26 Radio Frequency and Microwave Communication Systems

Information and communication have always mattered in agriculture (McNamara, et al. 2012). Humanity still faces a challenging future and filling the stomachs of the growing population is only one reason agriculture is critical to global stability and development (McNamara, et al. 2012). It is also critical because one of the most effective ways of reducing poverty is to invest in and make improvements in the agricultural sector (McNamara, et al. 2012). Given the challenges, the arrival of information communication technology (ICT) is well timed (McNamara, et al. 2012).

Smart agricultural systems make use of every available technology to improve production and increase efficiency. This includes adopting better communication systems across the industry. Historically, communication systems have been readily adopted by agricultural and rural communities. Australia’s Royal Flying Doctor Service (RFDS), which was conceived in 1912 by the Rev. John Flynn, became practical when an Adelaide (Australia) based electrical engineer, A.H. Traeger, developed a low-powered, portable, pedal-driven, Morse radio transmitter-receiver with a range of about 500 km (Anonymous 2014). This communication system made regular medical consultations and transport of doctors and patients in remote areas of Australia possible.

The same underlying wireless technology had other applications as well. In 1946, Ms. Adelaide Miethke instigated the idea for the School of the Air when she noticed how children from remote areas in Australia were all taught to use the Royal Flying Doctor radio service. She saw that there were other ways this network could be used and in 1948, the Alice Springs RFDS base was used to broadcast the first school lessons to children in remote places of central Australia. Just a few years later, the School of the Air (SOA) was officially established. Wireless technology was transforming agricultural communities.

More recently, Hornbaker et al (2004) reported on a system that increases the operational efficiency of multi-vehicle agricultural operations, such as harvest and planting. The system incorporates hardware, software and wireless connectivity to communicate with vehicle operators about the status and position of other vehicles and their grain bin fill levels and grain attributes. The system provides assistance to the operator to optimize the movement of harvesters, grain wagons and road transport so that logistical bottlenecks and time the harvesters are waiting to be unloaded in the field are minimized.

Communication technology and in particular, wireless technology are almost ubiquitous. Although examples like broadcast radio, television and telephones have been in common use for decades, modern communication systems are becoming more pervasive and much less to do with voice communication and much more to do with data communication and control. Radiofrequency and microwave fields
have been used for communication systems for a very long time. These waves can be channelled through cables, waveguides and open space to carry messages to and from transceivers near and far. This chapter will outline the key principles for using radiofrequency and microwaves to communicate.

26.1 Principles of RF and Microwave Communication

Radiofrequency and microwave communication systems use wavelengths that vary from a few centimetres to 1500 metres long. Each system transmits its signal on its own wavelength and tuning circuits are used to filter out all but one broadcast station from the incoming signals.

There are four main frequency bands that are used for radio broadcasting - short wave, medium wave, long wave and VHF (very high frequency). Television broadcasts use a higher range of frequencies than radio, which typically have wavelengths of about 500 mm. This is the UHF (ultra-high frequency) band. Data networking systems operate at microwave frequencies such as 2.4 GHz. One of the earliest applications of radiofrequency communication was wireless (or radio) transmission.

26.2 Principles of Wireless Communication

Wireless communication, as the name suggests, involves communicating a message without the use of connecting wires. To achieve this requires: the generation of radio waves (RF) using a carrier signal generator (oscillator); one or more frequency multiplication stages to shift the transmission frequency to a suitable range for broadcast; a modulator that encodes a message onto the carrier signal; a power amplifier to boost the final signal ready for transmission; a filter with matching network to remove unwanted sidebands and noise from the transmitted signal; a short transmission line (or wave guide) to connect to an antenna; and finally the antenna itself that transfers the electromagnetic waves into open space as efficiently as possible (Taub and Schilling 1971, Smith 1976).

A typical radio receiver has: an antenna system that receives the RF energy from open space; a short section of transmission line (or waveguide) to guide the incoming signal to the receiver circuitry; a filter that tunes to the desired carrier wave frequency; an RF amplifier that amplifies the energy of the incoming signal so that it is raised above the noise generated by the radio itself (Note: too much RF amplification can result in “spurs” or spurious mixer products, sometimes called cross-modulation or inter-modulation); one or more mixing stages in which the incoming RF signal is mixed with a second, internally generated RF frequency to produce a lower intermediate frequency (IF); one or more IF amplifiers that boost the signal; a detector, which extracts the modulated information from the IF signal, is used to extract the
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audio frequencies (AF) from the original carrier; and finally, an audio amplifier that increases the energy of the extracted data (Taub and Schilling 1971, Smith 1976). The type of detector circuitry depends on the type of modulation used to encode the data onto the carrier wave.

26.3 Modulation

There are three main features about electro-magnetic radiation, which can be altered to carry information (Smith 1976):
1. The intensity (or Amplitude) of the radiation
2. The colour (or Frequency) of the radiation.
3. The Presence and absence of the radiation (Pulses).

If the amplitude, or strength, of the signal is changed in a way corresponding to the information being sent amplitude modulation (or AM) is created. AM transmitters vary the signal level smoothly in direct proportion to the data being transmitting. Positive peaks of the signal produce maximum radio energy, and negative peaks of the signal produce minimum energy.

The main disadvantage of AM is that most natural and man-made noise is actually modulated onto the carrier like AM, and AM receivers have no means of rejecting that noise. Also, weak signals are quieter than strong ones, which require the receiver to have circuits to compensate for the signal level differences (Radio Design Group 2001). Amplitude modulation can be described by (Taub and Schilling 1971):

\[ E(t) = A\left[1 + m(t)\right]\cos(\omega t) \]  

(26.1)

Where E is the electric field, A is the applied carrier, m(t) is some time varying message signal, w is the angular velocity of the carrier wave, and t is time. The maximum amplitude of m(t) should be less than 1.0, otherwise the electric field will be over modulated causing cross over distortion.

In an attempt to overcome noise problems, Edwin Armstrong invented a system that would overcome the difficulties of amplitude noise (Taub and Schilling 1971). Instead of modulating the strength (or amplitude) of the transmitted carrier, he modulated its frequency. Though many engineers at that time said that frequency modulation (or FM) was not practical, Armstrong proved them wrong. Today FM is the mainstay of the broadcast radio services (Radio Design Group 2001). It is also popular for short haul data transmission and is commonly used in radio microphones.

In a frequency modulated system, the frequency of the carrier is varied according to the modulating signal. For example, positive peaks would produce a higher
frequency, while negative peaks would produce a lower frequency. At the receiving end, a limiting circuit removes all amplitude variations from the signal, thus eliminating much of the noise, and a discriminator circuit converts the frequency variations back to the original audio or data signal. Since the recovered data is dependent only on the frequency, and not the strength, no compensation for different signal levels is required, as is the case with AM receivers.

Frequency modulation can be described by (Taub and Schilling 1971):

\[ E(t) = A \cdot \cos \left[ \omega t + k \cdot m(t) \right] \]  

(26.2)

Where \( E \) is the electric field, \( A \) is the applied carrier, \( k \) is modulation factor (a constant), \( m(t) \) is some time varying message signal, \( \omega \) is the angular velocity of the carrier wave, and \( t \) is time. The deviation of the instantaneous frequency from the unmodulated carrier frequency is:

\[ \Delta f = \frac{k}{2\pi} m(t) \]  

(26.3)

Many FM broadcast stations now transmit sub-carriers on their signals. Sub-carriers are signals that are modulated on the carrier, just like the normal data signals, except that they are too high in frequency to be heard. Normal audio signals range in frequency from 20 to 20,000 Hz. Most sub-carriers start at about 56,000 Hertz (56 kHz). These sub-carriers are themselves modulated, sometimes with audio signals, such as background music, but more often with other forms of data (Radio Design Group 2001). Some of the information that is carried on these sub-carrier data services include: stock quotes, weather reports, news, sports, paging signals and differential GPS error corrections.

Various forms of pulse modulation (turning the carrier wave on and off) have been developed. Pulse amplitude modulation used the amplitude of regularly generated pulses to carry the message (Taub and Schilling 1971). This is somewhat analogous to amplitude modulation. Pulse width modulation uses pulses that begin at regular time intervals; however the duration of the pulses depends on the amplitude of the message signal. In both these cases, the message signal is analogue, implying that it has a variable value at any instant in time.
26.4 Simplex, Half-duplex and Duplex Communication Systems

Simplex communication is permanent unidirectional communication (Taub and Schilling 1971, Smith 1976). Broadcast radio and television would be classified as simplex systems. Some of the very first serial connections between computers were also simplex connections. Simplex links are built so that the transmitter sends a signal and the receiving device transforms the received signal into information. No traffic is possible in the other direction across the same connection. Many environmental data gathering systems, such as automatic weather stations and water gauging systems use simplex data transfer from the field site to some central data hub. In these cases, two way communications is seldom necessary so the system is designed to be as simple as possible.

A half-duplex link can communicate in only one direction at a time, but it supports two way communications (Taub and Schilling 1971). Walkie-talkies and citizen's band (CB) radios are common half-duplex communication devices in that the same frequency is used for both transmission and reception; therefore only communication can only take place while the radio channel is not in use by someone or something.
else. Half-duplex radio has been used for communication in rural and remote areas for a very long time.

Full-duplex communication is two-way communication, achieved over a physical link that has the ability to communicate in both directions simultaneously (Taub and Schilling 1971). With most electrical, optic fibre, two-way radio and satellite links, this can be achieved by using separate carrier wave frequencies for transmission and reception, to avoid interference during two way communication. In some agricultural systems this allows data to be transferred from the field to a central point and control signals to be sent from the central point to the field. For example, full-duplex systems could be used to manage an automatic irrigation system.

### 26.5 Digital Communication

As was pointed out in the previous chapter, data is commonly converted to digital form for processing in computers. Communication systems have also become digital. Frequency-shift keying (FSK) is one way of facilitating digital communication (Taub and Schilling 1971). FSK is a special form of frequency modulation in which digital information is transmitted through discrete frequency changes of a carrier wave. Binary frequency shift keying (BFSK) uses a pair of discrete frequencies to transmit binary information. The resulting carrier wave has the form (Taub and Schilling 1971):

\[
E(t) = A \cdot \cos [(\omega \pm \Omega)t] 
\]  

(26.4)

Where \( \Omega \) is a constant.

BFSK transfers data as a serial data packet, usually with: a leading address (to direct the data to its final destination over a network); the main data (encoded as binary numbers); and following bits that provide error checking services.

Unlike pulse modulation which allows for the absence of the carrier, BFSK provides a continuous carrier signal, irrespective of whether a 1 or a 0 is being transmitted. This provides a rudimentary link error check, somewhat like the 4 mA current used for data acquisition that was spoken about in the previous chapter.

### 26.6 Transmission Channels

Two options exist for transmitting data or information through a communication system: it can be via a physical channel such as a transmission line or wave guide; or it can be through free space. Both are commonly used in agricultural communication systems.
26.6.1 Transmission Lines

Common examples of transmission lines used for data communication are the twisted pair wires and coaxial cables.

An unshielded twisted-pair (UTP) cable consists of two braided copper wires with insulation around each individual wire. Twisted-pair cabling must follow exact specifications about how many twists or braids are permitted per meter of cable. Groups of unshielded twisted-pair wires are often placed within a protective jacket to form a cable. The wiring used for many short haul telephone systems and computer networks use unshielded twisted-pairs. Unshielded twisted-pair technology for data communications is growing rapidly and most data networks can now utilise unshielded twisted-pair wiring.

Shielded twisted-pair cable differs from UTP in that it has a much higher quality protective jacket with a greater insulation factor. Thus shielded twisted-pair has a longer signal transmission range. It is also less prone to electrical interference from outside sources. However, the majority of twisted-pair cabling is unshielded twisted-pair. Twisted-pair cabling is usually low in cost and easy to connect.

Unfortunately twisted-pair cabling is prone to electrical noise and interference. It generally has a low data transmission rate and can not transmit data very far without occasionally boosting the signal strength.

Coaxial cables, as shown in Figure 26.2, are a special case of the twisted pair where the return conductor is wrapped around the main conductor to provide additional mechanical protection and electrical shielding to the cable. Coaxial cable is capable of carrying network data at very high rates.

Coaxial cable has one central wire, which is surrounded by an insulating material. A stranded shield is wound over this insulating material to acts as the secondary conductor for the return path. All of this is protected by an outside protective jacket. Coaxial cable comes in different varieties and thicknesses. It also comes in different impedances. Impedance determines the amount of resistance offered to electrical impulses transmitted through the cable and is usually measured in ohms.

![Diagram illustrating the arrangement of Coaxial Cable.](image)
A uniform transmission line must be visualised as a “distributed circuit”, as shown in Figure 26.3. A distributed circuit can be described as a cascade of identical cells of infinitesimal length $dz$. The conductors used in a transmission line possess a certain series inductance and resistance. In addition, there is a shunt capacitance between the conductors and even a shunt conductance if the medium insulating the wires is not a perfect insulator.

![Distributed impedance in a transmission line](image)

**Figure 26.3:** Distributed impedance in a transmission line (Source: Amanogawa 2001).

### 26.6.2 Loss-Less Transmission Line

In many cases, it is possible to neglect the resistive effects in the transmission line.

![Inductive element](image)

**Figure 26.4:** Inductive element (Source: Amanogawa 2001).

From this analysis it is clear that:

$$V(z) + dV - V(z) = -j\omega L \cdot dz \cdot I(z)$$

\[ (26.5) \]
Therefore:

\[
\frac{dV}{dz} = -j\omega L \cdot I
\]  
(26.6)

**Figure 26.5:** Shunt capacitance (Source: Amanogawa 2001).

Now considering the shunt element:

\[
dI = -j\omega C \cdot dz \cdot (V(z) + dV) = -j\omega C \cdot dz \cdot V(z) - j\omega C \cdot dz \cdot dV
\]  
(26.7)

Now \( \lim_{dz \to 0} dz \cdot dV = 0 \); therefore

\[
\frac{dI(z)}{dz} = -j\omega C \cdot V(z)
\]  
(26.8)

Taking the derivative of equations (26.6) and (26.8) with respect to \( z \) yields:

\[
\frac{d^2V(z)}{dz^2} = -j\omega L \frac{dI(z)}{dz} = -\omega^2 LC V(z)
\]  
(26.9)

\[
\frac{d^2I(z)}{dz^2} = -j\omega C \frac{dV(z)}{dz} = -\omega^2 CLI(z)
\]  
(26.10)

These are wave equations, the solution of which is:

\[
V(z) = V_1 e^{-j\omega \sqrt{LC} z} + V_2 e^{j\omega \sqrt{LC} z}
\]  
(26.11)
In this case the general solution represents a wave propagating in both the +z and −z direction with a wave number of \( k = \omega \sqrt{\frac{1}{LC}} \) and a velocity \( c = \frac{1}{\sqrt{LC}} \).

Differentiating voltage with respect to \( z \) yields:

\[
\frac{dV}{dz} = -j\omega \sqrt{\frac{1}{LC}} \left( V_1 e^{-j\omega \sqrt{\frac{1}{LC}} z} + V_2 e^{j\omega \sqrt{\frac{1}{LC}} z} \right) = -j\omega L I
\]  

(26.12)

Thus:

\[
I = \sqrt{\frac{C}{L}} \left( V_1 e^{-j\omega \sqrt{\frac{1}{LC}} z} + V_2 e^{j\omega \sqrt{\frac{1}{LC}} z} \right) = \sqrt{\frac{C}{L}} V
\]  

(26.13)

Applying Ohm’s law, the intrinsic impedance of the transmission line is defined as:

\[
Z_0 = \sqrt{\frac{L}{C}}
\]  

(26.14)

### 26.6.3 Lossy Transmission Line

The series impedance determines the variation of the voltage from input to output of the cell, according to the sub-circuit shown in Figure 26.6.

![Figure 26.6: Serial elements (Source: Amanogawa 2001).](image)

The current flowing through the shunt admittance determines the input-output variation of the current, according to the sub-circuit shown in Figure 26.7.
In this case:

\[ Z_0 = \sqrt{\frac{j\omega L + R}{j\omega C + G}} \]  \hspace{1cm} (26.15)

and

\[ V = V_1 e^{-\frac{1}{2}R\left(\frac{L}{L + G}\right)\sqrt{\frac{L}{C}} z} e^{-j\omega \sqrt{\frac{L}{C}} z} + V_2 e^{\frac{1}{2}R\left(\frac{L}{L + G}\right)\sqrt{\frac{L}{C}} z} e^{j\omega \sqrt{\frac{L}{C}} z} \]  \hspace{1cm} (26.16)

Therefore the voltage will be attenuated with distance along the line. At high frequencies the unit resistance associated with the contraction of the current carrying cross-section becomes significant and the voltage wave traveling along the transmission line will be significantly attenuated. Therefore a transmission line has an effective upper limit to its frequency range. At microwave frequencies, a transmission line may only be used for a very short distance. A different system of transmission is needed to propagate radiofrequency and microwaves further than a few metres.

### 26.6.4 Optic Fibre

Although it is not so commonly used in agriculture, optic fibre, shown in Figure 26.8, is a special case of a wave guide for wavelengths near to and in the visible range of the electromagnetic spectrum. As depicted in Figure 26.10, when light passes from a material with a high refractive index, such as glass or plastic, into a material with a low refractive index, such as air, the light ray is bent back toward the interface surface. Thus there must be a stage at which the light ray travels along the surface of the glass. This is called the critical angle. If the angle at which the light ray strikes the surface is greater than the critical angle all the light will be reflected back into the glass. This is called total internal reflection.
In an optic fibre, light is shone into the end of the fibre; thus all the light strikes the internal surfaces of the fibre at an angle that is greater than the critical angle. Therefore the light stays inside the fibre rather than escaping out into the air. Therefore the optic fibre can be used to guide the light, just like the metallic wave-guides used for microwaves. Optical fibres come in two types: Single-mode fibres; or Multi-mode fibres.

Single-mode fibres have a small core (about 9 microns in diameter) and transmit infrared laser light (wavelength = 1,300 to 1,550 nanometers). Multi-mode fibers have a larger core (about 62.5 microns in diameter) and transmit infrared light (wavelength = 850 to 1,300 nm) from light-emitting diodes (LEDs). Some fibres have a very large core (about 1 mm diameter) and transmit visible red light (wavelength = 650 nm) from LEDs.

Optic fibre relay systems consist of a transmitter, for producing and encoding the light signals, the optical fibre itself, an optical regenerator, to boost the light signal and an optical receiver that receives and decodes the light signals.
The transmitter is close to the optical fibre and uses a lens to focus the light into the fiber. Lasers or LEDs are commonly used as transmitters. Lasers have more power than LEDs, but vary more with changes in temperature and are more expensive. The most common wavelengths of light signals are 850 nm, 1,300 nm, and 1,550 nm (infrared, non-visible portions of the spectrum).

An optical regenerator consists of optical fibers with a special coating that has been doped with a small amount of specially chosen impurity. The doped portion is pumped with a laser. When a degraded light signal comes into the doped coating, the energy from the laser allows the doped molecules to emit a new, stronger light signal with the same characteristics as the incoming weak light signal. Basically, the regenerator is a laser amplifier for the incoming signal. The receiver uses a photocell or photodiode to detect the light and convert this into an electrical signal.

Optic fibres can be composed of either glass or plastic. The plastic optic fibre cable is easier to install but it has a much shorter transmission distance than glass optic fibre cable. Optic fibre cable is capable of very high-speed data transfer. Since it does not carry electrical impulses; therefore it is less affected by electrical noise or interference. Optic fibre lines can not be tapped into very easily, making it an excellent choice for security reasons.

Optic fibre cable requires considerable skill and specialized equipment to install. Generally the price of fibre-optic cable can be quite high. The same can also be said for metallic wave guides. In many cases data must be transmitted over substantial distances. In these cases a radio link can be used.

### 26.7 Wireless Radio Channels

Wireless channels that use antennae and electromagnetic waves to transfer messages through free space are commonly used. An antenna projects the electromagnetic waves in a particular directs, depending on its radiation pattern. As outlined in Chapter 8, an important measure of an antenna’s performance is its gain. When considering a wireless radio link as part of a communication system, the gain of the transmitting and receiving antennae play a vital role in determining the distance over which the system can operate. This distance is determined by the Friis Transmission Equation:

\[ P_r = \frac{P_t G_t G_r \lambda^2 \tau}{4\pi R^2} e^{-2\alpha R} \]  

(26.17)

Where \( P_r \) is the received power (W), \( P_t \) is the transmitted power (W), \( G_t \) is the gain of the transmitting antenna, \( G_r \) is the gain of the receiving antenna, \( \lambda \) is the wavelenght of the carrier wave (m), \( \tau \) is the matching coefficient from the receiving antenna to the rest of the receiving circuity, \( \alpha \) is the attenuation coefficient of the medium though
which the electromagnetic wave passes, and R is the range between the transmitter
and the receiver (m).

The attenuation coefficient ($\alpha$) is defined in equation (4.11) in Chapter 4. The
matching coefficient for the antenna is (Bhattacharyya, et al. 2011):

$$\frac{R_a R_c}{|Z_a Z_c|}$$

(26.18)

Where $R_a$ and $R_c$ are the respective resistances of the antenna and the receiver
circuitry ($W$), and $Z_a$ and $Z_c$ are the respective impedances of the antenna and the
receiver circuitry. The matching coefficient ($\tau$) ranges between 0.0 and 1.0, with an
ideal match being achieved when $\tau = 1.0$.

Because wireless systems must contend with noise, it is important to ensure
that the received signal is stronger than the background noise. The power associated
with noise was defined in the previous chapter in equation (25.1). A useful measure
of performance is to ensure that the signal to noise ratio is well above 1.0. For a free
space wireless link the signal to noise ratio is:

$$S = \frac{P_s}{P_n} = \frac{P_0 G_s G_r \lambda^2 \tau}{4\pi k TBR^2} e^{-2\alpha R}$$

(26.19)

Where S is the desired signal to noise ratio for the wireless link.

Therefore longer wavelengths (i.e. lower frequencies) provide better signal to
noise ratios for wireless links. Other factors such as terrain, obstructions, and the
ability for the electromagnetic wave to be guided around the curvature of the earth
also influence the effective range of a wireless link. For most agricultural activities
these links are over moderately short distances and these other influences are not so
critical.

Automatic data acquisition and wireless data transfer systems are becoming
important for modern agriculture. One way of enhancing both the acquisition of
useful data and the transmission of this data over longer distances is to use networks
where the nodes of the network act as sensors in their own right and as boosters for
signals from more distant sensors in the network. These wireless sensor networks
are being developed for agricultural applications and will be discussed in the next
chapter.
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