data information across an open, unprotected air path to a light detector. Three distinct modes of optical telemetry are possible, known as point-to-point, directed, and diffuse:

- *Point-to-point telemetry* uses a narrowly focussed, fine beam of light, which is commonly used for transmission between adjacent buildings. A data transmission speed of 5 Mbit/s is possible at the maximum transmission distance of 1000 m. However, if the transmission distance is limited to 200 m, a transmission speed of 20 Mbit/s is possible. Point-to-point telemetry is commonly used to connect electrical or fiber optic ethernet networks in adjacent buildings.

- *Directed telemetry* transmits a slightly divergent beam of light that is directed toward reflective surfaces, such as the walls and ceilings in a room. This produces a wide area of coverage and means that the transmitted signal can be received at a number of points. However, the maximum transmission rate possible is only 1 Mbit/s at the maximum transmission distance of 70 m. If the transmission distance is limited to 20 m, a transmission speed of 10 Mbit/s is possible.
- *Diffuse telemetry* is similar to directed telemetry but the beam is even more divergent. This increases the area of coverage but reduced transmission speed and range. At a maximum range of 20 m, the maximum speed of transmission is 500 kbit/s, though this increases to 2 Mbit/s at a reduced range of 10 m.

In practice, implementations of optical wireless telemetry are relatively uncommon because the transmission of data across an open, unprotected air path is susceptible to random interruption. In cases where immunity to electromagnetic noise is particularly important, open path optical transmission is sometimes used because it provides immunity of the transmitted signal to electromagnetic noise at low cost. However, other ways of providing immunity to the transmitted signal against electromagnetic noise are often preferred despite their higher cost.

The usual alternative to open air path optical transmission for solving electromagnetic noise problems is to use fiber optic transmission. In cases where laying a physical fiber optic cable link is difficult, radio transmission is commonly used. This is preferred over optical transmission because it is much less prone to interference than optical transmission over an open air path, since radio waves can pass through most materials. However, there are some situations where radio transmission is subject to interference from neighboring radio frequency systems operating at a similar wavelength and, in such circumstances, open air path optical transmission is sometimes a better option.

8.6 Radio Telemetry (Radio Wireless Transmission)

Radio telemetry is normally used over transmission distances up to 400 miles, though this can be extended by special techniques to provide communication through space over millions of miles. However, radio telemetry is also commonly used over quite short distances to transmit signals where physical, electrical, or fiber optic links are difficult to install or maintain. This occurs particularly when the source of the signals is mobile. The great advantage that radio telemetry has over optical wireless transmission through an air medium is that radio waves are attenuated much less by most types of obstacle between the energy transmitter and receiver. Hence, as noted above, radio telemetry usually performs better than optical wireless telemetry and is therefore used much more commonly.

In radio telemetry, data are usually transmitted in an FM format. A typical scheme is shown in Figure 8.9, although other arrangements also exist. In this particular scheme shown, 18 data channels are provided over the frequency range from 0.4 to 70 kHz, as given in the table below. Each channel is known as a subcarrier frequency and can be used to transmit data for a different physical variable. Thus, the system can transmit information from 18 different sensors simultaneously.

Band	1	2	3	4	5	6	7	8	9
Center frequency (kHz)	0.4	0.56	0.73	0.96	1.3	1.7	2.3	3.0	3.9
Band	10	11	12	13	14	15	16	17	18
Center frequency (kHz)	5.4	7.35	10.5	14.5	22.0	30.0	40.0	52.5	70.0

Maximum frequency deviation allowed is ±7.5%

A voltage-to-frequency converter is used in the first FM stage to convert each analog voltage signal into a varying frequency around the center frequency of the subcarrier assigned for that channel. The 18 channels are then mixed into a single signal spanning the frequency range 0.4–70 kHz. For transmission, the length of the antenna has to be one quarter or one half of the wavelength. At 10 kHz, which is a typical subcarrier frequency

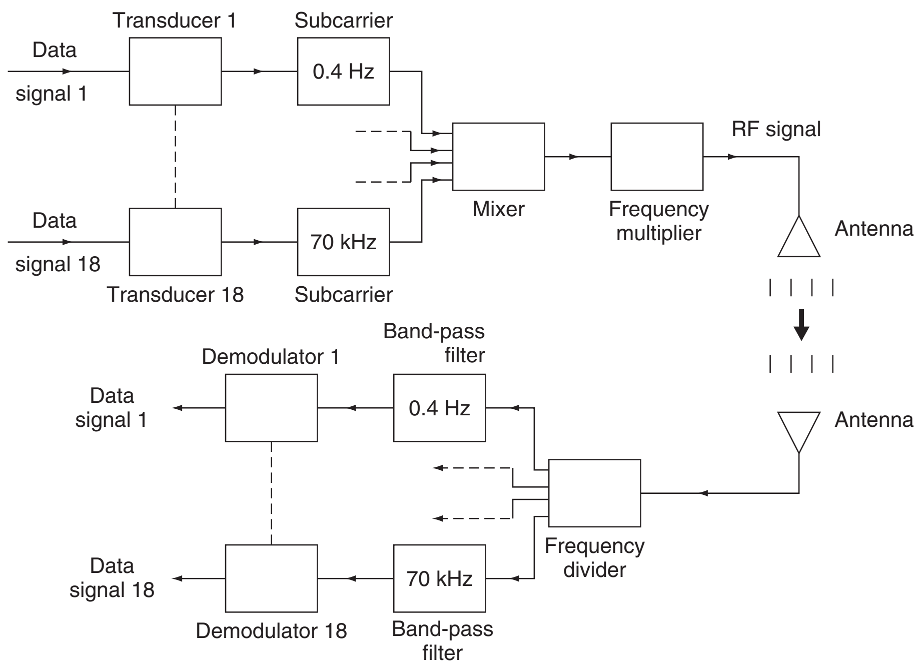

Figure 8.9

Radio transmission using a two-stage frequency modulation system.

in an 18 channel system, the wavelength is 30 km. Hence, an antenna for transmission at this frequency is totally impractical. In consequence, a second FM stage is used to translate the 0.4- to 70-kHz signal into the radio frequency range as modulations on a typical carrier frequency of 217.5 MHz.[2] At this frequency, the wavelength is 1.38 m, and so a transmission antenna of length 0.69 or 0.345 m would be suitable. The signal is received by an antenna of identical length some distance away. A frequency converter is then used to change the signal back into the 0.4- to 70-kHz subcarrier frequency spectrum, following which a series of band pass filters are applied to extract the 18 separate frequency bands containing the measurement data. Finally, a demodulator is applied to each channel to return each signal into varying voltage form.

The inaccuracy of radio telemetry is typically $\pm 1\%$. Thus, measurement uncertainty in transmitting a temperature measurement signal with a range of 0−100 °C over one channel would be $\pm 1\%$, i.e., ± 1 °C. However, if there are unused transmission channels available, the signal could be divided into two ranges (0−50 °C and 50−100 °C) and transmitted over two channels, reducing the measurement uncertainty to ± 0.5 °C. By using 10 channels for one variable, a maximum measurement uncertainty of ± 0.1 °C could be achieved.

In theory, radio telemetry is very reliable because, although the radio frequency waveband is relatively crowded, specific frequencies within it are allocated to specific usages under national agreements that are normally backed by legislation. Interference is avoided by licensing each frequency to only one user in a particular area, and limiting the transmission range through limits on the power level of transmitted signals, such that there is no interference to other licensed users of the same frequency in other areas. Unfortunately, interference can still occur in practice, due to adverse atmospheric conditions extending the transmission range beyond that expected into adjoining areas, and also due to unauthorized transmissions by other parties at the wavelengths licensed to registered users. There is a legal solution to this latter problem, although some time may elapse before the offending transmission is successfully stopped.

8.7 Digital Transmission Protocols

Digital transmission has very significant advantages compared with analog transmission because the possibility of signal corruption during transmission is greatly reduced. Many different protocols exist for digital signal transmission. However, the protocol that is normally used for the transmission of data from a measurement sensor or circuit is asynchronous serial transmission, with other forms of transmission being reserved for use

[2] Particular frequencies are allocated for industrial telemetry. These are subject to national agreements and vary in different countries.

in instrumentation and computer networks. Asynchronous transmission involves converting an analog voltage signal into a binary equivalent, using an analog-to-digital converter. This is then transmitted as a sequence of voltage pulses of equal width that represent binary "1" and "0" digits. Commonly, a voltage level of either +5 V or +6 V is used to represent binary "1" and 0 V represents binary "0." Thus, the transmitted signal takes the form of a sequence of 6 V pulses separated by 0 V pulses. This is often known by the name of *pulse code modulation*. Such transmission in digital format provides very high immunity to noise because noise is typically much smaller than the amplitude of a pulse representing binary 1. At the receiving end of a transmitted signal, any pulse level between 0 and 3 V can be interpreted as a binary "0" and anything greater than 3 V can be interpreted as a binary "1." A further advantage of digital transmission is that other information, such as the status of industrial equipment, can be conveyed as well as parameter values. However, consideration must be given to the potential problems of aliasing and quantization, as discussed in Chapter 6, and the sampling frequency must therefore be chosen carefully.

Many different mediums can be used to transmit digital signals. Electrical cable, in the form of a twisted pair or coaxial cable, is commonly used as the transmission path. However, in some industrial environments, the noise levels are so high that even digital data become corrupted when transmitted as electrical pulses. In such cases, alternative transmission mechanisms have to be used.

One alternative is to modulate the pulses onto a high-frequency carrier, with positive and zero pulses being represented as two distinct frequencies either side of a center carrier frequency. Once in such a frequency-modulated format, a normal mains electricity supply cable operating at mains frequency is often used to carry the data signal. The large frequency difference between the signal carrier and the mains frequency prevents any corruption of the data transmitted, and simple filtering and demodulation is able to extract the measurement signal after transmission. The public switched telephone network can also be used to transmit frequency-modulated data at speeds up to 1200 bit/s, using acoustic couplers as shown in Figure 8.10. The transmitting coupler converts each binary "1" into a tone at 1.4 kHz and each binary "0" into a tone at 2.1 kHz, while the receiving coupler converts the tones back into binary digits.

Another solution is to apply the signal to a digital-to-current converter unit and then use current loop transmission, with 4 mA representing binary "0" and 20 mA

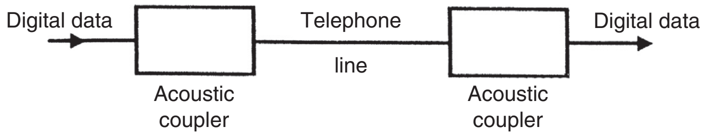

Figure 8.10
Telephone transmission.

representing binary “1.” This permits baud rates up to 9600 bit/s at transmission distances up to 3 km. Fiber optic links and radio telemetry are also widely used to transmit digital data.

8.8 Summary

This chapter on techniques for transmitting measurement signals over what can, in some circumstances, be quite large distances, completes the discussion on the different components that exist in a measurement system. However, as for some other measurement system components such as variable conversion elements, a mechanism for signal transmission is not needed in all measurement systems.

We started our discussion off by observing that signals can be transmitted from the sensor at the point of measurement to the rest of the measurement system in a number of alternative ways. As well as the alternatives of electric, pneumatic, optical, and radio transmission, both analog and digital forms exist as alternative transmission formats to carry the transmitted measurement signal.

We started off by noting that electrical transmission is the simplest way to convey measurement signals over some distance, but we noted that this has associated problems of attenuation of the measured signal and also a tendency for the measured signal to be corrupted by noise. We therefore went on to look at solutions to these problems. The first solution covered was to amplify the measurement signal to compensate for attenuation during transmission and to shield the transmission wires to minimize noise corruption. We went on to look at the alternative electrical transmission method known as current loop transmission, whereby the measurement signal is transmitted as a varying current rather than a varying voltage in order to better protect the measurement signal from induced noise. Finally, we looked at a solution that involved transmitting the measurement signal on a carrier wave using either AM or FM.

Our next subject was pneumatic transmission. We noted that this had the disadvantage of only transmitting measurement signals at relatively slow speeds and, in consequence, was now much less used than it has been in the past. However, we observed that pneumatic transmission is still used in three specific circumstances. First, since it is an intrinsically safe method of transmission, it is still used in some applications where intrinsic safety is required. Second, it provides an alternative to current loop transmission when a high level of noise immunity is required. Finally, it is convenient to use pneumatic transmission in pneumatic control systems where the sensors or actuators or both are pneumatic.

Our discussion then moved on to fiber optic transmission, where we noted that fiber optics provided both intrinsically safe operation and gave the transmitted signal immunity to noise corruption by neighboring electromagnetic fields. Attenuation of the transmitted signal along a fiber optic cable is also much less than for varying voltage transmission along an equivalent length of electric cable.

As well as optical transmission of measurement data along a fiber optic cable, we noted that it was also possible to transmit data optically across an air space rather than along a cable. We observed that this type of transmission existed in three forms, known as point-to-point telemetry, directed telemetry, and diffuse telemetry. Unfortunately, all of these alternatives suffer from the common problem of unreliability in data transmission because the transmission path is susceptible to random interruption when data are transmitted across an open, unprotected air path. In consequence, use of a fiber optic cable is usually preferred for transmission of the data, even though this is much more expensive than transmitting the data across an open air path.

We then went on to look at radio transmission. We noted that this is normally used over transmission distances up to 400 miles, but special techniques can allow communication through space over millions of miles. In addition, radio telemetry is also commonly used over quite short distances to transmit signals where physical electrical or fiber optic links are difficult to install or maintain, particularly when the measurement signal source is mobile. Although obstacles between the energy transmitter and the receiver can cause some attenuation of the transmitted measurement data, this problem is far less than that which occurs when attempts are made to transmit data optically over an open air path. While radio telemetry is generally reliable, two problems can occur, which are both related to the transmission frequency. Normally, licensing arrangements give each radio transmission system a unique transmission frequency within a given geographical area. Unfortunately, adverse atmospheric conditions can extend the range of transmission systems into adjoining areas and cause contamination of transmitted signals. A similar problem can occur when there are to unauthorized transmissions by other parties at the wavelengths licensed to registered users.

To conclude the chapter, we looked finally at digital transmission protocols. We noted that digital transmission has very significant advantages compared with analog transmission because the possibility of signal corruption during transmission is greatly reduced. While many different protocols exist for digital signal transmission, we noted that the one normally used for the transmission of data from a measurement sensor or circuit is asynchronous serial transmission. Having looked at how this works, we finished off by looking at the main two alternative means of transmitting the digital data, along a "twisted pair" or coaxial electrical cable, and as modulated pulses on a high-frequency carrier.

8.9 Problems

8.1 Discuss some reasons why it is necessary in many measurement situations to transmit signals from the point of measurement to some other point.

8.2 Discuss the main features of electrical, pneumatic, fire optic, and radio signal transmission. Give examples of the sort of situations where you would use each of these transmission methods.

8.3 Discuss the different forms of electrical signal transmission. What are the merits and demerits of each alternative form?

8.4 What is a current loop interface? Discuss some measurement situations where this would be the preferred form of signal transmission.

8.5 Pneumatic transmission is now rarely used in transmission systems. Why has this form of transmission fallen out of favor? What sort of conditions might cause a system designer to still specify pneumatic system in a new measurement system.

8.6 Discuss the main features of fiber optic transmission.

8.7 What are the principle advantages of fiber optic transmission. Given its significant advantages, why is fiber optic transmission not used more widely?

8.8 Discuss the three different ways in which fiber optic cables are used for signal transmission.

8.9 A fiber optic transmitter converts an electrical measurement signal into light and then injects this into the fiber optic cable. Discuss the important design features that maximize the proportion of the light produced in the transmitter that passes into the cable.

8.10 Discuss the main features of single-mode and multimode fiber optic transmission.