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Radio Theory De-Mystified

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Abstract
With increasing demands placed on plant managers to reduce operating costs, wireless is presenting attractive alternatives to buried cable and conduit runs. The issue at stake in choosing this alternative is reliability, and trust must be established before users will confidently invest in this technology. This paper will discuss the different types of radio that are currently in use with a focus on spread spectrum in process control applications. An explanation of how a radio works will be followed by a discussion of fixed frequency, direct sequence spread spectrum, frequency hopping spread spectrum and orthogonal frequency division multiplexing technology. Emerging radio standards will be reviewed and the audience educated on how to interpret specifications and how they differentiate one radio's performance from another. Classes of criticality for wireless applications will be studied. Range determinations, interference mitigation and multipath will be

addressed, along with issues surrounding the multitude of frequencies in use and the advantages and disadvantages of each.

Introduction

Industrial, commercial and consumer wireless products all have benefits that have outweighed a hardwired alternative, if one existed. However the requirements of all three for reliability, range, and throughput vary dramatically. The industrial world requires 100% reliability; no dropped calls, no pressing the remote button twice and no tapping the monitor. It just has to work – every time, all the time. Applications include SCADA (Supervisory Control and Data Acquisition) networks for water/waste water and oil & gas, replacing hardwired copper runs of remote sensors in plants and video monitoring of assets, gates and production processes. This paper will explain how a basic radio works and how to interpret specifications. It will then move onto standards and the issues RF installers need to understand and maintenance mechanics will need to know. No RF background is required for this paper to be of benefit and understandable to the industrial technician/engineer.

1.0 How a Radio Works

A radio transmits data by modulating electromagnetic (also called radio) waves at frequencies below those of visible light. The frequency, amplitude or phase angle can be modulated or combinations of the three. These are known as frequency modulation (FM or frequency shift keying (FSK)), amplitude modulation (AM or ASK), phase angle (PM or PSK) or a combination of elements such as quadrature amplitude modulation (QAM) which operates by changing the amplitude of two carrier waves that are 90 degrees out of phase of each other. The process of converting data into an electromagnetic wave or radio wave involves many components. Figure 1.0 below shows a block diagram.

If we ignore the brown and red items, we see a basic radio (narrow band, fixed frequency), as the inventors Marconi, Telsa etc built, with the same building blocks that are still used in fixed frequency radios today. Some examples of fixed frequency radios are UHF/VHF voice radios found on boats for marine voice communications and data radios for SCADA networks. By adding the components in red and brown we convert a narrow band fixed frequency radio into a Direct Sequence Spread Spectrum (DSSS) radio. By adding the components in red and green (and deleting components in brown), we convert this radio into a Frequency Hopping Spread Spectrum (FHSS) radio.

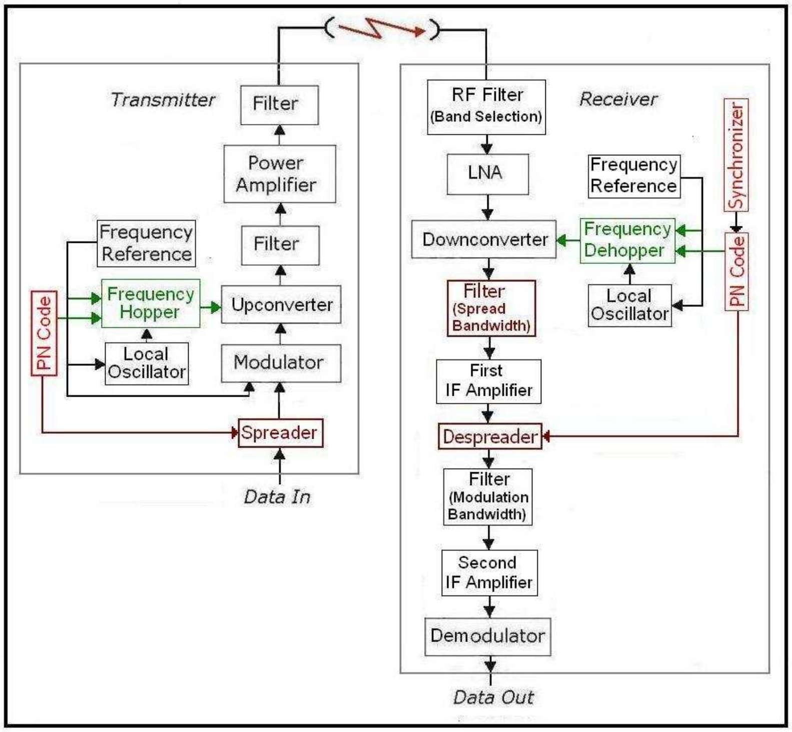

Figure 1.0

This paper will focus on sending digital data.

The Transmitter The first stage is the Modulator. The modulator does the data signal coding. Essentially it superimposes a digital signal onto an analog waveform. Additional overhead data will be inserted for things like error checking and an ID for the receiver to check.

Next the Upconverter combines the signals from the modulator and a stable local oscillator to create the carrier frequency. Some undesired frequencies are generated in this process so a filter is used to remove these.

For most industrial applications where some significant range is desired, or, where a high level of interference is present and a higher signal-to-noise ratio is required, a power amplifier is employed to boost the output power. Finally, to ensure compliance with FCC rules (more on this later), a final transmitter filter is used to remove any harmonics and spurious emissions.

The Receiver When a signal arrives at the antenna of the receiver, a voltage drop across the impedance of the antenna creates a voltage which is then becomes the signal used. Keep in mind that radios operating at the threshold of their reception, (for example -110dBm) are dealing with voltages in the range of nV (nano-volt) (a billionth of a volt). For any electronic device to be able to distinguish digital ‘0’s and ‘1’s from a voltage level this low gives you an idea of how sophisticated the task of designing a good radio is.

The first component is the RF filter. Essentially it eliminates RF energy from frequencies outside the band this radio is designed to utilize. We will talk more about filters in just a minute, but for now lets not minimize the importance of this filter. In a world with cell phones, radio stations, 802.11 networks etc, this filter has the very important job of eliminating background noise and only letting the desired frequencies through. A good investment here will have a significant impact on your radio's ability to discern signal from noise.

The low noise amplifier (LNA) boosts the signal closer to useable levels. It is a relatively low gain amplifier for the purpose of achieving linearity and ensuring the signals do not reach the saturation point. The signal is then down converted to a lower center frequency. This is accomplished by mixing it with a stable local oscillator frequency derived from the frequency reference subsystem. The signal is filtered again to remove the local oscillator and its image frequencies, then amplified again. The third filter's bandwidth is set to match the demodulator and the final signal is amplified again. High quality receivers have many stages of filtering whereas low quality receivers may have little or none.

The final component is the demodulator. It is responsible for determining if each portion of the waveform is a "one" or a "zero". As you can imagine, the more time you have to make this determination (a longer time period to study the waveform), the more accurate the demodulators prediction. When specifying a radio, you can determine this by looking up the over-the-air data rate. The slower the over-the-air data rate the more time the receiver has to make this determination and therefore a weaker RF signal can be used. However when that over-the-air data rate rises, the RF signal must be stronger as the receiver has a shorter time frame to make that judgment call. There are a few other factors that also influence the relationship between minimum received signal strength (and therefore range) to over-the-air data rate however this is an important one.

When noise is present, the signal going into the demodulator is fuzzy and the decision the demodulator must make as to whether this is a "one or "zero becomes more difficult. If the receiver can obtain an accurate copy of the transmitter timing clock, it will be able to determine the optimal point to sample the waveform. To do this, the receiver must phase lock its local oscillator to that of the transmitter, which requires an accurate internal clock. When combined with high quality filters and good quality amplifiers, they lead to a high performance receiver which exhibits greater RF range and better interference tolerance. The RF designer has many variables to consider with cost, performance and complexity trade offs.

Now I'd like to have a brief discussion about filters. In a high quality radio system designed for use in high interference industrial environments or mission critical military applications, the filters are often the most expensive component. An expensive filter will have very sharp cut off characteristics and an ideal filter will provide infinite attenuation of all frequencies outside of the bands desired. Real world filters are a compromise between cost, size and performance. Money spent here is often a wise investment if reliability and performance in the presence of interference is important. An external filter can be inserted in between the radio and the antenna if the internal filters are not sufficient.

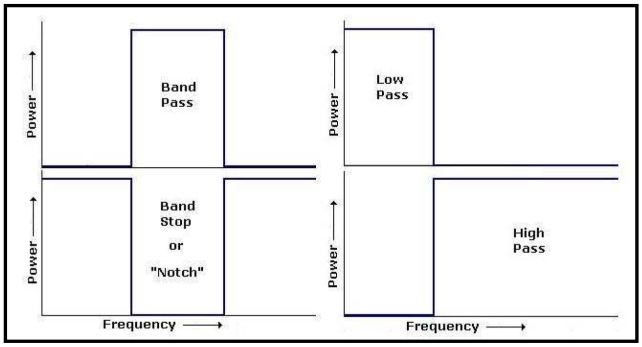

Figure 2 .0

Figure 2.0 shows common filter types. The square shape shows the ideal characteristics of a filter, however in reality the corners are rounded and the vertical lines never perfectly vertical. The more expensive the filter, the more closely it will resemble Figure 2.0.

2.0 Conversion Schemes

Fixed Frequency Radios A fixed frequency radio operates on a single frequency an is often referred to as a narrow band radio. For industrial or commercial users a license must be purchased from the government to operate the radio on a particular frequency in a particular area. Operation on that same frequency outside of that geographic area requires the purchase of another license. A typical bandwidth offered is 25KHz, however this is now being reduced to 12.5KHz to allow more users in the same geographic area. Note that the narrower the bandwidth the lower the over-the-air data rate, all other factors being the same.

The government licensing scheme works well in theory, however it does not account for the needs of mobile radio users such as construction site contractors wirelessly controlling machinery such as concrete pumper trucks. These vehicles are driven to different sites daily and competitive pressures have required that they utilize wireless technology. In this case, licensing either limits the geographic use of the machine or requires multiple licenses. Some operators will ignore the law, particularly when a triangulation by the FCC may take days – well after the operator has left the site. Another issue is the cost. Though the license fees are not onerous, they still represent a cost beyond that of the unlicensed bands.

In fixed installations (where the radio is permanently installed) such as in industrial plants or SCADA applications, the antenna mounting heights are restricted to prevent the radio signals from spilling over into other geographic areas that have been licensed to other users. To some extent, this does limit the range.

Multipath A major problem with fixed frequency radios is multipath. Multipath is a phenomena whereby two radio waves leaving a transmitter at the same time take different paths due to reflection, refraction, etc, and arrive at the receiver 180 degrees out of phase of one another. When these two sine waves are added together their phases cancel resulting in no reception. This is a common occurrence while listening to an AM/FM radio in a car in urban areas. The cars antenna receives two signals – one bouncing off a building and arriving 180 degrees out of phase of the radio wave that took a direct path. Because the car is mobile, by simply moving forward a few feet, the cars antenna is no longer in the null spot and reception picks up again.

Multipath is a major reason why fixed frequency radios have never become popular in industrial plants for permanently installed applications. They work fine for mobile workers – if voice communications are lost, the worker can simply move a few feet over out of the null spot with minimal or no lost productivity. However if the radio is bolted to the side of a tank for the purpose of transmitting the 4-20mA level signal to a control room a ½ mile away, it would only take a fork lift or piece of machinery to move such that a multi-path condition is created to cause the signal to be lost – potentially troublesome during a tank draining or filling process. Now if the radio could change frequency all null spots could be eliminated…

Spread Spectrum ISM Bands In the late 1980's the government recognized the need for greater access to the spectrum. It created the first Industrial Scientific Medical (ISM) band which spans from 902 to 928MHz. Later the 2.4GHz band was introduced and more recently the 5.8GHz band. These are unlicensed bands so no user fees are paid to the government. Instead each radio manufacturer must submit samples to the Federal Communications Commission (FCC) for approval and they can then be legally imported and sold. Each radio is assigned an FCC ID number and this appears on each unit.

Radios operating in the ISM bands are known as spread spectrum radios. There are several different types of spread spectrum radios such as Frequency Hopping Spread Spectrum (FHSS), Direct Sequence Spread Spectrum (DSSS) and Orthogonal Frequency Division Multi-plexing (OFDM) Spread Spectrum. We will come back to these spreading techniques later.

There are several rules for a radio to operate in the ISM bands. The primary ones are the transmit power must not exceed 1W (in North America) and the radio must not concentrate its power on any one segment of the band meaning that the radio must either change frequencies periodically or spread its power over a wide range of frequencies. This has lead to innovation that has allowed spread spectrum radios to serve a wide range of applications ranging from consumer to industrial.

Frequencies With three different ISM bands available, which one should you use? First there is the issue of range – as frequency increases, a radio's range will decrease, all other factors being equal. This applies to LOS (line-of-sight) applications, but even more so to non-LOS applications. In rough terms the relationship is somewhat inversely proportional between frequency and range. For example a 900MHz radio will have approximately three times the range of a 2.4GHz radio, all other factors being equal. In a non-LOS application, you may be relying on reflections to get the signal to the receiver. The higher the frequency, the more energy is lost upon each reflection, therefore in this scenario, the difference in range between a 2.4GHz radio compared to 900MHz would be even greater.

It is important to note the not all ISM bands are license free in all countries around the world. The 900MHz band is only license free in North America, parts of South America and Australia & New Zealand. The 2.4GHz band is license free is most countries world wide and acceptance is gaining for the 5.8GHz band. The primary reason why 2.4GHz consumer products have become very popular is because a manufacturer only needs to build one product to be able to market it world wide. On the other hand, the North American SCADA market is dominated by 900MHz ISM band radios and UHF/VHF licensed radios due to the superior range possible.

A second consideration is the size of each ISM band and its implications on how many radios can co-exist. The 900MHz band is 26MHz, the 2.4GHz band is 81MHZ wide and the 5.8GHz band is 15MHz wide. Naturally, the larger the band, the more radios that can co-exist in it.

Direct Sequence Spread Spectrum A direct sequence radio operates by spreading its power across a wide portion of the ISM band. Figure 3.0 describes this process.

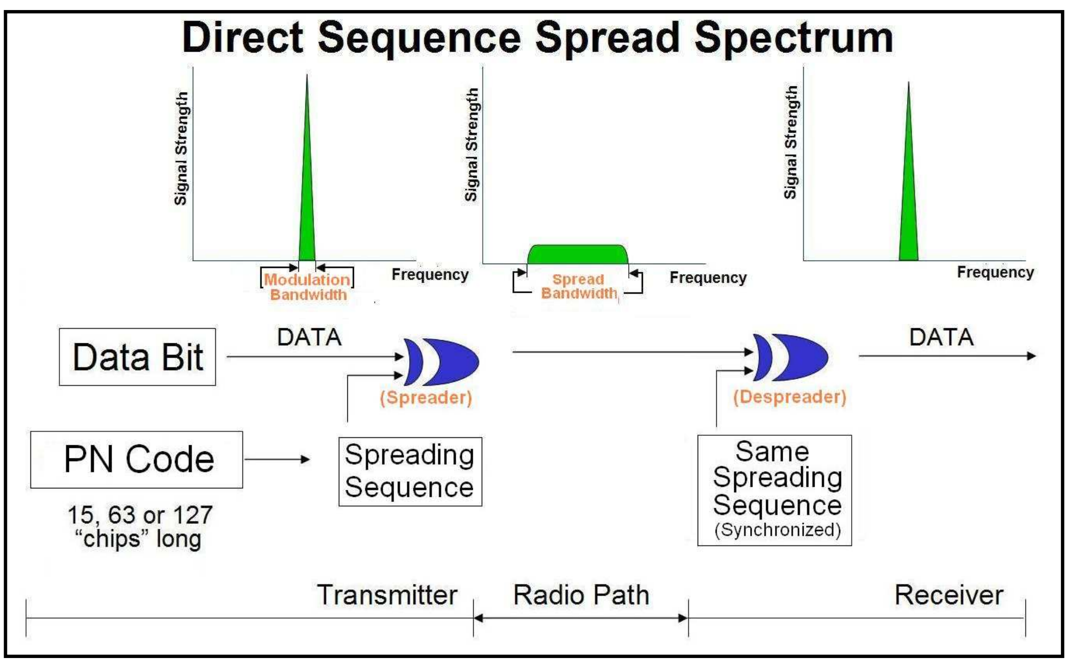

Figure 3.0

Essentially a signal is spread over bandwidths of 1-5MHz. This radio uses something called processing gain to suppress interference. The longer the chipping code, the greater the ability to suppress interference. However, this also means the occupied bandwidth increases, which requires that the receivers filters be set wider, which in turn means a larger opening for interference to enter the receiver's front end. A benefit of DSSS technology is that it has a relatively high over-the-air data rate. DSSS is the basis for 802.11b which allows data rates of up to 11Mbps. DSSS is susceptible to multipath. Some radios use two antennas to help resolve this – by having the antennas some multiple of the wavelength apart, if one antenna is in a null spot, the other will not be. This is common on 802.11 radios

In the presence of interference, this radio can suppress a limited amount while maintaining 100% throughput. However when the interference exceeds the jamming margin of the receiver, throughput drops to zero. The performance of this type of radio is either 100% or 0%.

Frequency Hopping Spread Spectrum A FHSS radio operates by changing frequencies or hopping around the spectrum. The hopping sequence must be pre-programmed into the transmitter and receiver and is a pseudo random sequence. If interference is encountered on one frequency, the radio simply hops to a new frequency and the protocol of the data being transmitted will typically do a retry. Figure 4.0 shows a FHSS radio.

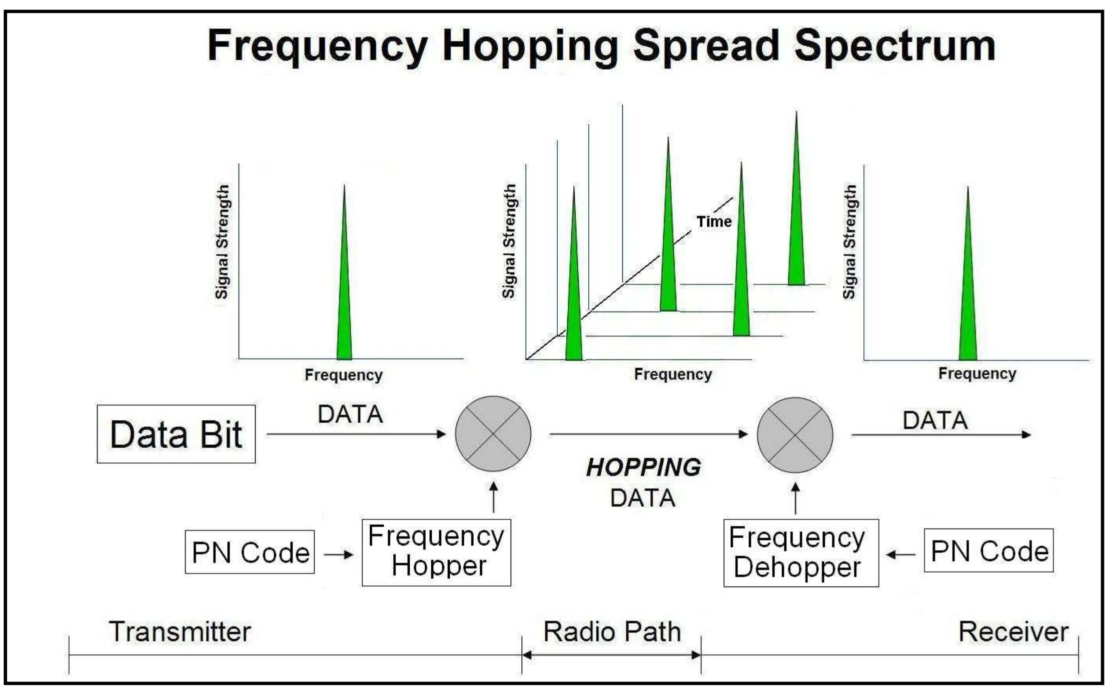

Figure 4.0

If interference is encountered on one frequency, when the radio hops to a new frequency, the protocol of the data being transmitted will typically do a retry. This leads to characteristics of decreasing throughput of the radio system as interference increases. Interference must be present across the entire ISM band in order to completely block this type of radio.

Due to the changing frequencies, this type of radio does not suffer from multi-path conditions like a fixed frequency or DSSS radio would. Because the wavelength differs with frequency, a multi-path condition on one frequency would not be repeated on other frequencies. When operated in typical industrial facilities where pipes, steel structures and machinery reflect radios waves, severe multi-path will result in reduced throughput, but will not completely jam the radio.

An FHSS radio will not have as high throughput as a DSSS radio. This is for the reason that it must change frequencies. Though this occurs very fast, the fact is the radio must turn off, change frequencies, then turn back on again. The rates between the two will be comparable, but the DSSS will have the advantage.

Orthogonal Frequency Division Multiplexing OFDM is a spreading method that divides signal data across a wide number of carrier frequencies that are transmitted simultaneously. What is unique about OFDM is that the carrier frequencies are spaced such that they are orthogonal - that is, they are designed to have the exact minimum spacing such that each carrier frequency does not interfere with any other. Figure 5.0 describes OFDM

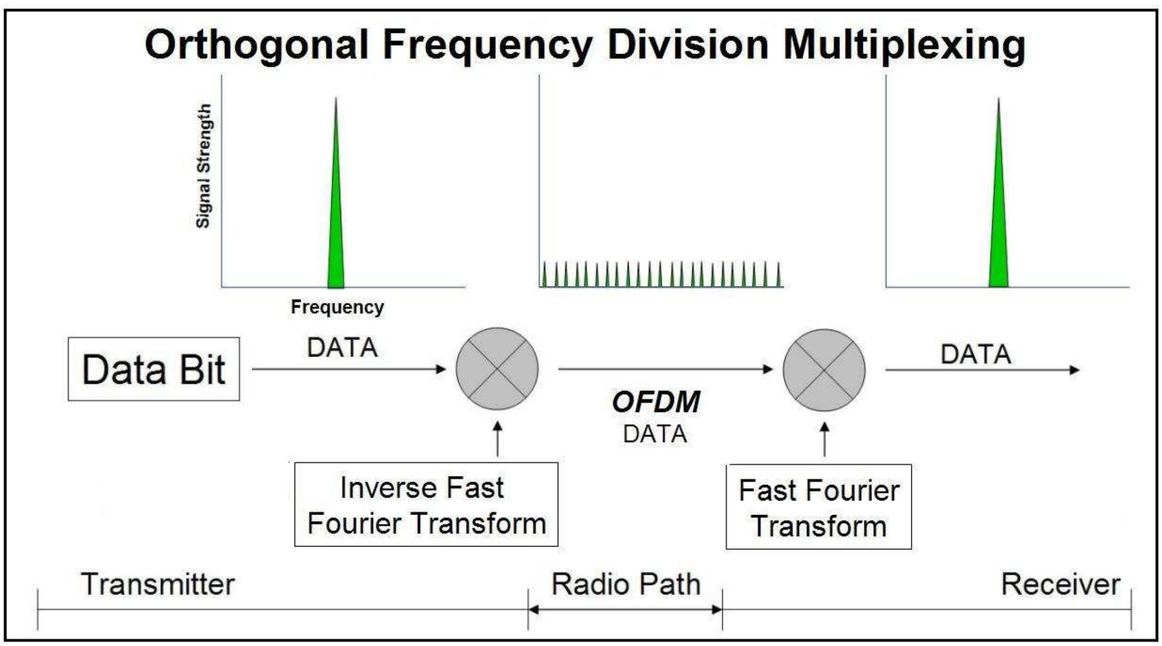

Figure 5.0

Advantages of OFDM include immunity to interference and multi-path. It also allows for very high throughput. OFDM is the basis for 802.11a and g protocols, each of which allows transmission up to 54Mbps. Most new cellular phone transmission schemes are based on OFDM as are new digital TV signals.

Disadvantages include sensitivity to Doppler shift and therefore limited use in high speed mobile applications. OFDM is also sensitive to frequency synchronization problems between the transmitter and receiver. This requires more complex circuitry to deal with.

3.0 Radio Standards

IEEE The Institute for Electrical and Electronic Engineers is a leading developer of industrial standards. They developed the 802.11 wireless standard for the networks we all use our homes and now industrial facilities. The Bluetooth specification was developed by Ericsson in 1994. IEEE later ratified the physical layer as the 802.15.1 standard in 2002. Bluetooth has since become popular for short range interconnection of devices such as wireless ear pieces for cellular phones and also industrial RS232/485 links in plants. Similarly, the physical and MAC layers of the Zigbee development were first ratified by IEEE as 802.15.4 in 2003. Zigbee products are gaining acceptance for a wide range of consumer and commercial uses.

802.15.1 802.15.1 is a wireless standard that uses FHSS in the 2.4GHz band. It is limited to short range applications, with the maximum range being approximately 100m (450 feet). There are different classes of 802.15.1, each stipulating different transmit powers and associated ranges, and implications of battery life/power consumption. The over-the-air data rate initially was 750Kbps, however the latest standard to be ratified offers data rates of 2.1Mbps.

802.15.4 The 802.15.4 standard uses DSSS in the 900MHz band in North America and the 2.4GHz band in most other countries. It was intended as an improvement upon 802.15.1 in terms of lowered cost, longer battery life and mesh networking capability, however differs from 802.15.1 in that its over-the-air data rate is much lower. In the 900MHz band, the data rate is 40Kbps and in Europe in the 2.4GHz band the data rate is 250Kbps. 802.15.4 enabled chips now cost approximately $1 allowing it to be used in a wide range of applications.

ISA100 This standard is being created by the International Systems and Automation Society (ISA). Its intention is to create a global wireless standard suitable for use by the industrial community, such that wireless devices made by different manufacturers can communicate with one another. Some of the requirements include longer range, security of data (encryption) and reliability in the presence of heavy interference. At the time of this writing, the first draft is out for comment and the standard is not yet ratified. The standard is based on two technologies combined – DSSS with frequency hopping. Specifically it is based on 802.15.4:2006 that changes frequency. Therefore the interference issues that cause concern for DSSS radios will be mitigated by moving to different frequencies.

The transmit power is not specified in the standard. Instead it will be regulated by the country the radio is operated in. This means up to 1W of transmit power in the Americas and 100mW in most other countries. Though the 802.15.4 standard allows for both 900MHz and 2.4GHz, the author is not aware of any available 900MHz chip sets. This means initial installations will be operating in the 2.4GHz band. Mesh capability mean that wireless instruments can relay data from more distant instruments to get the information to a control room, increasing the effective range. Encryption has been specified in layers 2 and 4, ensuring the security of the data.

WirelessHART The WirelessHART standard was ratified by HCF members in 2007 and is based on the IEEE 802.15.4 using DSSS with frequency hopping. It allows users to gather HART diagnostic data from remote instruments wirelessly. Currently compliance testing criteria are being formed such that manufacturers can submit a product for testing, and once approved, can include the HART7 moniker on the product.

4.0 Classes of Applications

The ISA100 committee has created a matrix that shows six classes of criticality for wireless applications. Refer to Figure 6.0

Safety	Class 0 : Emergency action ***(always critical)***
Control	Class 1: Closed loop regulatory control ***(often critical)***
	Class 2: Closed loop supervisory control ***(usually non-critical)***
	Class 3: Open loop control ***(human in the loop)***
Monitoring	Class 4: Flagging ***Short-term operational consequence*** ***(e.g., event-based maintenance)***
	Class 5: Logging & downloading/uploading ***No immediate operational consequence*** ***(e.g., history collection, SOE, preventive maintenance)***

Figure 6.0

Class 0 refers to critical control or safety where such action will prevent an explosion/fire or severe damage. Class 1 refers to wireless application where the link is used for closed loop control such as positioning a control valve on a critical process. Class 2 is also closed loop control but very common on SCADA networks where only set point control is being performed over the wireless link. This is very common in the water/waste water industry where a programmable logic controller (PLC) located at each lift station monitors the pump but the set-point is transmitted from a central location. Class 3 is open loop control such as a crane operator watching his crane as he controls it with a radio remote control system. Class 4 is alerting – such as low battery voltage on a sensor, whereby the system can continue to operate for some period of time but will eventually need servicing. Class 5 is logging or downloading of historical data. There is no immediate consequence if the data link is lost – once restored the data can be accessed.

Radios are available for all classes of applications. The military has had the capability to detonate missiles via radio link when they go astray, and now there are radios that have SIL certification for industrial class 0 applications. They will cost a lot more than a radio suitable for a class 5 application. The responsibility is on the end user to access the criticality and time sensitivity of each application and select the appropriate equipment.

5.0 Interference and Co-existence

Interference comes from a variety of sources. These include intentional emitters such as other radio products and unintentional emitters such as variable frequency drives (VFD) and arc welders. However since radio field strength decreases inversely to the square of the distance from the transmitter, separating adjacent radios systems slightly has a large effect on their signal-to-noise ratio. This works in our favor when we want to have a large number of independent radio systems operating in the same industrial facility.

Increase the Separation Distance By moving a receiver's antenna away from a source of interference such as a VFD or other transmitter you can resolve most interference problems. For radio systems with transmit powers up to 5W, a rule of thumb is to ensure receivers are located at least 2m (6 feet) vertically or 3.1m (10 feet) horizontally away from the interfering transmitter. Naturally, the more powerful the source of interference, the greater the separation distance should be.

Filters and Frequencies If the filters used in radio systems had the ideal characteristics as shown in figure 3.0, (vertical cut off lines and sharp right angles), this paragraph could be omitted. However real world filters have curves. This means that the closer the source of interference to the desired signals, the lower the attenuation. For example, if a radio operating in the 902-928MHz band experiences interference from a paging system operating at 929MHz and a fixed frequency radio at 450MHz, the paging systems signals are likely to pass through the filters with much less attenuation than the 450MHz radio. Therefore, if you're choosing an antenna mounting location on the roof of a building already populated with other antennas, locate your antenna furthest from the radios that are closest in frequency.

When there are several radio systems all operating in the same ISM band, the increased interference levels may result in reduced range. Essentially a higher signal level is required to compensate for the higher interference level.

Antennas and their Beam Angles Antennas have plots and specifications that show in which directions they radiate most of their energy. Yagi antennas, for example, radiate most of their energy in the direction they are aimed, with a small amount of energy coming off the rear of the antenna, but virtually no energy is radiated immediately above and below. As such, avoid placing a receivers antenna directly in front of a yagi antenna of another radio system to minimize interference.

6.0 Range and Propagation

There are two methods of determining a radios range. The first is to test the link with the same type of radio you are planning on installing. That is, to take the transmitter and temporarily locate it where it will be mounted and then walk or drive to the remote site with the receiver. (Lets not forget that for very short range applications, such as wirelessly transmitting the temperature off a rotating kiln to a receiver 10m (30 feet) away, this is not necessary). The real world test is the most accurate. By moving the receivers antennas to different mounting locations and observing any changes in the received signal strength, you can determine the optimal location for the antenna. This method works well for most medium range applications, and is mandatory for applications where there are obstructions in the path and attenuation through buildings or trees cannot be accurately calculated. However as the range increases, the mounting heights of the antennas also increases. For ranges expressed in miles, if a roof top is not available, towers may need to be built, and as such it may not be possible to test the system as you may not be able to elevate the antennas without towers already present. In this circumstance a propagation study is recommended for long distance links.

A propagation study involves gathering the GPS co-ordinates for each location. This data is entered into a software program that contains the topographical data for the area. The radios specifications are entered, and the software program then calculates how high each antenna needs to be mounted. Once this is known, the expense of towers can be estimated and the cost for the entire installation determined in advance. Figure 7.0 shows a path profile. The software program will also estimate the received signal strength and calculate the predicted reliability of the link. It is important to note that these propagation studies do not take into account buildings or trees in the path. Antenna heights or locations may need to be adjusted to accommodate this.

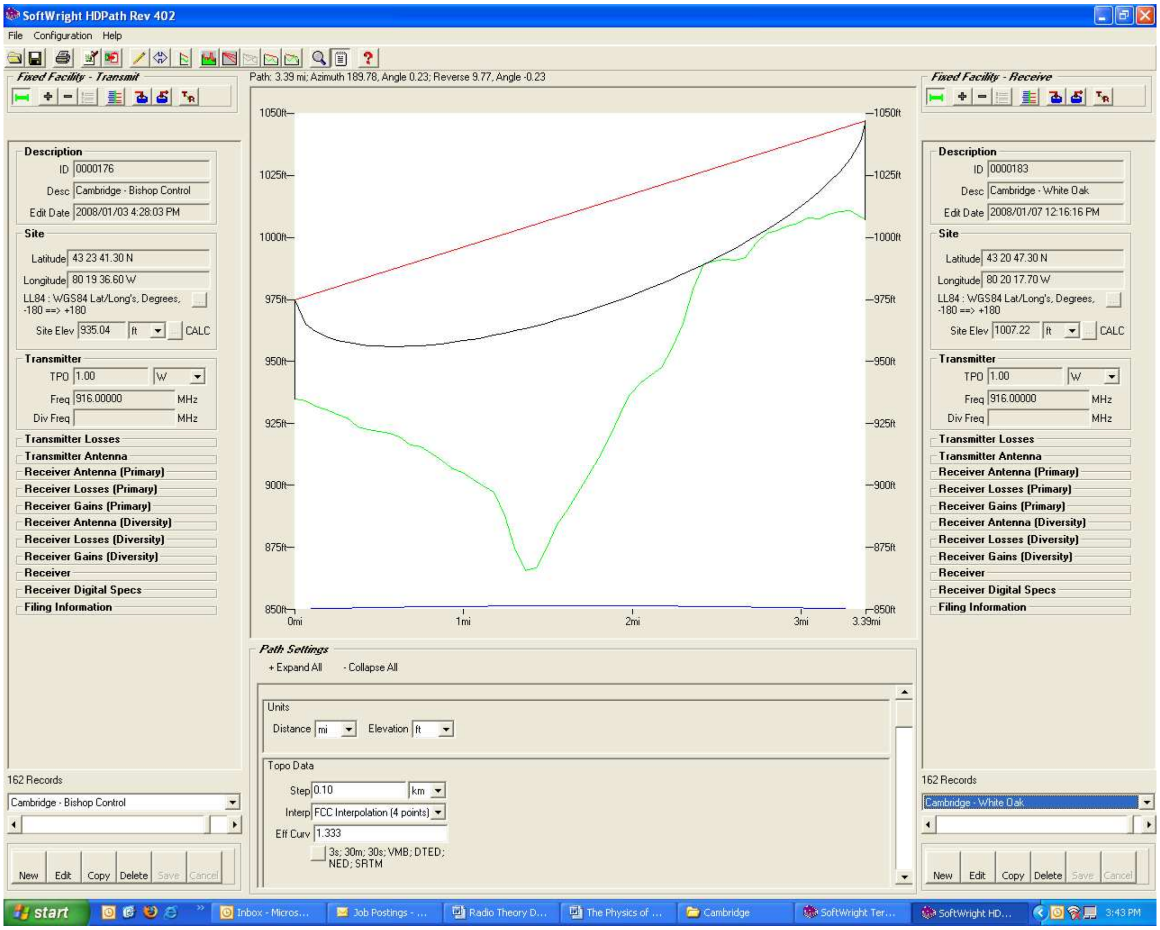

Figure 7.0

7.0 Interpreting Radio Specifications

When it comes to specifications printed on data sheets, two main factors make it difficult for end users to compare products – specmanship (ratcheting up your specs to match the competition) and a lack of specifications. Another common tactic is using unequal criteria to compare radios. The biggest offender is range specifications. Because there is no standard to compare the ranges to, some manufacturers quote the absolute maximum while others quote a maximum with a 20dB fade margin built-in, since no reliable link would be designed to operate at the absolute maximum. However there is a fail proof method of determining which radio will yield the best range and for shorter links, which will give the largest fade margin.

Transmit Power This is fairly obvious – the more power the greater the range. Also, the more power the stronger the signal, and any interference must also be stronger before it poses a problem. For maximum reliability, the stronger the signal, the better. Transmit power is only half the equation – the other half is the receiver sensitivity.

Receiver Sensitivity This specification tells how sensitive the receiver is, and therefore how good its ability is to detect a very weak signal. It is expressed in dBm and the lower the number the better the receiver. For example a receiver rated at -110dBm is a more sensitive receiver than one rated at -100dBm. Unfortunately this specification is not comparable between manufacturers. This is because some specify the sensitivity with a bit error ratio (BER) of 10^6 (one errored bit of one million transmitted) while others specify the sensitivity at a BER of 10^4 (one errored bit of ten thousand transmitted). Some manufacturers use a packet error ratio as their modulation schemes transmit data in blocks or packets, and either the entire packet is valid or the entire packet is invalid. Many manufacturers do not specify the BER or the packet error ratio for their receiver sensitivities and some do not specify the receiver sensitivity at all. Instead one has to rely on the other criteria described in this section.

Some radios are capable of multiple over-the-air data rates, and each data rate will have a corresponding receiver sensitivity. Sometimes the receiver sensitivity is specified at the lowest over-the-air data rate yielding the best number.

Frequency As mentioned earlier, the higher the frequency, the shorter the range of the radio system, all other factors being equal. For maximum range and maximum object penetration ability, select the lowest available frequency.

Over-the-Air Data Rate Ignore the range specifications and instead compare the over-the-air data rates. The radio with the lowest over-the-air data rate will have the greatest range, all other factors being equal. This can be seen by comparing the receiver sensitivity specifications on 802.11 radio systems. 802.11b is capable of data rates ranging from 1Mbps to 11Mbps. As the data rate increases, the receiver sensitivity decreases – resulting in reduced range. You can also test this with a wireless laptop linked to an 802.11 access point – as you walk away from the access point, observe the data rate in the wireless configuration screen.

8.0 Conclusion

Reliable radios require complex designs and expensive filters. A higher priced radio system will provide better overall performance and robust radio links. There are many different conversion schemes, each with advantages and disadvantages, and each has a place in the consumer, commercial or industrial markets. The adoption of radio standards will ensure that end users have the choice of several vendors to purchase products from. Many radios can happily co-exist as long as there is some physical separation between them and they do not all use the same frequency. The range of a radio system can be determined by field tests or using propagation software. An astute engineer can compare radios to one another though manufacturers do not always make it easy.