Using Spread Spectrum Radio Communication for Power System Protection Relaying Applications

Scope:
This project developed a document describing the application of protective relays using spread spectrum radio communication for power system protection schemes. This document presents background information, bibliography, and recommendations. It discusses spread spectrum radio communication technologies and topologies that may be applicable for use in protective relay schemes. It discusses practical considerations of interfaces, interoperability, reliability (security and dependability), availability, security against intrusion, and economics for spread spectrum radio communication.

Purpose:
There was no IEEE document describing the application of protective relays using spread spectrum radio communication. Protective relaying and spread spectrum radio communication technologies are rapidly changing and expanding. Understanding the opportunities and limits of these technologies is important to their successful mutual application. This document was coordinated with the Audio Tone Guide to minimize duplication of effort. This document provides information to assist in the application of spread spectrum radio communication technologies for protective relay schemes. Descriptions of some working systems and their performance is provided.

A Report to the IEEE Power System Relaying Committee,
Prepared by: IEEE/PSRC Working Group H2

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1.0 Introduction

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Protective relaying and spread spectrum radio communication technologies are rapidly changing and expanding. Understanding the opportunities and limits of these technologies is important to their successful mutual application. This document provides information to assist in the application of spread spectrum radio communication technologies for protective relay schemes. Descriptions of some working systems and their performance are provided.

The original scope indicated that this document would include recommendations, but the working group determined that recommendations are not warranted or needed in this report document.

2.0. Bibliography

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3.0 Typical Protective Relay Applications

3.1 General description

The purpose of this section is to describe the application of peer-to-peer communications technology to power system protection. The application examples assume that a communications media exists between IEDs, and the IEDs can communicate with each other. Each application example starts with a description followed by the benefits such as improved protection, cost savings, space savings, etc.

The following are some of the examples of application of peer-to-peer communications applications and various other applications can be found in the literature [1].

3.2 Intrasubstation Applications

3.2.1 Enhanced Transformer Differential Protection

The pickup and slope of a percentage differential relay are set to prevent relay misoperation due to transformer magnetizing current, CT ratio mismatch, transformer tap changing, and CT saturation during through faults. The transformer ratio can change by as much as ±15% due to load tap changer (LTC) operation. In order to prevent misoperation of the differential relay, the slope must be set much higher than 15% when the transformer is equipped with an LTC. Setting the slope of the percentage differential relay to higher values reduces the relay sensitivity for high-resistance faults in the transformer. The transformer ratio error introduced by the LTC operation can be digitally corrected in the differential relay if the tap position of the LTC is known to the differential relay. This information could be transmitted via wireless communication from the LTC control to the transformer differential relay, which then would adjust its tap settings to maintain sensitivity without sacrificing security.

3.2.2 Breaker Failure

Breaker failure is the condition of a breaker which, when called to trip, fails to interrupt the current flowing through the breaker. Breaker Failure Initiation (BFI) is issued in conjunction with a breaker trip signal. BFI then starts a timer (typically 7 to 15 cycles). If, at the expiration of the timer, current is still flowing through the monitored breaker, a "Breaker Failure" trip is then issued. This trip signal is to be logically "sealed in.” If the breaker current falls below the reset threshold or a breaker change of state is detected, a "Breaker Failure Reset" is issued. A Breaker Failure Trip can affect as little as one breaker or as many breakers as are connected to a bus (10 to 20). A Wireless LAN implementation of the above eliminates a separate timer/current measurement function, a Breaker Failure Lock-Out relay and all the wiring associated with it.

3.2.3 Fast Bus Overcurrent Trip

It is desirable to provide high-speed protection for bus faults. The normal method for this has been to use differential protection due to its high selectivity and therefore high speed. In applications where the cost of differential protection is not warranted, protection of the bus is often provided by overcurrent relays on the bus mains. Normally in this case, the coordination interval required to coordinate with the feeder relays would lead to clearing times in the order of 400 to 500 ms or more.

In applications where the loads on the bus are fed radially, as is typically the case on distribution and often sub-transmission, the fast bus overcurrent trip method has been gaining popularity. In this scheme, the feeder protection relays must signal their status to the bus main relay. When a fault occurs on a feeder, both the feeder relay and the bus main relay will detect it. The bus main relay is set with a time delay only long enough to give the feeder relay time to signal that it has detected the fault also.

If the bus relay does not receive the signal (indicating that the fault is not on a feeder and therefore on the bus), it trips. This high speed blocking scheme allows the bus relay to trip much faster than if it had to rely on traditional coordination intervals.

In this scenario, the assumption is made that feeder protection is adequately redundant so that reliable detection of feeder faults can be assumed.

One limitation of current implementations is that hardwired logic limits the number of bits of information that can be exchanged between the feeder relays and the bus main relay. In an evolving fault or during simultaneous internal and external faults, the simple logic associated with a hardwired scheme may be insufficient, resulting in a misoperation. The benefit of a wireless implementation is that the bus relay can know which feeder is signaling and which phases are faulted. Thus, if the bus relay detects that a fault exists on both A and B phases, but it is only signaled that a fault exists on A phase of a feeder, it could determine that a bus fault exists on B phase and trip. In existing hardwired schemes, it would be blocked. Existing scheme logic currently requires use of output relays on the feeder relays hardwired to contact sensing inputs on the bus main relay. The number of inputs and outputs on each relay could be reduced making these devices more compact and less expensive. Extensive interconnect wiring and auxiliary relays could be eliminated.

3.3 Intersubstation Relay Protection Scheme Applications

3.3.1 Line Protection Schemes

Pilot protection schemes are used to provide instantaneous tripping coverage for a fault anywhere within a protected line section. In order to accomplish this, the pilot scheme requires a communication channel to exchange information between relay terminals. A general description of existing pilot schemes is as follows:

3.3.1.1 Permissive Overreaching Transfer Trip (POTT)

In this scheme, each line relay terminal has pilot relaying set to overreach its remote end relay terminal. Each line relay terminal also has an independent communication channel, which typically transmits a guard signal to its remote end terminal under normal system conditions. When a fault is detected by a pilot relay, it causes the guard signal to drop out and a permit trip signal to be sent to the remote end terminal. A pilot trip occurs only if both the pilot relay detects a fault and a permissive trip signal is received from the remote end. This is a secure scheme requiring proper communication channel operation in order to obtain a pilot trip.

3.3.1.2 Directional Comparison Unblocking (DCUB)

This scheme is similar to the POTT scheme except it also allows for a pilot trip without a permissive trip signal being received from the remote end for a short duration after a loss of the communication channel. This “loss of guard” trip window is an adjustable setting typically between 150-300 milliseconds. The scheme is provided for applications where power line carrier is used as the communication channel on the line being protected. This is a secure scheme requiring proper communication channel operation in order to obtain a pilot trip, yet it also provides some dependability to address the situation where a fault can result in the loss of a communications channel.

3.3.1.3 Directional Comparison Blocking (DCB)

For a DCB scheme, each line relay terminal has pilot relaying set to overreach its remote end relay terminal. Additionally, each terminal also has reverse direction (or in some cases non-directional) relaying that is typically called “carrier start” relaying. This carrier start relaying acts to send a block trip signal to its remote end terminal and prevent a relay trip since the fault would be external to the protected line for a reverse direction carrier start application. If the fault is internal to the protected line, the pilot relaying either does nothing or stops any block trip signal that may be sent, as in the case of a non-directional “carrier start” application. A pilot relay trip occurs when the pilot relaying detects a fault and a block trip signal is not received. This is a dependable scheme requiring proper communication channel operation in order to prevent over tripping.

3.3.1.4 Direct Underreaching Transfer Trip (DUTT)

In this scheme each line relay terminal has pilot relaying set to underreach its remote end relay terminal. Additionally, the relaying from each end needs to overlap. When a pilot relay detects a fault, it trips the local relay terminal and sends a transfer trip signal to the remote end terminal to clear the fault. This scheme requires a reliable communication channel for proper operation.

3.3.1.5 Phase Comparison

In a phase comparison scheme each line relay terminal essentially makes a phase angle comparison of the local and remote end line currents to determine if a fault is internal or external to the protected line section. Basically, in-phase currents indicate an internal fault and 180° out-of-phase currents indicate an external fault. Typical relay systems utilize either a single 3 phase composite sequence filtered current or individual phase currents which in either case are converted to a square wave signal for actual comparison. The relaying may also be set with either blocking or permissive type tripping logic. With regard to the communication of information, the scheme may be single phase comparison which makes a local and remote phase angle comparison every other half cycle of the power system sine wave, or it may be a dual channel which makes a comparison on both half cycles. For this scheme, communication channel performance requirements are dependent on the type of pilot relay tripping logic selected.

3.3.1.6 Current Differential

In a current differential scheme, the local and remote end line currents are measured and compared to detect a difference in current. When sufficient difference is detected, the fault is identified as an internal fault. This scheme requires current magnitude and phase information, which may be sent as a single 3 phase composite current signal or alternatively a signal may be sent to allow for comparison on an individual phase basis. This scheme generally has higher a channel bandwidth requirement than other pilot schemes and requires a reliable communication channel for proper operation.

3.3.1.7 Direct Transfer Trip

This scheme is used to send a direct trip to a remote end line terminal, generally either because the local station does not have an interrupting device or in order to provide a backup function to ensure remote end clearing. It can be installed to transfer trip in one or both directions, and generally does not have any type of trip supervision. For this reason a secure communication channel is required. To increase the security of the scheme a dual channel scheme requiring a trip signal from both channels may be used.

3.3.2 Distributed Generation on Utility Feeders

As an example, a customer (Merchant Generator) has installed generation at their facility and has capacity in excess of their load. The facility is served from a utility feeder that has only a few other customers on it with a total load less than available generation from the customer.

The utility would like access to this extra generating capability at times when capacity resources are low and will request customer to operate its generators. To maximize generation availability, the customer must run its generators in parallel with the utility feeder. This parallel operation and the likelihood of back-feeding into the utility's feeder bus suggests that a method of changing the characteristics of the utility's feeder overcurrent relay be adopted to backup the feeder fault detecting function of the customer's main circuit breaker protection.

Benefits of using peer-to-peer wireless communications include:

- Replaces dedicated communication link and I/O interface hardware.
- No need for costly dedicated transfer trip channel from utility substation to customer breaker.

- Logical elements can reside within the overcurrent relay rather than with external logic elements.
- No need to establish line-side voltage source for synchronism check or voltage block closing.
- No separate Supervisory Control And Data Acquisition (SCADA) needed at customer's site.

4.0 Spread Spectrum Radio Communication

4.1 General description and characteristics

The communications industry began using spread spectrum technology several years ago in an effort to provide a low-cost, easy to install communications medium for use in a variety of settings. The spread spectrum technology was adopted because it allowed multiple users to occupy the same frequency band with a minimum of interference to the other users. This technology has been used in numerous applications including cordless phones, wireless Ethernet and point-to-point communications. In the United States, spread spectrum technology almost exclusively utilizes the frequency bands the Federal Communications Commission (FCC) has reserved for unlicensed applications. This means that to operate a spread spectrum device, no transmit license is required. However, the FCC will not guarantee exclusive use of the frequency, as is the case with licensed frequencies. The bands authorized for spread spectrum emissions are; 902-928 MHz, 2400-2483.5 MHz, and 5725-5850 MHz.

Spread spectrum technology uses, primarily, two methodologies to transmit messages. These two methods are Frequency-hopping spread spectrum and direct sequence spread spectrum. A third technique, Orthogonal Frequency Division Multiplexing, is now included in 802.11a standard at 5GHz, and is very likely to be used for UWB (Ultra Wide-band) communications as well. These techniques are briefly described below, followed by tables showing relative performance characteristics:

4.1.1 Frequency-Hopping Spread Spectrum Technology

Frequency-hopping spread-spectrum (FHSS) uses a narrowband carrier that changes frequency in a pattern known to both the transmitter and receiver. Properly synchronized, the net effect is to maintain a single logical channel. To an unintended receiver, FHSS appears to be short-duration impulse noise.

4.1.2 Direct-Sequence Spread Spectrum Technology

Direct-sequence spread-spectrum (DSSS) generates a redundant bit pattern for each bit to be transmitted. This bit pattern is called a chip (or chipping code, also sometimes referred to as chirping code). The longer the chip, the greater the probability that the original data can be recovered, and, of course, the more bandwidth required. Even if one or more bits in the chip are damaged during transmission, statistical techniques embedded in the radio can recover the original data without the need for retransmission. To an unintended receiver, DSSS appears as low-power wideband noise and is rejected (ignored by most narrowband receivers).

4.1.3 Orthogonal Frequency Division Multiplexing (OFDM) Technology

Orthogonal frequency division multiplexing is a Fast Fourier transformation based multi carrier modulation technique. Instead of transmitting the data serially over a single fast data channel, it relies on multiple carriers to transmit data in parallel using the entire allocated channel bandwidth. OFDM is currently used for wire-based communications, such as Asymmetric Digital Subscriber Line (ADSL), and broad band power line carrier; and forms a basis of the 802.11a standard, which uses 52 sub carriers, occupying 20MHz segments of the 5GHz band, with maximum data rate of 54 MBps.

Each of these technologies has their strengths and weaknesses, and depending on the application and environment, one may perform better than the other.

4.2 Factors that affect Spread Spectrum Radio performance

The following tables provide information about the characteristics and relative performance of spread spectrum radio bands and techniques.

Table 4.1. Unlicensed spectrum frequency bands

Frequency range	**Band**	**Comments**
900-928 MHz	ISM	Limited availability: US, Canada, Australia, parts of South America, 868 MHz in EU
2400-2483.5MHz	ISM	20 dBm EIRP limit in EU
5150-5250 MHz	U-NII / HyperLAN2	Indoor use only
5250-5350 MHz	U-NII	
5470-5725 MHz	HyperLAN2	
5725-5850 MHz	ISM	
5750-5825 MHz	U-NII	

ISM – Industrial, scientific and medical
U-NII – Unlicensed national information infrastructure
HyperLAN2 – High performance radio based local area networks

Table 4.2. Comparison of the ISM frequency bands

	Frequency Band		
	900 MHz	**2.4 GHz**	**5.7 GHz**
Interference levels (current crowding)	Highest	Median	Lowest
Bandwidth	28 MHz	83.5 MHz	125 MHz
Free space attenuation	Lowest	Median	Highest
Antenna gain/size ratio	Lowest	Median	Highest
Antenna mounting and feed considerations	Lowest	Median	Highest
Atmospheric effects	Lowest	Medium to High	Highest
Multipath fading	Median	Lowest	Highest

Table 4.3. Comparison of RF modulation technologies

	FHSS	DSSS	OFDM
Basic spreading strategy	Interference avoidance	Interference minimization	Data rate maximization
Spectrum Utilization	Lowest	Median	Highest
Range	Lowest	Median	Highest
Multipath fading rejection	Median	Lowest	Highest
System Complexity	Lowest	Median	Highest
Maximum data rate	Limited by FCC rules	Median	Highest
Latency	Highest	Median	Median
Power Consumption	Lowest	Median	Highest
In-band interference behavior	Dynamic data frame dropout on occupied channels	Graceful degradation until jamming margin is exceeded followed by total link failure	Adaptive data rate reduction
Loss of synchronization (penalty)	Highest (seconds)	Lowest	Low
Out of band interference rejection	Lowest	Highest	Medium to High

FHSS – Frequency Hopping Spread Spectrum
DSSS – Direct Sequence Spread Spectrum
OFDM – Orthogonal Frequency Division Multiplexing

4.3 Path Engineering Considerations [2]

Because Spread Spectrum Radios are fairly modular and often unlicensed, there is a tendency to believe that they will work flawlessly without much installation planning. Path engineering often means placing the transceiver units up high at each end, pointing them towards each other and seeing if they "talk". If they do, the installation is said to be complete. Meanwhile at times the "engineers" wonder why the path becomes disrupted momentarily, only to perform properly upon further investigation. While trial and error engineering may be suitable for voice grade or emergency communications, it is not suitable in situations where high reliability is required.

Depending on the nature of the data using the radio path, the end-to-end data may be capable of accepting a fairly poor path. Since Spread Spectrum Radios are digital, the data errors can result in dropouts, or erroneous bits. Protocols can deal with these. In most cases the data is not misinterpreted, it is removed. The removal can result in a data dropout or a request for resend. If the data is being used for power line protection, the reliability will be severely impacted. Protection engineers are very accustomed to the terms security and dependability as factors of reliability. However, when the communications is digital, time often becomes a factor.

Protocols aside, the best way to assure the most reliable data, with consistent time delays is to engineer the path. Engineering the path consists of identifying the aspects of the signal path that will affect the signal quality. Evaluation of the path will determine if the path will meet the performance objectives prior to actual installation. When the path is short there may be more than adequate receive signal strength to make the path factors effects minimal. However as the path length increase, the path factors tend to affect the path to the extent that the signal may fade away at the time when you need it most.

4.3.1 Path Issues

The path between the two locations needs to be studied with regard to obstructions. The term Line-of-sight, is used to describe the fact that the two locations can "see" each other. Climbing towers and using human sight, a spotlight, a laser or study can do this. Study involves looking at the topography of the earth as well as any manmade obstructions such as water towers, siloes, trees, buildings etc. There are computer programs available that use the National Geophysical Data Center, NGDC topology data and user supplied tower data to show clearances. However manmade objects will need to be identified independently.

4.3.2 Bending of the Path

As the path length increases factors such as the refractive index of the air and the curvature of the earth must be factored in. The refractive index of the air will cause the beam to bend downward being somewhere between a straight line and a path that follows the curvature of the earth. Because the refractive index of the air changes, a factor called K was developed to describe the bending of the wavefront relative to the true earth radius. The path can change dramatically over time so when looking at potential obstructions, various values of K should be used. This will assure that under different refraction situations the path remains unobstructed. Generally 3 different values of K are used. K = infinity is where the signal path follows the curvature of the earth. K = 2/3 is where the earth is considered to have a greater curvature. This is often referred to as earth bulge. The nominal value used to evaluate the path under normal atmospheric conditions is K = 4/3. The path is often displayed graphically with respect to the earth and the location of obstructions. There are two different methods used to express the earth and path: flat earth, and curved earth. Flat earth shows the earth flat and the path curved. With curved earth, the earth is shown with its nominal curvature and the path varies in curvature where K = infinity is a straight line.

4.3.4 Fresnel Zones

While the majority of the energy leaves the antenna in the aimed direction, other incident energy is emitted at various angles. The main energy is emitted in what is referred to as the main lobe with the remaining energy in multiple side lobes. The lobes that make up the antenna pattern are very design dependent. The receiving antenna has a similar pattern. The receiver sees the sum of all of the energy received from its antenna. Some of the energy from the lobes can bounce off of objects and arrive at the receive antenna 180 degrees out of phase or in phase with the main lobe, effectively subtracting or adding to the energy seen by the receiver. If the reflected 180 degree signal is strong enough it will effectively null out some of the receive signal causing a fade. This phenomenon is the reason that objects outside the line-of-sight path can disrupt the quality of the signal.

A Fresnel Zone is a locus of points between the transmitter and receiver where a reflection off that point will result in out-of-phase or in-phase relationship at the receiver. There is a formula that determines these points based on the wavelength and the distance along the path from each endpoint. This is a three-dimensional path looking like a football with the end points at the transmit and receive antennas.

The boundary where the reflected waveform is 180 degrees out of phase (1/2 wave) is called the 1st Fresnel Zone, the boundary where the reflected waveform is 360 degrees out of phase (2 and ½ waves) is called the 2nd Fresnel Zone. Graphically the Fresnel Zones would look like concentric footballs. Odd number Fresnel zones will cancel some of the main lobes, while even number Fresnel Zones will add to it. As the number increases, the reflected energy has to travel further, thus having less destructive capability. As the frequency gets higher the Fresnel Zones get smaller. Therefore, as the frequency gets higher, the clearance from obstructions, such as trees, gets larger.

The path survey needs to be examined to assure that any path obstruction is not within the 1st Fresnel Zone for the greatest reliability. Generally the first 0.6 of the first Fresnel Zone must be clear of obstructions in order to assure a reliable radio path. Objects such as trees, buildings, hills that protrude into the 1st Fresnel Zone will weaken the signal and may prevent reliable communication. The K factors mentioned previously need to be taken into account as they can effectively bend the signal path into the Fresnel Zone.

4.3.5 Reflections

Smooth surfaces such as lakes, flat areas of earth, billboards, or building surfaces can reflect radio signals causing attenuation much in the same way as an object in the Fresnel Zone. Water is especially difficult because it can have a temperature gradient above its surface that can act as a reflector that changes height. It may be necessary to change the path such as raising one site and lowering another to make the path more reliable.

4.3.6 Rain Attenuation

As the frequency increases, particularly above 10 GHZ, rain can cause attenuation. At these higher frequencies, the wavelength is small enough that raindrops approach ¼ wavelength. The National Weather Bureau maintains information stating rain data for various locations through out the United States. The rainfall rate as well as the percentage of the path affected by rain can be used to determination the attenuation factor.

4.3.7 Free Space Loss

Free Space Loss is the loss factor that would exist if the path between the transmitter and receiver were unobstructed. The losses are primarily due to the fact that the beam widens as it travels from the source to the destination. The reference is considered to be two isotropic antennas located at a given distance assuming a given frequency. An isotropic antenna is defined as one that radiates or receives energy uniformly in all directions. Isotropic antennas are used for a reference and any gain from the actual antennas is added when calculating the actual path loss.

4.3.8 The Atmosphere

Oxygen absorbs microwave energy to some extent. The absorption will increase with frequency. Additionally water vapor will contribute to losses.

4.3.9 Antenna Gain

An antenna is capable of focusing its energy in a given direction. The comparison between an isotropic antenna, explained earlier, and the energy focused in the desired direction and angle is called gain. Gain is generally referred to in decibels.

4.3.10 Fade Margin

The fade margin is the general term that describes the quality of the path under normal circumstances. The fade margin describes the margin that the nominal signal has with respect to the level in which the receiver will no longer function. A larger number will allow a greater level of path disturbance while maintaining a usable signal.

The following contribute to the fade margin over the complete signal path:

Transmitter Power Level
Combiner/Hybrid/Coupler Loss
Connector loss
Feedline Loss
Connector Loss
Antenna Gain
Radome Loss (antenna cover)
Free Space Path Loss
Atmospheric Losses
Radome Loss
Antenna Gain
Connector Loss
Feedline Loss
Connector Loss
Combiner/Hybrid/Coupler Loss
Receiver Signal Sensitivity

While a larger fade margin is desirable, there is a minimum for a given situation that will assure that the system will work reliably. If the fade margin is too small, small disturbances like rain, show, beam bending, etc, will disrupt communications. In analog systems the signal at the receiver will become gradually noisy as the level approaches the sensitivity point. With digital systems however, the data quality remains constant until a certain level and degrades quickly as the signal level approaches the receiver sensitivity.

4.3.11 Reliability Factors

There are several factors that affect the reliability of the path. These factors can be stated numerically and used to calculate the expected outage time of the path called the reliability factor. As stated above, the greater the fade margin the more immunity the path will have to these factors. There are various factors that can degrade the path separately or at the same time. These occur randomly, and can vary in degree. The total reliability factor can be used to determine the unavailability or the probability of an outage often referred to as a percentage. In paths employing multiple hops, the total reliability is the sum of each of the unavailability percentage factors and subtracting that figure from 100.

4.3.12 Terrain and Humidity Factor

A factor can be developed based on the roughness of the terrain and the general humidity.
Terrain can range from very smooth land or water to mountainous, rough areas. The humidity can range from high in coastal areas to very dry in desert climates. The factors at given intervals are integrated to come up with one total path factor.

4.3.13 Climate Factor

The nominal temperature for the path can be a factor contributing to the reliability. Gulf coast or tropical environments vs. mountainous areas can be identified.

4.3.14 Path Reliability

Availability and unavailability is stated in terms of a year. A path that is 99.998% available would be unavailable 5.26 minutes per year. The required reliability is very dependant on the application. For protection applications a very reliable path is required. Cost, naturally, comes into play. The formula for propagation unavailability is related to the topographical factor, the climate factor, the frequency, the path length and the fade margin. When it comes to applying radio to Protection, it is important to understand that disruptions due to the path are not related to the risk of a power system fault. The risk of a path issue at the same time as a fault is independent, however they can occur at the same time.

4.3.14.1.0 Path Reliability Improvements

The most basic method of improving the path is to increase the fade margin. This can be done by increasing the transmitter power, receiver sensitivity, using lower loss feedline, higher gain antennas as well as making the path shorter. If all of the above has been maximized then one of the diversity methods can be used.

4.3.14.1.1 Space Diversity

Space Diversity uses two (or more) antennas “listening” to the same signal. The technique works on path disruptions that reflect the beam. Diversity will not offer much improvement in situations where ducting or earth bulge block or steer the signal away from the receiving antenna. The assumption is that one of the two antennas will still receive an adequate signal to operate the system. Two separate feedlines are used to send the signals to separate receivers. The two are separated and fed into associated switching or combining equipment. The resultant is delivery of the best data to the end device. The two antennas are generally mounted to the same structure. The spacing may be in the order of 80 feet at 2 GHz to 30 feet at 11 GHz. This results in more tower expense, as the tower has to support the extra weight of another antenna and feedline. Additionally, the lowest antenna height must be the one used for the path calculations assuring Fresnel clearance. The second antenna is mounted higher. Thus a taller tower will be required. This technique also provides a second receiver that provides redundancy should the primary fail.

4.3.14.1.2 Frequency Diversity

Frequency Diversity utilizes two transmitters operating on two frequencies either in the same frequency band or sometimes two different bands. The reliability improvement comes from the reduced chances of both frequencies fading at the same time. Spread Spectrum radios can take advantage of the fact that the frequencies used are always changing; hence, same band frequency diversity may not provide enough improvement to make the investment worthwhile.

4.3.15 Putting the data together

Either a number or a formula that goes into a series of formulas is used to determine the overall path quality. The material referenced in this section is considered the “bible” for determining path quality. [2]

4.3.16 Summary

There are several factors that can affect the quality of a microwave path. Unfortunately, the gift of a short path working without any engineering effort can give a false sense of security. Since each path differs, it is not possible to define when trial and error is effective and when true path engineering must be done. However, if it is clear that the trial-and-error path is not functioning properly, engineering may show why and identify what to do about it. If the greatest level of reliability is required for protective relaying, engineering should be done.

5.0 Requirements for Successful Operation

5.1 Requirements on relays

Relays that generate encoded messages that can be used for pilot protection are easiest to apply with this technology. Teleprotection devices that utilize digital communication messages or packets are also compatible with this technology. Not all teleprotection systems and radios are compatible. It is best to check with the equipment manufacturers for recommendations and interoperability test results.

5.2 Requirements on teleprotection

All teleprotection communications systems contain noise and /or error detection required to provide optimum security against mis-operations due to noise. Unless specifically accounted for in the radio software, the teleprotection message must be tolerant of the delays associated with packeted communications.

5.3 Requirements on communication

Spread spectrum radios are available from many vendors. These radios operate similar to half duplex modems. Radios that allow setting of the operating characteristics are preferred for teleprotection applications. The following are examples of some typical communication modes and parameters that need to be minimized or disabled via settings or through the use of special firmware:

- Forward error correction
- Message acknowledgement
- Retry or retransmission
- Data buffering

These features are applied to data modems and radios so that they may provide continuous, reliable data. This is important when the data or data packet is sent one time.

Teleprotection systems send continuous packets. These messages are designed so that everything needed is contained in one or two messages or packet. These messages or packets are continuously sent. This continuous transmission allows commands to get through even when one or more of the messages are corrupted. This provides speed, security, and dependability without the use of forward error correction, data buffers and re-transmissions.

Forward error correction introduces a delay at the receiver. Teleportation systems rely on continuous transmission of packets with built in error detection. It is faster to discard an errored message or packet and move on to the next than it is to determine and fix an errored bit or bits.

Message acknowledgment (Ack/Nak) and retransmission are used to keep data reliable. Radios send data between each other with packets. The transmitting radio will hold a packet in a buffer after it is sent. When the receiving radio receives and successfully decodes the packet it sends an Acknowledge (Ack) message back to the transmitting radio causing it to send the next packet. If the receiving radio does not successfully decode the packet it sends a Not Acknowledged (Nak) message back to the transmitting radio. When a Nak is received the same packet is resent for as many times as the number of the retries setting.

This retransmission can cause a trip, guard or analog value that is no longer applicable to the system conditions to be delivered resulting in a mis-operation or failure to operate.

There can be many Spread spectrum radios operating in close proximity to each other. Frequency hopping is used to minimize collision between radios as they switch between frequencies.

5.4 Radio protocols

A common radio protocol used with Ethernet radios is IEEE 802.11b. For security reasons it would not be advisable to use a standard open protocol for protection. Radios with schemes that allow communication only with other radios identified by call book, serial number or some network ID is preferred for this application. Radios that implement these security measures are less likely to be interfered with.

5.5 Speed

Throughput time should always be considered when choosing a transceiver for use with a teleprotection system. Most data transceivers will buffer data introducing throughput delays. It is typical to have 50 to 500 ms of through delay on a data modem. Teleprotection systems need to operate in 20 ms or less in order to be effective. Adding 50 ms of delay defeats the purpose of adding the expense of a pilot channel to a protection scheme.

5.6 Interoperability

The FCC has allocated certain frequency bands for unlicensed operations. In order to promote innovation, competition and efficiency, the rules do not mandate the radio's modulation characteristics.

The FCC regulates the overall effective radiated power; the allowable transmit time per time interval and the interference requirements. By using Spread Spectrum modulation, the system can send more data, faster, with, increased power compared to a single frequency radio using a fixed bandwidth. The interference requirement includes the fact that unlicensed operations cannot cause interference with licensed operations, and unlicensed operations must tolerate any interference from either licensed or unlicensed users.

Because of these requirements, each manufacture has a custom radio system design. In most cases the radio systems between different manufacturers will not be able to communicate with each other. In fact, it is very possible that different model radios from the same manufacturer may not communicate with other. It is also possible that the same model radios may not communicate with each other, or may have an elevated error rate, if they have different hardware or firmware versions. While this may seem like a limitation it actually allows the systems with perfectly matched radios to operate with minimal interference.

Even if multiple manufacturers claim to interoperate, it is wise to stay with the same exact radio type on all sites that communicate with each other. That does not mean that all radios used by a particular user must be the same. The radios on a given path should be the same because each path is independent.

5.7 Standards

The following are some of the popular standards for wireless communications:

- **IEEE 802.11** defines the standard for wireless Local Area Networks (LANs) encompassing three incompatible (non-interoperable) technologies: Frequency Hopping Spread Spectrum , Direct Sequence Spread Spectrum , and Infrared.

- **IEEE 802.11a**: This standard runs at 54Mbps, and devices that use it are more expensive than both 802.11b and 802.11g standard devices. 802.11a uses the relatively uncluttered 5Ghz frequency band, and has a range of around 25-75 feet (7.6 to 23m, approx). 802.11a's big stumbling block is that it's not compatible with any other standard - so you cannot mix and match devices that use this standard and other standards.

- **IEEE 802.11b**: Also known as 'Wi-Fi': Currently the most popular wireless standard out there, it has the advantage of being the cheapest of these three standards. 802.11b runs at 11Mbps, and uses the more crowded 2.4Ghz band, with a range of 100-150 feet (30.5m to 45.7m, approx).

- **IEEE 802.11g**: This is a new standard, with a bandwidth of 54Mbps. It's much cheaper to implement in wireless devices than the 802.11a standard, however it's more expensive than 802.11b. It again uses the crowded 2.4Ghz band, with a range of 100-150 feet (30.5m to 45.7m, approx), and is compatible with 802.11b standards - although when communicating with an 802.11b device, the 802.11g device will only work at 11Mbps.

- **Bluetooth**: Another standard, that is mainly used for Personal Digital Assistants (PDAs) and other mobile wireless devices. It has a very short range of only 33 feet (approx 10m) and uses the crowded 2.4Ghz band. It also has a relatively low bandwidth of only 1.5Mbps compared to other standards. Bluetooth is designed for low-traffic networks, which is why it's being used in devices like wireless mobile phone headsets. It can be useful for transferring files between your PDA, computer, and mobile phone.

- **IEEE 802.15.1** is a Wireless Personal Area Network standard based on the Bluetooth™ v1.1 Foundation Specifications.

- **IEEE 802.15.4** is a standard for low-rate, wireless personal area networks. The standard defines the "physical layer" and the "medium access layer". The specification for the physical layer, or PHY, defines a low-power spread spectrum radio operating at 2.4 GHz with a basic bit rate of 250 kilobits per second. (There are alternate PHY specifications for 915 MHz and 868 MHz that operate at lower data rates, but they're not as popular).

- **ZigBee** builds upon the 802.15.4 standard to define application profiles that can be shared among different manufacturers to provide interoperability.

5.8 Security

Protection schemes that use communications to perform their function involve multiple types of security. From a protection standpoint, the term security is used to describe the freedom from unwanted operations (e.g. false trips). From a communication standpoint, the term security may have multiple meanings. In one case, it describes an assessment of the likelihood that corrupt data, such as that caused by error bursts and data crosses, may pass undetected through communication equipment, resulting in what appears to be good received data. The other perspective involves the undesirable affects of intrusion or evesdropping on the communications channel.

From a communication perspective, spread spectrum radio can be made inherently secure. The technology was developed during World War II and used subsequently by the military because of its ability to reject jamming and the difficulty it presents to the enemy attempting to intercept its transmissions. Having said that, the spread spectrum radio will only be secure if efforts are made to take advantage of its normal propensity for security. One school of thought is that if spreading techniques are random, difficult to detect and kept secret, the radios will be quite secure. This school of thought is based on the rationale that if an industry standard spreading technique is utilized, such as an open architecture that allows multiple manufacturers and types of equipment to all have access, then the inherent security of the radio is lost and other security measures must be put in place. The network industry is continually working on enhancing the security of the wireless network, but whether it is adequate for use in protective relaying would have to be determined by the individual user.

The other school of thought is that security is enhanced if a standard open architecture is used that is tested to ensure its security against known intrusion techniques.

From a protection standpoint, most schemes that rely on communications typically have built-in supervision to prevent unwanted operation during spurious communications security lapses. Directional comparison pilot communication schemes have built-in supervision that requires internal protection elements to operate in conjunction with a received trip signal before the relay can trip. Direct tripping schemes, however, are more susceptible to communications security lapses, and therefore must be treated with more diligence. Using multiple messages, requiring multiple received data bits to change state, or requiring a specific sequence of received bits may offer added protection security.

In general a secure protection scheme can be designed using Spread Spectrum radio communications, with a tested protocol and suitable relay logic.

5.9 Interference Characteristics and Mitigation Techniques

The use of unlicensed frequency bands for power system protection and control is very appealing due to low cost of ISM band transceivers. It is however necessary to keep in mind the original intention of the FCC Part-15 regulations which was to open the ISM band to shared digital communications. It is this sharing that presents the biggest challenge for protective relaying applications. In order to coexist with multiple users, successful spread spectrum products must be able to tolerate the presence of interfering signals within and outside of their operating band.

Our main application challenge is achieving reliable power system protection while exchanging messages over inherently unreliable communication channels. While spread spectrum based ISM band communications are inherently unreliable, they can be made highly available (>99.9% of time) by applying proper path engineering and system design techniques. By taking into account inherent limitations of the individual spread spectrum communication channel and implementing adequate safeguards at the application (protection scheme) level, it is often possible to take full advantage of the low cost unlicensed band technologies.

The choice of spread spectrum modulation technique and its ability to cope with congested RF environment will significantly influence the way in which interference induced problems are presented to the application. At this time, most of the long haul (>1mile) systems are implemented using the FHSS technology, which can detect and adaptively avoid congested parts of the frequency spectrum. Detection and avoidance process results with random frame loss (collisions), which must often be handled at the application level. Frame loss situation is somewhat better in rural areas, and can be significantly improved by using directional antennas.

Instead of relying on interference avoidance like its FHSS counterpart, DSSS technology uses the interference minimization approach. Multiple DSSS systems can operate in the same frequency band with graceful degradation of the overall signal to noise ratio proportional to the total number of simultaneous users. This degradation continues until reaching a definite “jamming margin” at which time DSSS operation gets disrupted. If the interference is short, the system will reacquire synchronization and continue normal operation similar to its FHSS counterpart. Long interference may however result with total communication system failure. This does not necessarily mean that DSSS systems are significantly inferior to their FHSS counterparts, but does bring to light the need to provide continuous real-time communication channel monitoring and the need to make it available to the underlying protection application.

OFDM technology is most commonly optimized for high speed / data throughput. It holds distinct potential for adaptive interference avoidance. OFDM can use extensive forward error correction and redundant data transmissions, thus promising to improve communication channel latency and reliability performance indices. Despite the potential, at the time of this writing, no utility grade unlicensed OFDM systems have been deployed.

Due to the shared nature of the unlicensed communication bands it is impossible to reliably predict amount of interference that will be encountered over the system lifetime. Almost like foliage, the amount of interference can be expected to increase with time as multitude of consumer solutions is introduced into the market. While interference cannot be prevented, it can be continuously monitored and reported, making it possible to act before the situation adversely affects protection system performance.

Short summary of applicable protection system strategies is given below:

- Communication messages must be exchanged continuously and as often as possible (app. every 3 to 16ms) with approximate knowledge of the next message arrival time.
- Communication based protection must be built on top of reliable conventional backup schemes. It should be designed to offer improved performance based on communicated data (available >99% of the time), while retaining autonomous operation based on local measurements.
- Communication channel failure must be detected and acted upon (by momentarily disabling the communication based protection) in the timely manner (individual message failure monitoring). Additional statistics indices documenting actual channel performance need to be collected and should be used for remote indication / alarming purpose.
- Communication channel message corruption must be detected reliably and unambiguously regardless of the type of the corruption mechanism involved. Additional redundancy often needs to be inserted in the message, with authoritative guidance given in IEC 60834-1 (1999)[4].
- Sequence numbers and / or time stamping is necessary in order to reject the inadvertently delayed data frames.
- Depending on system criticality, message authentication methods may be necessary in order to prevent the malicious external attacks. Due to real time nature of protection messages and limited information content, full encryption is often regarded as unnecessary.
- Critical systems, which require high security, or cannot tolerate intermittent communication channels should not rely upon commercial ISM band spread spectrum radio technologies.
- Multiple radio co-location (within the same cabinet, operating on the same or different frequency bands) requires careful planning. It can cause unintended system interactions due to insufficient

shielding, power supply filtering, antenna coupling or leaky antenna feeds. Additional shielding or output power reduction may be required.

6.1 Relay to radio

The most common relay-to-radio interface is RS-232 serial data, however, Ethernet interfaces are gaining some popularity. Another sub-topic is lightning protection of the data interface. There is a lot of attention paid to lightning protection of the antenna system and little paid to the data lines and power supply inputs. This is where we see most of the lightning-related failures in our products.

6.2 Antennas

The single most important item affecting radio performance is the antenna system. Careful attention must be given to this part of an installation, or the performance of the entire system will be compromised. High quality, gain antennas should be used at all master and remote stations. The antennas should be specifically designed for use at the intended frequency of operation.

Antennas are made by a number of manufacturers and fall into two general categories, omni-directional, and directional. An omni-directional antenna provides equal radiation and response in all directions and is therefore appropriate for use at master stations, which must communicate with an array of remote stations scattered in various directions. At remote stations, a directional antenna such as a yagi is typically used. Directional antennas confine the transmission and reception of signals to a relatively narrow lobe, allowing greater communication range, and reducing the chances of interference to and from other users outside the pattern. It is necessary to aim these antennas in the desired direction of communication (i.e., at the master station).

Antennas used for Spread Spectrum Radio application include parabolic dish, yagi, and dipole. Dish and Yagi antennas are directional, so they are typically used in point-to-point radio applications. Dipole antennas are omnidirectional, so they are typically used in short-range multi-point radio applications, or at master stations in multi-point communication systems. Yagi antennas are also polarized, so the orientation of antenna is important.

6.2.1 Yagi Antenna

A basic Yagi antenna, as shown in figure 6-1, consists of several straight elements, each measuring approximately 1/2 the electrical wavelength. The Yagi is inherently a balanced antenna, but is typically fed with coaxial cable. A matching device is used to connect the coaxial cable to the *driven element*.

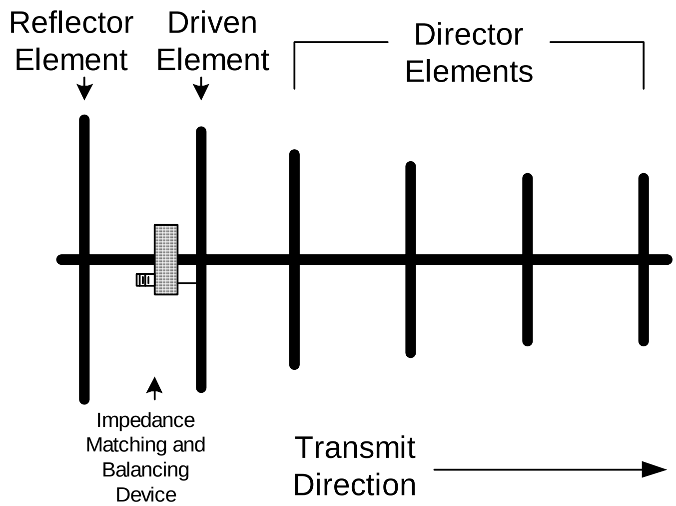


Figure 6-1 Six-Element Yagi Antenna

The driven element of a Yagi is the only element directly coupled to the coax. Parallel to the driven element, and approximately 0.2 to 0.5 wavelengths on either side of it, are straight rods or wires called *reflectors* and *directors*. A reflector is placed behind the driven element and is slightly longer than 1/2 wavelength; a director is placed in front of the driven element and is slightly shorter than 1/2 wavelength. A typical Yagi has one reflector and one or more directors. The antenna propagates electromagnetic field energy in the direction running from the driven element toward the director(s), and is most sensitive to incoming electromagnetic field energy in this same direction.

The Yagi antenna not only has a unidirectional radiation and response pattern, but it concentrates the radiation and response. Figure 6-2 shows the typical directional field of a Yagi antenna. The more directors the Yagi has, the greater the *forward gain*.

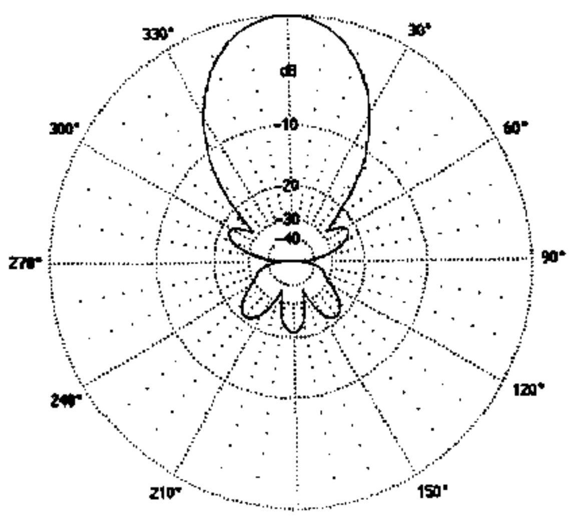


Figure 6-2 typical radiation pattern of a Yagi antenna

6.2.2 Antenna Installation

Spread spectrum radios are line of sight systems. Line of sight in this case is not defined as a straight line between two points, but rather a three-dimentional area between two points defined as the Fresnel (fre-`nel) Zone. The Fresnel Zone can be viewed as a signal cone surrounding the entire radio path with the largest diameter in the center between the two antennas as shown in figure 6-3. See 4.3.4 and 9.3 (ii) for more details on Fresnel Zones.

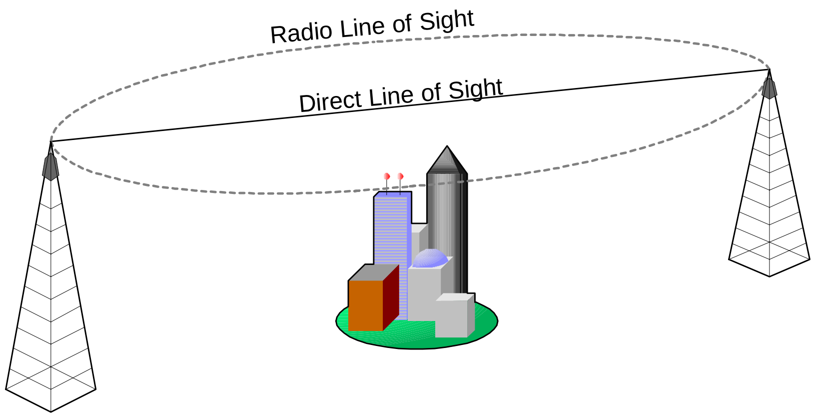


Figure 6-3 Radio Line of Sight

For a reliable link 60% or greater of the Fresnel zone needs to remain clear of obstructions.

6.2.2.1 Yagi Antenna Mounting

When more than one Yagi antenna are pointing within 45 degrees of each other, rotate the antenna orientation by 90 degrees with respect to each other to minimize interference. Maintain 4 to 10 feet of vertical seperation on the antenna tower as well, as shown in figure 6-4.

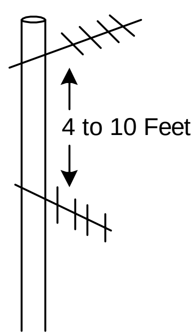


Figure 6-4 Yagi antenna mounting

6.2.3 Evaluating Path Quality

Except for short-range paths that can be visually evaluated, a path study is generally recommended for new installations. A path study predicts the signal strength, reliability and fade margin of a proposed radio link. While terrain, elevation and distance are the major factors in this process, a path study must also consider antenna gain, feed line loss, transmitter power, and receiver sensitivity to arrive at a final prediction.

Path studies are normally performed by a communications consultant or a system integrator who uses topographic maps or a software program to evaluate the feasibility of a proposed path. Computer-assisted studies have become very popular in recent years and greatly simplify the process of path planning. Although path studies provide valuable assistance in system planning, they are not infallible. It is difficult, for example, to consider the effects of man-made obstructions or foliage growth without performing an actual on-the-air test. Such a test can be done using temporarily installed radio equipment.
Ideally, a radio site will provide enough natural elevation to clear surrounding terrain without the need for a tall antenna tower. In these cases, the station antenna can often be mounted to a short mast and affixed to the equipment building or to an existing utility pole. If site elevation is not sufficient, a tower or other support structure must be used to raise the antenna above surrounding obstructions.

How strong is strong enough?
The strength of radio signals in a well-designed system must exceed the minimum level needed to establish basic communication. This excess strength is known as the fade margin, and it compensates for variations in signal level, which may occur from time to time due to foliage growth, minor antenna misalignment, or changing atmospheric losses.
While the required amount of fade margin differs from one system to another, experience has shown that a level of 20 to 30 dB above the receiver sensitivity threshold is sufficient in most systems. Manufacturers of radio telemetry products often provide a means for direct measurement of received signal strength using a DC voltmeter, terminal, or diagnostic software. Consult equipment manuals for details.

6.2.4 Antenna Mounting Considerations

The antenna manufacturer's installation instructions must be strictly followed for proper operation of a directional or omni-directional antenna. Using the proper mounting hardware and bracket ensures a secure mounting arrangement with no pattern distortion or de-tuning of the antenna. Mount the antenna in the clear, as far away as possible from obstructions such as buildings, metal objects, dense foliage, etc. Choose a location that provides a clear path in the direction of the associated station. The end of the antenna (furthest from the support mast) should face the associated station. Final alignment of the antenna heading can be accomplished by orienting it for maximum received signal strength. Most radio equipment includes provisions for measuring signal strength.

Polarization of the antenna is important. Systems that use a vertically polarized omni-directional antenna at the master station must use vertically polarized (elements perpendicular to the horizon) remote antennas. Cross-polarization between stations can cause a signal loss of 20 decibels (dB) or more.

6.2.5 Feed lines

The importance of using a low-loss antenna feed line is often neglected during radio installation. Using the wrong cable can cause huge reductions in efficiency and these losses cannot be recovered with any amount of antenna gain or transmitter power. For every 3 dB of feed line loss, half the transmitter power will be lost before reaching the antenna. To illustrate the importance of this loss, consider the following: At 950 MHz, a 100-foot/30.5m length of RG-8A/U coaxial cable (commonly used at VHF and lower frequencies) introduces a loss of about 8.5 dB. A 5 Watt transmitter operating into such a feed line would produce only 700 milliwatts at the antenna, and a similar loss in receive sensitivity would occur.

On the other hand, a 100 foot/30.5m length of 7/8 inch semi-rigid coaxial cable operating under the same conditions will introduce only 1.28 dB of insertion loss, and will deliver 80% of the transmitter's power to the antenna.

The choice of which feed line to use depends on: the length of cable required to reach the antenna, the amount of signal loss that can be tolerated, and cost considerations. For long-range transmission paths, where signals are likely to be weaker, a low-loss cable type is recommended, especially if the length of the cable must exceed 50 feet/15m. For a short-range system, or one that requires only a short antenna feed line, a less efficient cable may be acceptable, and will cost far less than large diameter semi-rigid cable.

6.3 Repeaters

Repeaters, as their name implies, are devices placed at intermediate locations along the communications path to receive and re-transmit, or repeat, the communications signal. Repeaters may be used to extend the communications path length, or route the path around known obstructions. To fulfill their function, they need the same utilities as any other radio terminal; namely, power supply and antenna mounting structure. The installation is typically comprised of two transceivers and two associated antennas, one for each direction along the communications path.

Repeaters will add to the overall communications signal delay, which will degrade the performance of high-speed protection schemes. However, they may be necessary for the successful operation of the communications system.

6.4 Power supply

Typically, Spread Spectrum radio transceivers must be supplied by a power source that meets the following criteria:

Transceiver Power Requirements	
Operating Voltage(s):	6-30 Vdc Total Operating Range
Typical Nominal Voltage(s):	6, 12, 13.8, 14.5 and 24 Vdc
Transmit Current (TX):	< 500-700ma @Nominal Voltage
Receive Current:	< 100-125ma @Nominal Voltage
Idle Current:	< 30-65ma @Nominal Voltage

The requirements listed in the preceding table are not all inclusive. Therefore, it is recommended that you consult with the respective transceiver manufacturer for specific power requirements for each individual manufacturer’s model of Spread Spectrum radio transceiver.

Power supplies are critical to the operation of the radio, when applied for power system protection applications. DC power supplies are prefered, although AC power supplies may be used if supplied by an Uninterruptible Power Supply (UPS). Most existing radio power supplies operate from 6 to 30 volts DC. Many utility and industrial substations have 48 vdc or 125 vdc battery systems. Some radio manufacturers are may offer optional 48 or 125 vdc power supplies. If not, dc-dc voltage convertors may be required to power the radios from the substation battery systems.

Power supplies on radios used for power system protection applications should meet the new IEEE Standard 1613-2003, "Standard Environmental and Testing Requirements for Communications Networking Devices in Electric Power Substations". This standard uses the environmental requirements for relays specified in IEEE Standards C37.90.1, “IEEE Standard for Surge Withstand Capability (SWC) Tests for Relays and Relay Systems Associated with Electric Power Apparatus”, C37.90.2, “IEEE Standard for Withstand Capability of Relay Systems to Radiated Electromagnetic Interference from Transceivers”, and C37.90.3, “IEEE Standard Electrostatic Discharge Tests for Protective Relays”. Using the same rigid standards as those for protective relays applied in utility applications will help to ensure robust operation even when exposed to severe conducted and radiated transients and electromagnetic interference.

6.5 Settings, Programming, Diagnostics

Network diagnostics is an important tool for identifying and troubleshooting radio problems. There are certain parameters that at a minimum should be provided as part of the diagnostics program for each radio site. These are received signal strength, noise level, percent receive rate, operating temperature, and operating voltage. For simple point-to-point networks like those typically used in protective relaying, these parameters are usually sufficient. Radio current draw and antenna Voltage Standing Wave Ratio (VSWR) may also be provided. For more elaborate networks, like those used in SCADA, there are many other parameters that are needed for proper network management. Controlling the settings of network radios remotely is also possible with some diagnostics software.

Some manufacturers do not require any special software to program their radios. These radios use simple dumb-terminal emulation programs, such as HyperTerminal, which is included in most Microsoft Windows operating systems. PDAs are often used for radio programming when in the field. At least one manufacturer is releasing a radio configuration utility that provides enhanced capabilities, including the ability to store, recall and download radio-setting files.

7.0 Economics

7.1 Intersubstation applications

Spread spectrum radio communication offers significant opportunities for economical intersubstation communications-assisted protection. Spread spectrum radios can be installed with power supply, coaxial antenna lead, and simple Yagi antenna for a few thousand (US) dollars per terminal.

The single most significant cost item may be the antenna mount. In some cases, the antenna can be tripod mounted on the control house roof, or attached to an existing substation structure for very little cost. A separate pole or tower may be required to establish the height and direction needed for proper signal propagation and line-of-sight operation, adding to the overall installation.

In comparison, fiber optic ground wires cost about US $25,000 per mile, installed; power line carrier coupling devices, transceivers, and wave traps may cost US $50,000 or more per terminal, installed.

7.2 Intrasubstation applications

Spread spectrum radios potentially reduce or eliminate the cost of some hardwired connections in power system substations. These cost savings may potentially be greater in open type substations with outdoor breakers, busses, and transformers. Small dipole antennas, placed on the substation control house roof, and on individual outdoor cabinets could provide sufficient signal strength to permit radio-based communication for protection applications. Indoor applications, with metal enclosed or metal encapsulated switchgear may offer greater challenges because of the difficulty in creating signal paths through the metal switchgear cabinets.

8.0 Examples

8.1 Intersubstation

8.1.1 Intersubstation Direct Transfer Trip Application

An open breaker transfer trip scheme was installed between the utility XYZ substation and ABC processing plant as shown in Figure 8.1.

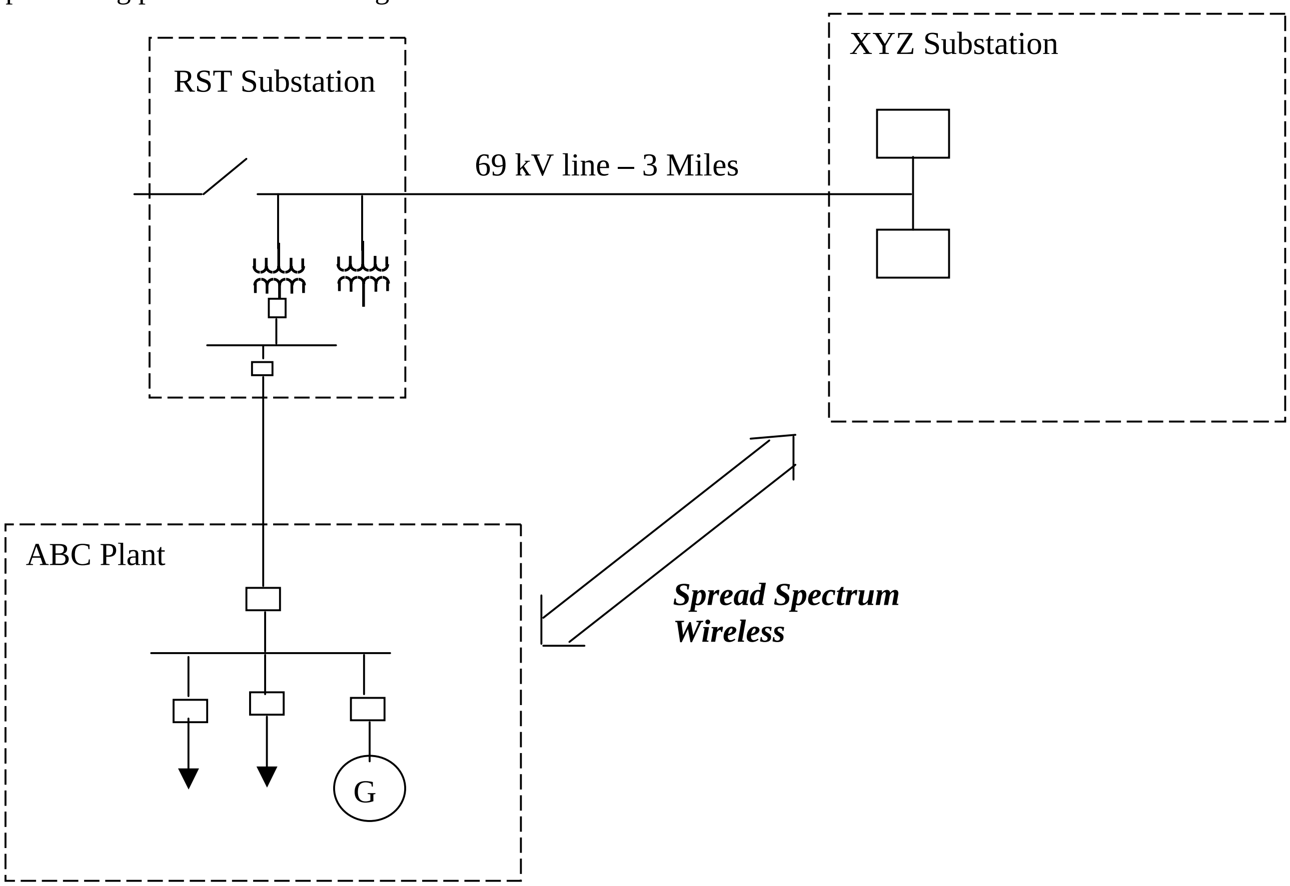


Figure 8.1 System diagram for open breaker direct transfer trip scheme.

The distance between two sites is about three miles and preliminary study indicated that a 30 ft antenna at both ends would provide good communication path between the sites as indicated in Figure 8.2. The height of the actual antenna at ABC plant is about 150ft.

The ABC Plant installed 14 MVA generator to support their load. On loss of the 69 kV source to RST substation, the interconnection breaker at the customer site is tripped after 2 seconds if their generator is on-line. The communication system uses 900 MHz Spread Spectrum Radios to communicate between the two sites.

The scheme was installed in December 2002 and has operated properly without any problems.

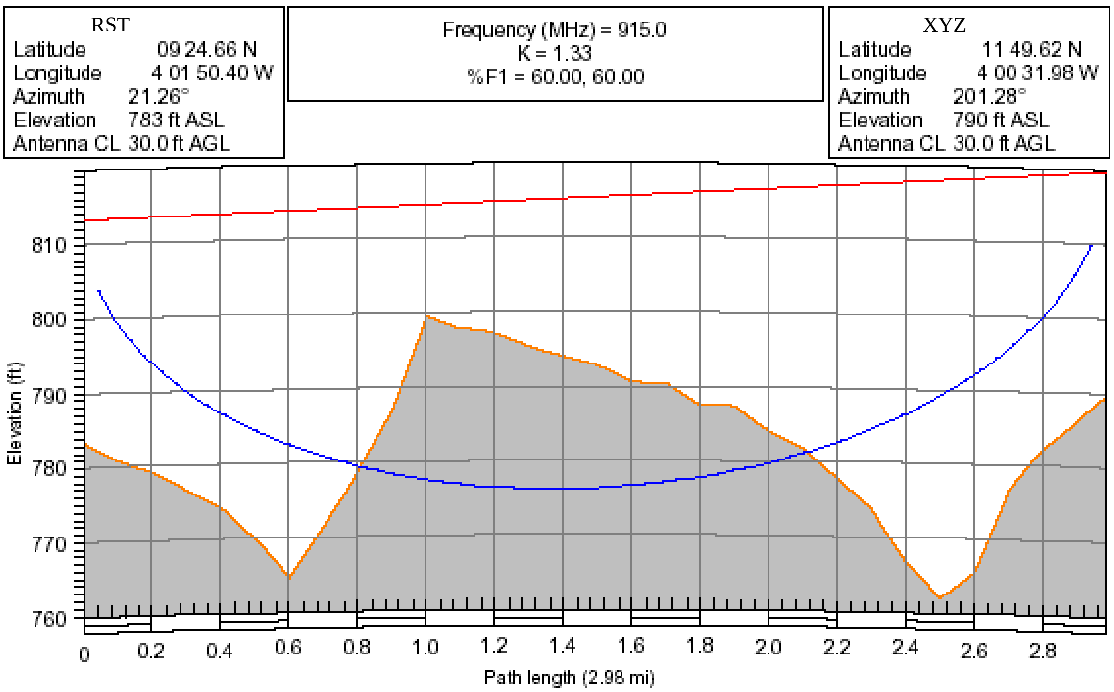


Figure 8.2 Profile of the path between the two sites

8.1.2 DTT and POTT Application

In 1996, one major utility was forced to abandon certain microwave frequencies when the federal government auctioned off these frequencies to communication companies. Spread Spectrum Communications was selected to replace the previous communications schemes at selected locations.

Two point-to-point applications were implemented at three locations, as shown in figure 8-3. The radios use the 2.4 GHz range and have a one watt output. The channel delay time has not been recorded but the manufacturer specifications list an acquisition time of 500 microseconds and transmission delay of 50 microseconds (radio only) and 100 microseconds (10 mile path).

One application is bi-directional direct transfer trip on two lines between two locations (AV to DS). Transfer trip is initiated by relaying such as breaker failure which keys two signals to the remote end of the affected line. The distance is about 8.9 miles.

The other application is permissive transfer trip between two locations (AV to LR) of two parallel three terminal lines. Line relaying at LR initiates sending a permissive signal to AV for the faulted line. Line relaying at AV and the reception of the permissive signal (via microwave) from FW initiates sending a permissive signal to LR for the faulted line. Line relaying at AV and the reception of the permissive signal from LR initiates sending a permissive signal to FW for the faulted line. One terminal (LR) also sends direct transfer trip to the other end (AV). Transfer trip is initiated by breaker failure at LR which keys two signals to AV. The distance is about 4.4 miles.

The scheme has been in operation since 1996 without any misoperations.

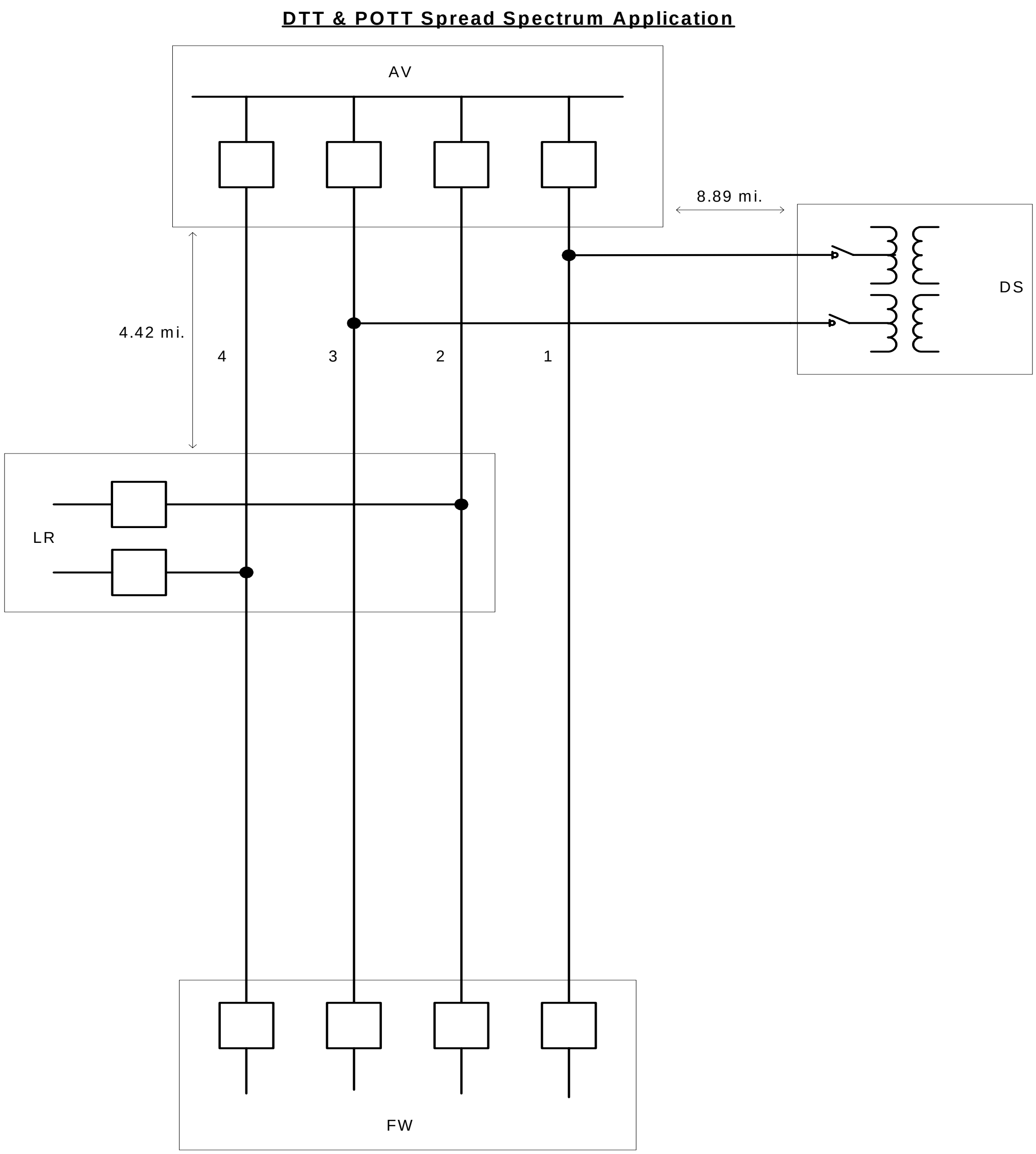


Figure 8-3 One line diagram of the Transfer trip scheme using Spread Spectrum Communications

8.1.3 Utility Experience Using Spread Spectrum Radios For Protection Systems

A power utility company starting utilizing unlicensed 2.4 GHz spread spectrum radios to replace long copper communications cables where high ground potential rise or difficult terrain were problems. The experience with the spread spectrum radios for cable replacement was generally successful. The first cable was replaced with spread spectrum radios in 1996. A total of four cables met the criterion for spread spectrum radio replacement and have been replaced due to age and deterioration. Only one of the four spread spectrum radio systems carried a protection signal and this was a blocking signal in a DCB scheme applied on a 230kV transmission line.

With the western energy crisis of 2001 the company attempted to meet its market demands with the purchase and rapid construction of a 124MW natural gas turbine power plant. The power plant was to split an existing 138kV transmission line currently utilizing a DCB scheme over power line carrier. The existing SKPR-MNJ1-ELMR 138kV line would become two 138kV transmission lines. One line would become the two terminal SKPR-DNPR 138kV line of approximately 24 miles and the other line, the DNPR-ELMR-MNJ1 138kV line, would be a three terminal line with a 2 mile leg from DNPR to ELMR and a 4.7 mile leg from ELMR to MNJ1.

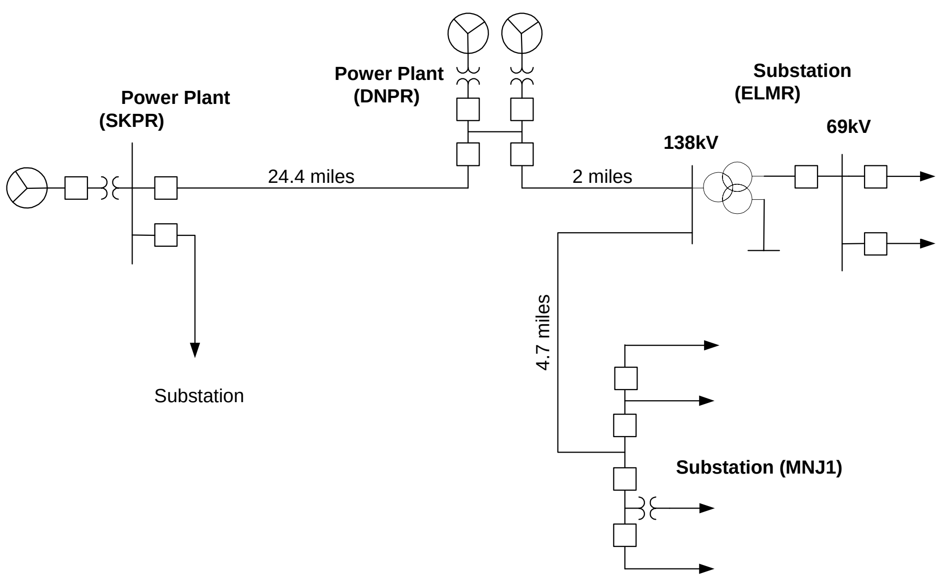


Figure 8-4: Power system single line diagram, addition of the DNPR Power Plant

8.1.3.1 Implementation of Spread Spectrum Radios

The System Protection engineers planned to implement standard line protection packages of dual multi-zone distance relays at each terminal and utilize the digital relay-to-relay communication technology in a POTT scheme. The existing line protection at the SKPR, ELMR, and MNJ1 would be upgraded to match the new line protection to be constructed at DNPR. A communications system that could be deployed rapidly to meet the 8 to 10 weeks construction schedule posed a significant problem. The communications systems identified to meet the POTT communications needs were leased lines, spread spectrum radios, a licensed microwave system, or a fiber optic system. The licensed microwave system and a fiber optic system were ruled out due to cost and construction time. The unlicensed spread spectrum radios seemed to fit the construction speed requirements to meet the construction schedule and allowed the utility to assure performance over the communications path. The communications engineers developed a plan to integrate the various communications systems to allow the protective relays on each end of lines to communicate with each other.

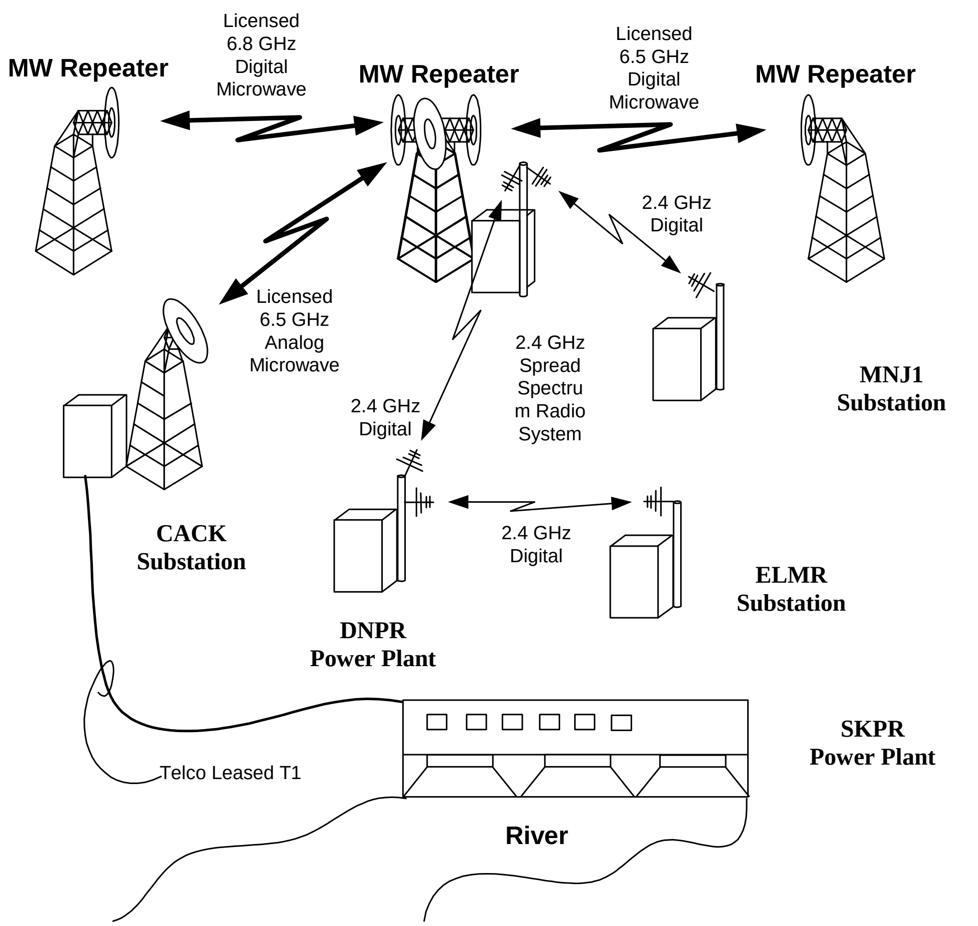


Figure 8-5: Communications system diagram

The spread spectrum radio system, which was built and integrated into an existing licensed microwave system, is drawn above. The system allows the DNPR relays to transmit data signals on two separate and isolated circuits. The common equipment in each circuit is the hot-standby spread spectrum radio and the digital communications channel bank. The digital communications channel bank has been configured with redundant power supplies and redundant DS-1 and subrate interface cards.

The data message for the two-terminal DNPR-SKPR line travels from DNPR to MHMW Microwave Repeater Station (MHMW) via the 2.4 GHz spread spectrum radio where the data is routed to the MHMW-CACK 6.5 GHz analog microwave system. At the CACK station the message is placed on the local telephone company's T1 circuit that terminates at the SKPR. The SKPR relays interpret the receive data message and constructs the transmit data message to be transmitted back to DNPR via the same path in the reverse order.

The DNPR-ELMR-MNJ1 communications path and routing is a little more complicated due to the three terminal transmission line and the direction between the three terminals. Two communications circuits are required for the dual distance relays that are applied for line protection. Each of the two communications channels corresponds to a set of three relays, one located at each terminal of the three terminal transmission line. Each of the two communication circuits transmits the data messages in an opposite circular fashion.

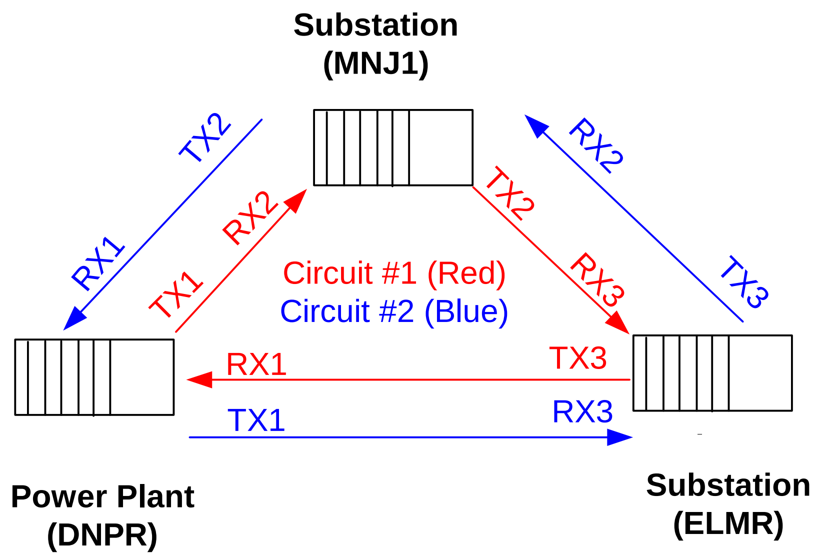


Figure 8-6: Conceptual communications signal routing

Circuit #1 transmits the data message from DNPR to MNJ1, from MNJ1 to ELMR and finally from ELMR back to DNPR. Circuit #2 transmits the data message from DNPR to ELMR, from ELMR to MNJ1and finally from MNJ1 back to DNPR. The programming of the relay is such that the local relay interprets the second bit of the received data message as permission from the other two terminals of the three terminal line. Each local relay constructs the individual transmit message bits (TMBs) in the following fashion:

TMB1= KEY + YT, where YT=!52a (Open PCB keying)
TMB2=(KEY*LP3)+(YT*LP3), where LP3=RMB1

Thus at each end the corresponding receive message bits (RMBs) are:

RMB1=LP3, Permissive signal received from previous station in the circle
RMB2=PT, Permissive signal received from the other two stations

The first communications path, starting at DNPR, starts with the distance relay constructing the transmit message and issuing that data message to Port 2 of the relay which has an analog modem connected to it. The analog modem is wired to an analog to digital card in the digital communications channel bank that has a T1 connection to both the DNPR-MHMW and the DNPR-ELMR hot standby 2.4 GHz spread spectrum radios.

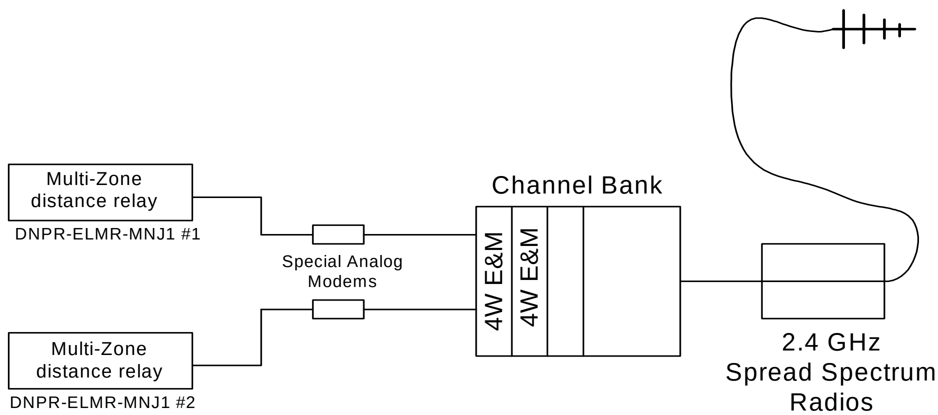


Figure 8-7: Protective relay and communications interface

At MHMW the received data message is routed through a digital communications channel bank to the MHMW-MNJ1 2.4 GHz spread spectrum radios where the message is transmitted to MNJ1. The data message is received by the spread spectrum radios at MNJ1 and routed to a digital communications channel bank with a digital to analog card. The data message is then routed to the analog modem connected to the distance relay and the relay interprets the received data message. The MNJ1 distance relay constructs the transmit data message and sends the data message back to MHMW via the same path by which it was received.

The data message from MNJ1 is transmitted back to MHMW where it is rerouted to the DNPR-MHMW radio via the channel bank. The data message is routed via the digital communications channel bank at DNPR to the DNPR-ELMR 2.4 GHz spread spectrum radio where it is transmitted to ELMR. The data message is received by the spread spectrum radios at ELMR and routed to a digital communications channel bank with a digital to analog card. The data message is then routed to the analog modem connected to the distance relay and the relay interprets the received data message. The ELMR distance relay constructs the transmit data message and sends the message back to DNPR via the same path by which it was received.

The data message is received by the spread spectrum radios at DNPR and routed to a channel bank with a digital to analog card. The data message is then routed to the analog modem connected to the DNPR distance relay and the relay interprets the received data message.

The second communications path follows a similar circular loop but in the opposite direction of the first communications path as shown in the conceptual signal routing, Figure 8-6.

8.1.3.2 Problems

The startup of the spread spectrum communications system revealed two problems with the original installation: 1) transmission delays of the permissive signal and 2) an unacceptable level of outage time. The distance relays monitor the communication channel for data errors and communication outages. The distance relays provided a communication log that indicated a frequent loss of communications. Satellite end to end testing revealed a time delay of the PT signal that was longer than expected.

The time delay for high speed tripping, from fault initiation to receipt of permission from both remote terminals, was measured during satellite end to end testing and found to range from 2.3 to 4.75 cycles depending on fault type and location. The delay through the analog modems was specified to be 12 ms, or less, @ 9600 baud from input to output of a back-to-back connected modem pair. Thus the expected time delay through the all three analog modems is 24 ms (1.44 cycles) for the PT signal on this three terminal line configuration. The expected tripping time via PT signal is the sum of the relay decision time, 1.25 cycles, plus the total analog modem time, 1.44 cycles, plus the channel delay of 1ms for a total estimated time delay of 46 ms or 2.75 cycles.

The communications engineers felt that the speed of the system could be improved by changing how the PT signal was sent to the remote terminals. It appeared that routing the RS-232 digital message directly to a Sub Rate, SRU, card in the digital communications channel bank, eliminating the analog modem, could reduce the delay of the PT signal. The SRU card has a back to back through put time of 6 ms, half of the time of the analog modem. Thus the analog modems were removed and the electric interface to the digital communications channel bank changed from the 4W E&M card to the SRU card, eliminating the conversion of the RS-232 signal to an analog signal. The reduction in propagation time in the communications scheme is assumed to be at least 12 ms. Testing has not been performed to confirm this time reduction.

The protection engineers also felt the programming of the protective relays could improve the clearing speed at DNPR Power Plant and at MNJ1 Station. The 138kV/69kV autotransformer at ELMR is protected with a differential relay scheme that activates a direct transfer trip (DTT) scheme to trip DNPR and MNJ1. This allows the zone 2 protection elements at DNPR and MNJ1 to be set to reach beyond the ELMR 138kV bus but short of the ELMR 69kV bus. The transformer protection direct transfer trip (DTT) scheme is implemented to ensure that the line is tripped for a transformer fault at ELMR. Recognizing that the permissive signal from the ELMR terminal was not required at DNPR and MNJ1, the speed of the communications assisted tripping was shortened. Relay system #1 and its communications system shorten the MNJ1 communications assisted tripping time by eliminating the requirement to wait for the ELMR permissive receive signal to propagate through the communications system. Likewise, relay system #2 and its communications system will speed up the DNPR communications assisted tripping. The reduction in tripping time at MNJ1 and DNPR is approximately 6 to 8 ms. The ELMR terminal must still wait for both MNJ1 and DNPR permissive signals to be allowed to trip high speed for faults on the line.

The frequency and duration of the loss of communications was more than the protection engineers felt was acceptable for a permissive relaying channel. Two hundred and fifty-five errors were recorded on each of the dual primary protection packages within a 56-hour window with the highest amount of the errors determined to be re-syncing errors with outages just under a minute long. A few parity errors, data errors, and framing errors were also recorded. The communications logs from the protective relays demonstrate the problems that were encountered.

In November of 2001 the Western System Coordinating Council, WSCC, Relay Work Group and Telecommunications Work Group produced a guideline for the WSCC (the WSCC changed its name to Western Electric Coordinating Council, WECC, in 2002) members to adhere to when designing communications systems for protection schemes. The following table identifies the availability numbers that a communications schemes must have to meet the WECC guidelines.

The following table is Table 2 from the Performance Table section of COMMUNICATIONS SYSTEMS PERFORMANCE GUIDE FOR PROTECTIVE RELAYING APPLICATIONS November 21, 2001

Table 8.1 Functional Availability and Redundancy Requirements

Class	Circuit Application	Minimum End-to-End Functional Availability
1	A bulk power transmission line or RAS requiring totally redundant protection systems	99.95% 265 outage minutes per year One 24-hour outage every 5.4 years
2	A bulk power transmission line or RAS not requiring totally redundant communication and protection systems	99.5% 44.8 outage hours per year Redundancy may be used to achieve this availability
3	A non - bulk power transmission line that may require communications protection to satisfy power quality or other requirements of a given utility or customer	95% 438 outage hours per year Redundancy may be used to achieve this availability

The communications logs from the DNPR relays are shown below to help identify the frequency of the communications errors and availability numbers.

```
DNPR-ELMR-MNJ1 PRI 1          Date: 09/10/01    Time: 07:17:26.520

Communication Channel Error Summary

For 09/07/01 23:04:46.996 to 09/10/01 07:17:26.520

    Total failures    255              Last error: Re-sync
    Relay disabled      0
    Data error          3              Longest failure: 0 00:00:56.927
    Re-sync           251
    Underrun            0              Unavailability   0.001116
    Overrun             0
    Parity error        1
    Framing error       0
```

The availability number for this Class 2 circuit is 99.88, which meets the guidelines produced by the WECC RWG and the TWG.

```
DNPR-ELMR-MNJ1 PRI 2          Date: 09/10/01    Time: 07:18:59.825

Communication Channel Error Summary

For 09/07/01 21:26:19.515 to 09/10/01 07:18:59.825

    Total failures    255               Last error:  Re-sync
    Relay disabled      0
    Data error          7               Longest failure:  0 0:00:57.344
    Re-sync           181
    Underrun            0               Unavailability   0.001114
    Overrun             0
    Parity error       56
    Framing error      10
```

The availability number for this Class 2 circuit is 99.888, which meets the guidelines produced by the WECC RWG and the TWG.

It should be noted that the performance of the spread spectrum radio system met the guidelines produced by the WECC; however, it is unsettling to see errors in the communications system longer than just a few seconds.

The communications engineers re-examined antenna azimuths, and radio settings to try to reduce the resynchronization errors that were being recorded. A key concern was that the antenna azimuths were within 25 degrees to one another at the DNPR site as well as the MHMW site.

Shown below is the DNPR to MHMW spread spectrum radio path. The antenna, transmitter, and receiver data for each site is included in the small boxes.

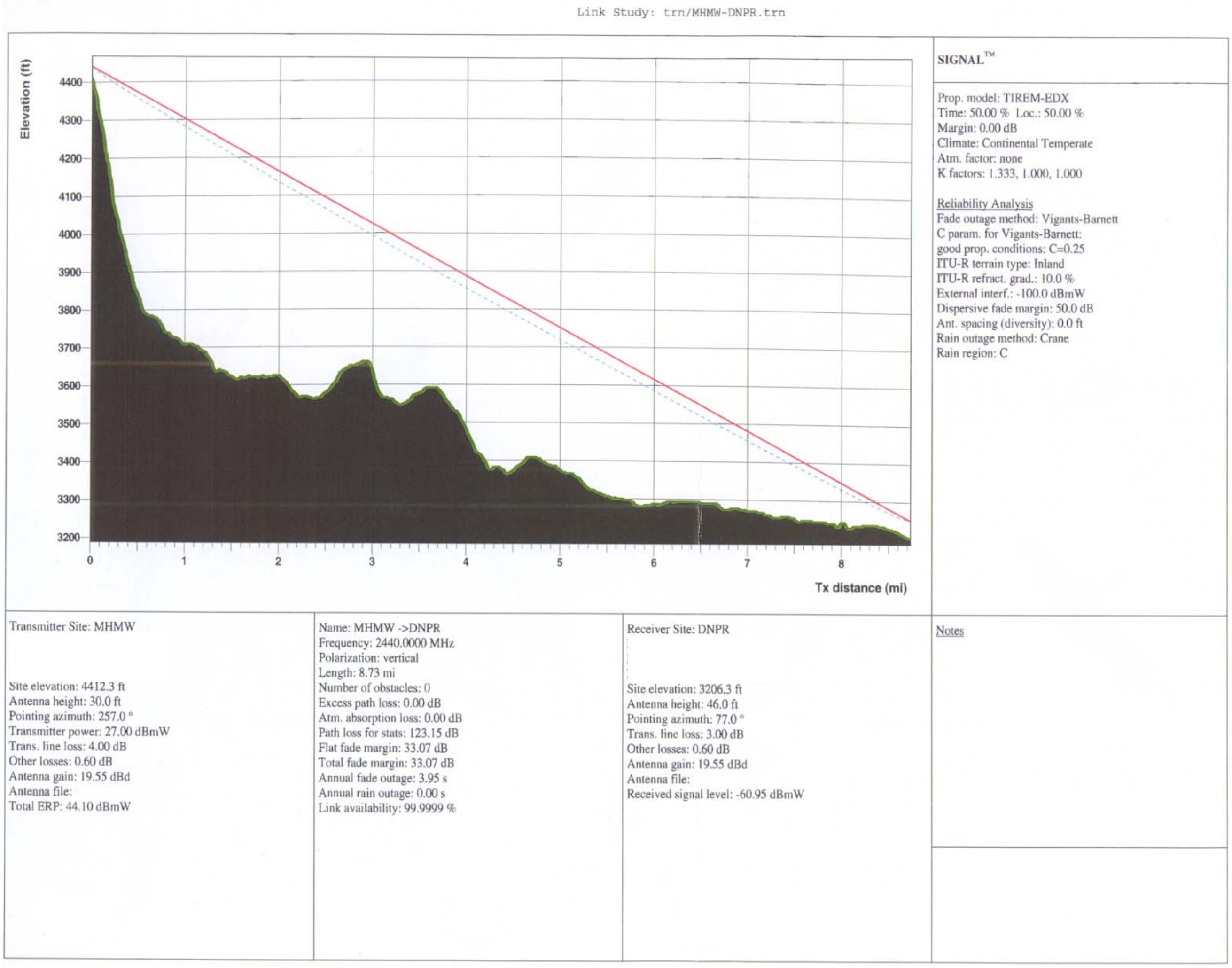


Figure 8-8: Computer Analysis Study Results of DNPR-MHMW radio path

Notice that the path is fairly short at just under nine miles, has a high availability number, and has a good fade margin. The fade margin on this path is 33 dB; meaning the transmitted signal can sustain a loss of 33 dB and the receiver for the path will operate at a 10^{-6} bit error rate. The difference in antenna azimuth at DNPR between the DNPR-MNHW path and the DNPR-ELMR path is 93.1 deg – 77 deg = 16.1 deg. The polarization of the DNPR-MNHW path is vertical and the DNPR-ELMR path polarization is horizontal.

Shown below is the DNPR to ELMR spread spectrum radio path. The antenna, transmitter, and receiver data for each site is included in the small boxes.

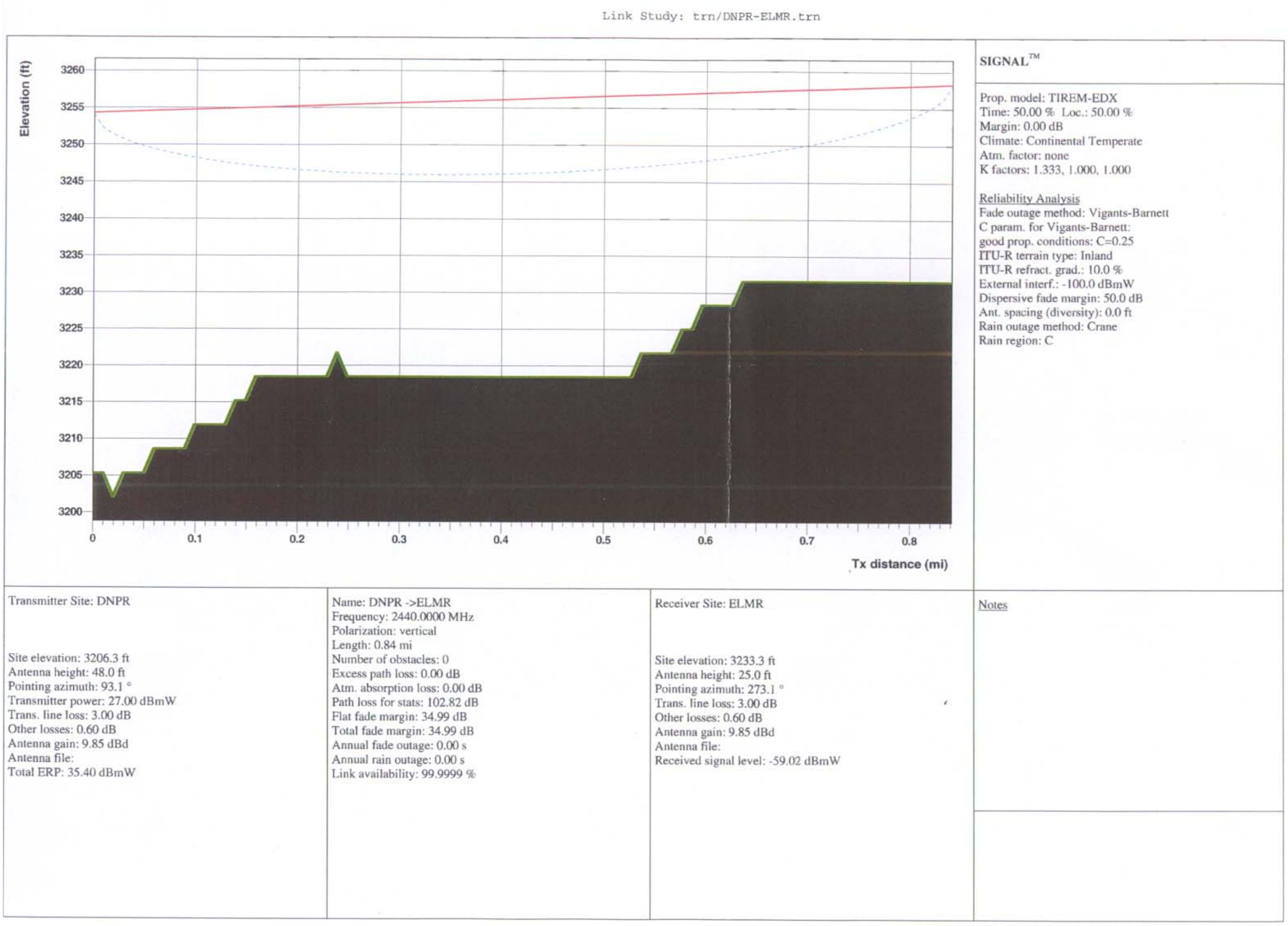


Figure 8-9: Computer Analysis Study Results of DNPR-ELMR radio path

Notice that the DNPR-ELMR path is very short at just under one mile, has a 35 dB fade margin, and a high availability number.

This path was originally designed and built using yagi antennas at both the DNPR and the ELMR locations. To try and improve the isolation between the two adjacent radios the antenna were changed to flat panel antennas. The hope was that the flat panel antenna’s radiation pattern in the vertical direction would reduce some of the interference. After the installation was complete the communication engineers feel that this modification had resulted in only a small improvement.

Shown below is the MHMW to MNJ1spread spectrum radio path. The antenna, transmitter, and receiver data for each site is included in the small boxes.

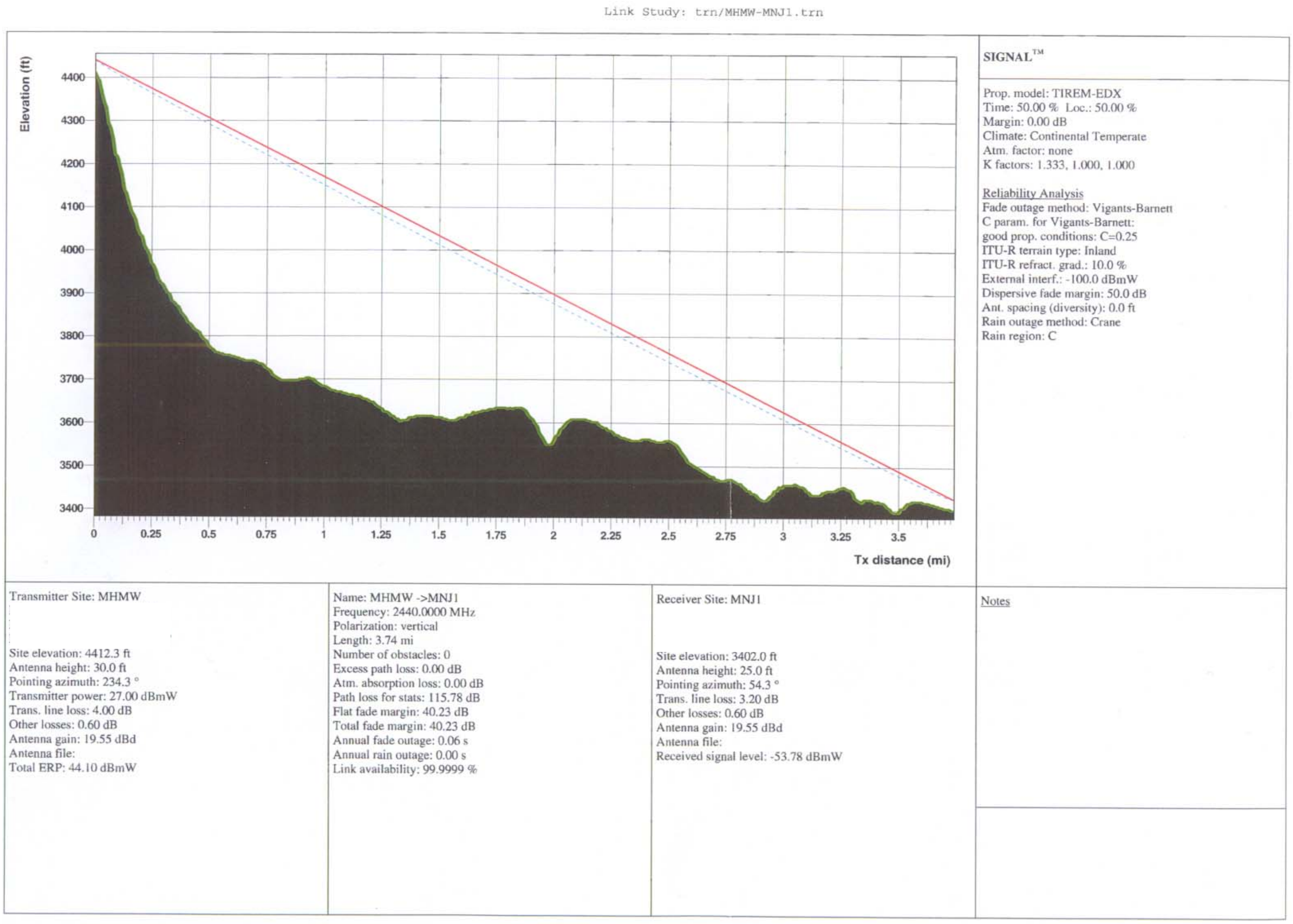


Figure 8-10: Computer Analysis Study Results of MHMW-MNJ1 radio path

Notice that the MNHW-MNJ1 path is short at just under four miles, has a 40 dB fade margin, and a high availability number. The difference in antenna azimuth at MNHW between the MNHW- DNPR path and the MNHW-MNJ1 path is 257.0 deg – 234.4 deg = 22.6 deg. The polarization of the DNPR-MNHW path is vertical and the MNHW-MNJ1 path polarization is horizontal.

The communications engineers determined that the transmitters of the radios at the same site were interfering with the adjacent receivers. This led the engineers to change the radio frequencies to try to eliminate interference from the adjacent radio. In the figure below the spread spectrum radio frequencies listed first are the frequencies that where initially used. The bold text indicates radio frequencies that were changed on each path. Once the frequencies were changed, the resynchronization problems were reduced but not completely resolved.

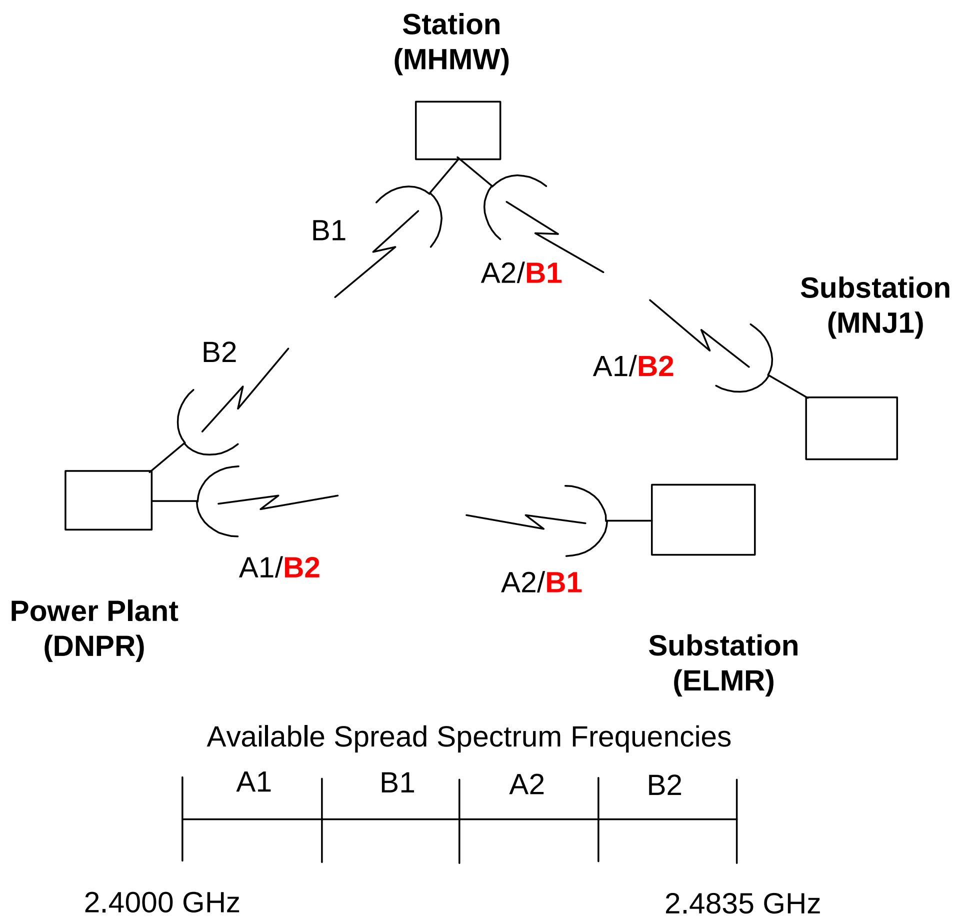


Figure 8-11: Spread Spectrum Radio System and Radio Frequency Selections

8.1.3.3 Conclusion

The communications system that was built in conjunction with the new Power Plant has provided valuable experience with spread spectrum radios and the problems that can be encountered. This installation has met the need of the utility to provide telephone communications, SCADA circuits, data circuits and communications for the protection of transmission lines. Although spread spectrum radios have provided an inexpensive alternative to conventional communication systems employed by utilities it does not come without its problems. The spread spectrum radio system chosen is an unlicensed radio system in which interference from another user is always a potential risk. Many times these problems can be resolved through coordination with other users; however, the risk of interference must be considered and weighed carefully.

8.2 Intrasubstation

The working group was unable to find examples of power system applications using Spread Spectrum radio within the confines of a substation.

Appendices

Appendix A.1 Related Activities

- UTC UTILITY WIRELESS APPLICATIONS TASKFORCE
- IEEE PSRC H5 Peer-to-peer Communication

Appendix A.2 Hyperlinks

http://www.conformity.com/0008emc1.html

http://www.airlinx.com/index.cfm/id/1-13.htm

Appendix A.3 Path Engineering Considerations and Example

i. Site selection

Microwave (M/W) path engineering is as much an art as it is a science in many respects. Fortunately most of what will be encountered in the most path engineering efforts can be described mathematically and usually a reasonable answer can be found to most path anomaly episodes. The art is to be able to predict what characteristics (or anomalies) are governing on any potential path route and to design safeguards that will mitigate outage causing scenarios. Site selection is important and where choice is permitted the path designer needs to pay attention to siting issues such as site elevation above mean sea level (AMSL), soil suitability for tower or pole placement, zoning, etc.

For most applications site locations are fixed in that communications are required between an existing substation and a customer's new generator location. Therefore, under this scenario, the designer may only be able to influence the location of the most inexpensive antenna placement within the sites. Should repeater sites be necessary however, the opportunity to create two operational friendly paths would be the goal so that overall circuit availability meets operating expectations.

At the substation as well as at the generator the most preferable location is next to the control house adjacent to relay and/or multiplex devices. Every effort should be made to keep antenna cables as short as possible while providing the appropriate amount of clearance above the terrain and obstacles within the influence of the path being designed.

Before continuing with site and equipment placement issues, the air needs to be cleared concerning the attempt to transmit through building walls and trees. It is indeed possible to transmit through some walls and through trees at 900 MHz. It has been done successfully many times, however IT IS NOT ADVISABLE. If the intent is to design a predictable highly reliable path between substation and generator especially where high speed and high availability is a requirement it may not be possible within the non-licensed bands. 900 MHz will penetrate some walls and will work however its long-term predictability is suspect based on what else could be unknowingly placed in the path adjacent to the walls being penetrated. One should not count on this type of engineered path to exhibit reliable operations long term. "Blasting through trees" is also possible and has worked but, like penetrating walls, if conditions change such as tree foliage density and new growth in the path these paths may exhibit unwanted operational characteristics. One never knows when a building could be built in this path as well and this is a real possibility since the path will have a low over the earth "clearance" so that a building of even modest height could block the path.

It is advisable to first test the path under full foliage under both dry and wet conditions and walk the path to guarantee that new growth won't intensify the denseness of the forest to a point where the signal level is attenuated beyond the receiver's ability to recognize it. Also the chance of a tall building blocking the path is reduced as the height of the path centerline increases. It is also possible to operate with grazing or partially blocked paths or one that utilizes an enhancing multi-path propagated receive signal. Multi-path reflection situations can be highly unstable in the 900 MHz and 2.4 GHz band if the reflection point to Fresnel Zone boundary is constantly changing due to variations in the equivalent earth curvature [expressed in an equivalent earth radius factor (K) times the actual earth radius I]as is the case with an over water hop that is prone to high and low tides amplifying the variation. Be advised that use of 900 MHz and 2.45 GHz narrow band FHSS systems yield the highest system gains but could be problematic if the hardware is not designed to guard against interfering signals, i.e. using FHSS with very narrow frequency filters for all narrow band operation in the 128Kb/s range will improve (lower) the receiver's usable threshold as much as 20 to 21 dB over DSSS wide-band systems. Both bands are not prone to power (ducting) fades as the 5.8 GHz band is. This is a consideration especially on longer paths.

The 900 MHz band, usually the preferred band for long and short narrow-band relaying applications, is a highly congested band in urban and suburban environments therefore unless the hardware takes care in producing efficient anti-jamming receiver characteristics, high speed applications could be problematic. If perceived as such the higher frequency bands may be the remedy but an intermediate repeater site may be needed if paths are very long or the direct path blocked. The application and the area congestion demographics may be the controlling factors as to which band to use and if a repeater site should or could be built.

Since more than a few substations sit in flood planes, it would be desirable to mount the radio and all support equipment along with the relay equipment above the 100-year flood plane level. Intermediate (repeater) site selection, in addition to the flood plane and path clearance issues, basically revolves around choosing economical and zoning friendly sites to minimize extremely long paths on any one path segment.

For example, if we had a narrow band FHSS application (128kb/s) located in the coastal Carolina area operating at 5.8 GHz (I know it's fictitious but bear with me) that strives to maintain a path availability of 99.999%(5-9s, or no more than ~5.3 (315 seconds) minutes of expected downtime per year), what would be the longest path segment we could stand to guarantee the 5.3 minute maximum expected outage per year? There are a number of factors that can be manipulated to yield a reasonable per path distance under achievable fade margins. Now given the pessimistic atmospheric influences that ravage Florida, i.e. @ c=4 & t=60^0F) and assuming a +18.5 dBm transmitter output and an ~ -100dBm (Narrow-band @128kb/s) Receiver Threshold (10^{-3} BER point), the longest path length utilizing a 4 ft. parabolic antenna (34.6 dB gain) at both ends and elevated to a height of no than 120 ft (5/8"coax and connector loss –7.0 dB per end), would be limited to ~16.5 miles.

At 900 MHz this same application (with the desired expected downtime) would yield a longest path, utilizing 22.3 dB gain, 6 ft. grid parabolic reflector mounted 120 ft AGL, attached a +30dBm transmitter talking to a Narrow-band filtered (@128kb/s) receiver that can maintain communications to –108dBm(10^{-3} BER point), all other parameters the same except compensated for lower frequency effects, would theoretically be about 56 miles.

For those that are interested the predicted one way annual outage formula is:

$$\#SES/yr. = .4 \times c \times f \times t \times D^3 \times 10^{-FM/10}$$

where: c is the climatic factor for the Carolinas = 4
f is the operating frequency in Ghz = 5.8 or .9
t is the average yearly temperature in F = 60^0
D is the distance in miles
FM is the resultant fade margin from the path gains and losses formula [transmitter output – sum

of cable losses + sum of antenna gains – path loss – receiver threshold = +18.5 –6.5 + 34.6 –136.4(~ loss at 16.5 miles) + 34.6 –6.5 –(-100) = ~38.2 dB @ 5.8Ghz.]

For the 0.9GHz example we have a 130.5dB path loss and arrive at –60.9 dBm at the receiver yielding an ~ 47.1 dB FM. The path loss is calculated as:

$$PL_{dB} = 96.6 + 20\log_{10}(f) + 20\log_{10}(D)$$

An example using these equations is given in Table A, examples A1, A2, and A3.

A suitable site's characteristics are based on the application requirements. If high speed, 6-9 reliability paths are required to transmit trip signals in 5 to 12 milliseconds are necessary, a site that will support a clear line of site path economically delivering < 32 SES of predicted path outage per year is the order to be filled. High availability routes [less than 32 sec downtime per yr.] are the most expensive to build, usually requiring a combination of hardware, shorter paths (more repeaters), space, frequency or even route diversity.

If, on the other hand, best effort transmission is all that is required (i.e. IP data transmission situation . . . e-mail, "Generator Islanding" prevention), the signal could be transmitted through trees and walls and as long as it can be determined with fair certainty that a signal always "eventually" gets there (i.e. in less than 1 to 2 seconds). Then lower reliability paths could be considered. In contrast to the 6-9 reliability paths, this scenario may not demand that a tower be built. Hardware redundancy may be all that is required to achieve overall 4-9 reliability (these will yield lower availability i.e. 50 to 55 expected minutes of expected path generated downtime per year). The relay engineer needs to understand that this 4-9 path is iffy at best and may be okay for voice transmission and if the transmission of the trip signal will only occur during favorable atmospheric conditions then a 4-9 path is acceptable. The bottom line is to secure a location for an intermediate repeater site that will meet the minimum overall circuit availability needs based on the application set by the relay engineer. In 99.9% of the cases a 4-9 reliability will not cut it. Also it is important to note that the fades that we are guarding against for tripping protection are the longer lasting power fades where antenna de-coupling occurs; i.e., ducting at >3GHz, not the short duration (.2 – 2sec) multi-path type that can occur during reflective situations such as water accumulation or ice formation on a flat field at the wrong (even) Fresnel Zone boundary that occur more frequently on excessive clearance paths at frequencies usually below 3 GHz.

One last note on path reliability; it is generally felt that over the course of a year that 500 to 1000 seconds of expected path outage won't coincide with an electrical disturbance that would normally trigger a trip condition.

Please note that added to path down times, in order to get a good handle on actual circuit availability, the equipment availability figures must be factored in with path figures. Equipment figures are based on Mean Time Between Failures (MBTF) and Mean Time To Repair (MTTR) and are manufacturer driven.

Unfortunately many times substations are placed in path unfriendly locations. Usually these terminal sites in low lying areas do not promote clear line of sight paths and will force expensive, tall tower construction if high path availability is a must. When considering towers to mount antennas, care must be taken to consider local community zoning regulations. It may be prohibitive to install tall RF transmission structures. Expensive fiber implementation may hold the only hope in this case, where the downside of a fiber build is the cut fiber scenario (the infamous dig-in or "back-hoe" outage). Unless the fiber is placed in service in a redundant route fashion the availability is again questionable.

M/W paths, as mentioned earlier, need to have a line of "radio" sight that is relatively free from obstructions if a guarantee of high availability is necessary. (See Figures D1, D2, and D3 for path obstruction example and Fresnel zone clearance calculations)

Other site considerations include the proximity to airfields and military installations since compliance with government regulations in determining lighting and/or painting of antenna structures is mandatory.

Also a repeater site that forces one or both paths over water or low flat terrain or sites near high power radar installations should be avoided if possible. The atmosphere adversely affects the values of K (figure of merit that depicts M/W beam and its relationship to the earth's curvature) and C (climatic factors) over flat low-lying areas, farmland and over water.

A complete description of the site clearing and leveling requirements is necessary to assess the viability of the site.

Locating power and telephone facilities is important and the robustness (or lack there of) of the power supply could mandate emergency generators sized to carry the load through a the worst case power outage scenario (east coast hurricanes, mid-west tornadoes, west coast earthquakes, northern climates snow and so on. When utilizing emergency generators a weekly exercise schedule is absolutely necessary. Hopefully this will enhance the probability that the unit will operate when called upon. Pay particular attention to single phase and open neutral faults in 3 phase power supply situations to guarantee the generator auto-start feature will correctly come on line when needed (i.e. the control system will isolate and start the generator upon failure of any phase if a three phase AC power source employed.

Related to and in addition to zoning issues are building code restrictions. Be certain that before a prospective repeater site is developed that all necessary devices (i.e. generators, buildings, towers, fuel tanks environmental retention pits, etc., can be placed on site). Other human oriented environmental issues such as noise, site screening requirements, etc., should be considered.

ii Fresnel Zones and Fresnel Zone boundaries:

See page 38 [2] for a complete description however, if we could see a M/W beam and were able to look at the beam coming at us the Fresnel Zone boundaries would look like a series of concentric circles where the boundary radii of each zone is the following mathematical relationship.

$\mathbf{F_n = 72.1[(nd_1d_2)/(fD)]^{0.5}}$ where:

$\mathbf{F_n =}$ is any Fresnel Zone boundary measured in feet from the centerline of the M/W beam.

N = is the Fresnel Zone boundary number increasing outwardly, sequentially from the centerline.

$\mathbf{D_1}$ = the distance from one terminal of the path to a point of interest in the path (usually the anticipated reflection point)

D = Total path length in miles

$\mathbf{d_2 = D - d_1}$

f = frequency in GHz

The primary emphasis in most path related calculations involves F_1 and once F_1 is known any F_n can be calculated as follows: $\mathbf{F_n = F_1(n)^{0.5}}$

Why is this calculation important? Once the Fresnel Zone boundary is known at the point of interest (in addition to an accurate path terrain profile) a determination can be made as to, advantageously positioning antennas at each end of a path to avoid a negatively reflective signal situation if multi-paths are thought possible on the path under design. Multi-path propagation from refracted as well as reflective waves are the major cause of path reliability problems. All heavy route and light route clearance requirement calculations are based on a variation of the F_1 formula in that a specific fraction namely 0.3, 0.6 or 1.0 x the F_1 value at various K factors(normal range used varies from K = 5/12 to 4/3)is used to set the clearance criteria above the possible problematic area.

iii Free Space Attenuation and the Effect of Fresnel Zone Radii, Terrain, and Obstructions on Path Reliability

As eluded to earlier there are two levels of reliability mandated by different clearance criteria that microwave path engineers normally design to. One is called "Heavy Route" and the other "Light Route." As described in the reference material (R. F. White, Engineering Considerations)

The following are the official descriptions:

For "heavy route", highest-reliability systems:
At least 0.3F1 @ K = 2/3 and 1.0F1 @ K = 4/3, whichever is greater. In areas of very difficult propagation, it may be necessary also to ensure a clearance of at least grazing at K = ½.(for 2 GHz. For paths > 36 miles, substitute 0.6F1 @ K = 1.0.)
We are really referring to high reliability and low reliability based on the relay application, i.e. high speed transfer trip to clear a fault on the 115Kv (and higher) systems versus a trip signal sent to the generator to prevent "islanding" respectively. Therefore the words "heavy route" and "light route" have no real meaning in this discussion.

For "light route" systems with less stringent reliability requirements:

At least 0.6F1 +10 ft @ K = 1.0

In order to understand what this means a dissertation on what these letters mean is necessary. As before all that follows can be found in the references so the explanation typical "heavy" and "light" route example. Lets' start the discussion. Figures A1, A2, and A3 show examples of Free Space Attenuation (A) that can be expected between any two isotropic antennas as:

$$\mathbf{A(dB) = 96.6 + 20\log_{10}(F) + 20\log_{10}(D),}$$

Where: **A** = free space attenuation in dB
F = frequency, in GHz
D = path distance, in miles

Therefore at 1 GHz and one mile in length, the path loss would be 96.6 dB, at 2 miles the loss increases by 6 dB and every time the path length doubles the loss increases by 6 dB. The same is true for a doubling the frequency. This says that we can go further the lower the frequency we utilize, equipment-operating characteristics notwithstanding. This calculation is important because it provides one of the major components to the all important Fade Margin / Path Reliability / Severely Errored Second determination formulas which will be developed later in this discussion and shown on Table A examples A1, A2, and A3

The next important concept that needs to be understood is that of obstructions and how they affect the path loss calculation. Trees for example tend to exhibit properties that "cause dispersion of RF energy and affect the vertical clearance." At center line grazing a loss of approximately 6 dB (makes the path look twice as long as it really is) is realized and as the trees grow and the forest becomes increasingly denser, this loss will increase. Tree growth is the reason to add an additional 10 to 15 extra feet of clearance over and above K factor and Fresnel Zone calculation results.

Man-made obstructions are another matter altogether. These obstructions are also denser than the atmosphere and will also have a tendency to bend downward (or sideward/upward) the M/W radio beam until the obstruction excessively penetrates the beam to the point where it totally blocks the signal. It must be noted that an obstruction can play an important positive role in blocking a destructive reflective beam from reaching the receiving antenna as well. Setting antenna heights such that a potentially destructive reflection is blocked at a bridge abutment on an over water path is one example of obstructions playing a positive role in path design.

The direction of a radio beam will be altered under diffraction, refraction and reflection situations. (pages. 6 through 20 and 37 through 40 [2] explains M/W beam behavior) The important points are discussed herein:

Earlier in various discussions the terms, Fresnel Zone, Earth Curvature Factor (K), Climate-Terrain Factor (I), Modified Refractive Index (M) were alluded to. These will be described only briefly since the reference material goes into great detail on the subject matter.

iv. K Factors, Reflections and Refractions Re: Multi-path Propagation

What is K factor? [See pg.11 through 20 [2]] The discussion about K factor begins with a discussion on "curvatures". The relative position of the M/W beam to the earth involves an understanding that the earth's equivalent curvature due to atmospheric conditions will bulge (sub-refractive condition) or sag (super-refractive condition) relative to the position of the M/W beam. (Actually the atmosphere is acting on the beam to bend it upward, downward or on some paths both) We can either depict the beam on a path profile showing a flat earth/sagging beam or a bulging earth/straight line beam. All path profiles should include the following information:

A. An accurate terrain profile plotted on graph paper with distance on the horizontal axis (scale a multiple of 1" = 2 miles or 4 miles) and elevations (1" = 200 ft. or 400 ft.) on the vertical Axis. If this scaling is used, a convenient "Equivalent Earth Profile Curves" (figure 4 in the C2 appendix of [2])) could be utilized to plot the path under various "K" conditions.

B. The proposed location of the antennas one at each end of the path with an indication of the structure type.

C. A positioning of obstructions from the United States Geologic Survey (USGS) maps and field surveys. A Clinometer should be used to accurately measure tree heights as well as buildings if their heights are not known.

D. A path drawn from the end point curved or straight depending on whether a flat or curved earth profile is used.

E. Fresnel Zone boundaries added to the top of the obstructions showing where the various Fresnel Zone clearance points are.

F. Tree height extension of 10 to 15 ft where trees cross the path.

G. A legend explaining the meaning of the obstructions and percentage of first Fresnel Zone clearances. K is controlled by the atmosphere and is based on a formula involving the "Radio Refractivity of Air" = **$N = 77.6x[P/T]+ 3.73x10^5x[e/T^2] = -40$ units/km for a normal atmosphere**

Where: P is the total atmospheric pressure

T is the absolute temperature in degrees Kelvin

e is the partial pressure of water vapor in millibars

K then mathematically becomes:

$K = 157/(157+dN/dh)$ (dN/dh is the atmospheric density gradient of a radio beam's refractivity with respect to height. (Determines the degree of beam bending).

In a normal atmosphere K is ~4/3. Most of the time the path designer is concerned with 3 values of K.(page 43 of [2])

A. "Minimum value of K which determines the degree of earth bulging and directly affects antenna placement and this value establishes the lower end of the clearance range over which reflective path analysis must be made."([2])

B. Maximum value of K. This is useful on reflective paths "where it establishes the upper end of the clearance range over which the analysis must be made."([2])

C. "Median or normal value to be expected over the path. Clearance over this condition should be at least sufficient to give free space propagation on non- reflective paths. This is important on reflective paths in that under normal K conditions the clearance should not fall on or near an even Fresnel Zone boundary."([2]) See Slides 127 thru 132 ([3]) for a visual illustration of the effect of K factor Fading.

Refraction can occur when elevated layering of the atmosphere occurs as well as over knife-edge type obstacles. This can cause multipath propagation and depending on the delay of the incoming multipath refracted signal can be additive or subtractive in nature and can cause unwanted fading. Some if not all of this problem can be cured by proper antenna alignment such the incoming multipath is effectively "Notched out" and allowed to enter the antenna between its main and side lobes. See slides 121, 122, 125, and 126 in Harris' Digital Systems Applications Seminar, Volume 1 for a visual depiction of this phenomenon.

The criteria for heavy and light route path availability stated earlier should be used and in most cases will suffice to guarantee expected reliabilities. See Figures D1, D2, D3 for sample path profile depicting the effect of the operating frequency as well.

v. Influence of Atmosphere, Terrain and Obstructions

Most of what will be discussed in this part can be found in: "Engineering Considerations for Microwave Communications Systems" by Robert F. White, GTE Lenkurt Inc. 1983[2], and Harris Corporation Communication Division's "Digital Microwave Systems Applications seminar Volume I and II, 1995-2000", by R.U.Laine([3]). All phrases in quotations are from these references cited. In addition to the above references various papers found in Harris Corporation Communication Division "Microwave Link Engineering Technical Paper Collection" September 2000 (updated to August 2001) contributions by R.U Laine, A. Ross Lunan, Wiley Quan, Keith Bromberg, Barry Johnson, Remi Chayer and W. Shaw from Harris Corp. Microwave Communications Division, Redwood Shores, CA. References are intended to support path specific and not vendor specific equipment issues.

M/W propagation adheres to many of the physical laws and properties of light. Issues such as path obstruction, reflection, refraction and diffraction as well as interference (both constructive and destructive) will be discussed in this and in the upcoming parts of this section. The effects of rain and fog on each frequency band (some affect primarily 5.8 GHz) will be mentioned. The concept of Fresnel Zones will be discussed. Including reflective path/antenna height anti-fade coordination.

Basically "Fresnel Zones are a series of concentric ellipsoids surrounding the center line of a path." They will be defined and discussed in detail and are very important in antenna height selection, at times necessary to position an antenna on a tower to avoid a negatively reflective path.

Typically a M/W beam is shown as a straight line but it is a "wave" and propagates like a wave demonstrating wave front characteristics most importantly a "sizable transverse area." This wave front must be allowed to propagate from one site to the next basically unobstructed. Anywhere from 0.3 to 1.0 times the first Fresnel Zone radius is necessary for unobstructed propagation and this choice of clearance level is determined by the reliability required. The calculation of Fresnel Zone radii and its relationship to atmospheric conditions and reliability is discussed and illustrated in the references, with sample calculation provided in the Figure C.

"The M/W beam (wave front) is influenced by the terrain between sites and by obstacles in or near the main centerline of the path." This sentence speaks volumes and indeed volumes have been written about terrain and obstacle influences. A brief discussion follows.

As a M/W beam travels from point A to B along the earth's surface it tends to follow a straight line unless it "is intercepted by structures in or near the path." The atmosphere has an effect on this straight-line path due to the variation with height in the atmosphere's dielectric constant. The path therefore will normally exhibit a slight downward (toward the earth) bending and in the temperate areas of the world the "K" factor is 4/3. The beam will tend to bend toward the more dense air (or over more dense objects) and therefore the "radio horizon is extended."([2]) "Space Diversity" path engineering sometimes uses this phenomenon such that during the day, the main path is controlling and in the evening when the air close to the earth appears denser (over hot humid areas especially) the diversity path becomes the controlling path and since the diversity receive antenna is usually placed 10 to 15 meters below the main antenna the necessary tower height may be adjusted downward allowing for a less expensive installation. The amount of bending varies with "temperature changes, pressure, and humidity (water vapor content). At times the beam will exactly follow the earth's curvature and at times the earth will appear to bulge (referred to as a substandard surface condition) effectively limiting the total path distance that could ideally be achieved. This happens when "the surface temperature is abnormally high or when the water vapor content of the atmosphere is increasing with altitude."[2] (See pages 41 – 45 for a complete explanation and mathematical treatment of atmospheric effects). At other times the earth appears to bend away from the beam in what is called a "super standard" or "super-refractive" atmospheric condition and allows for possible interference from remote microwave signals normally blocked by the earth's terrain. This can happen when there is "a rise in temperature with altitude or a decrease in water vapor content or both."[2] This is another reason to limit the main path height to that elevation that will "just get you there" with the added consideration for tree growth in the path if trees do cross the path.

Still more severe atmospheric condition exist where abrupt changes in the atmosphere's Modified Refractive index (M) with altitude will cause a condition known as "ducting." In this scenario the atmosphere acts as a moving wave-guide that can totally misdirect the beam away from the receiving antenna or cause an additive effect to temporarily re-concentrate the microwave energy to increase the receive level. These ducts (usually not a factor at 900 MHz and 2.4 GHz) can occur at the surface and elevated away from the surface. During this condition the K factor takes on a negative value and the atmosphere is said to be in a super-refractive mode. On short paths this phenomenon is not a problem, however on paths greater than 20 miles it can cause antenna de-coupling and thus becoming a serious factor for consideration. Understanding microwave antenna patterns, how to manipulate them and the effect of Fresnel Zones and K factor issues are a must if one is to successfully engineer microwave paths. See Slides 131 and 132 in reference [3] for a depiction of K factor distribution.

At the higher frequencies rain and fog can provide another fly in the ointment. Here the issue is droplet size density of fog and intensity of rainfall. Generally, the worst areas for high intensity rainfall in North America are in the tropical areas of Florida, the gulf and southern Atlantic coastal regions. Rain most affects the 5.8 GHz band, and for all practical purposes can be ignored at 900 MHz and 2.45 GHz.

The loss per mile for a cloudburst condition in the 5.8 GHz band is ~ 1.0 dB/mile. For a 15 mile at 5.8 GHz, a path that is operating in Florida must have 15 dB extra receive level figured into the fade margin design to guarantee successful operation in the event a 15 mile tropical cloud traverses the path and delivers a 4 inch per hour deluge. Fog was mentioned, however, at frequencies below 12 GHz, it has virtually no effect. The above-mentioned 15 mile, 5.8 GHz path would experience no more than ~ 1 dB of loss. An even smaller issue is atmospheric absorption. It is mentioned however it has no discernable affect at frequencies below 6 GHz. And less than 50 miles in length.

Like the atmosphere, the terrain and the obstructions that grow or are built on the terrain over which a M/W signal traverses will aid or will detract from the receive level. There are a few "rules of thumb" that over the years have proven out and have served to minimize the effects of the atmosphere as well as equipment performance (or non-performance) and initial design assumption shortfalls.

1. Minimize paths that propagate over water and low lying marshy areas and flat farmland.
2. Those paths that have the above conditions contained within should be engineered to have the potential reflective paths blocked by antenna adjustment so that a low height obstruction may serve to block the reflective path or adjust the heights of the antenna so that the reflection occurs on an odd Fresnel Zone boundary. This latter technique is effective only if the height of the reflective surface is stable and does not change.
3. The use of space diversity can many times minimize the effects of the atmosphere and terrain improving a 4-9 reliability path to one of 6-9s or better. This is more expensive that a hot-standby hardware diversity scenario because additional antennas and wave-guide are necessary. Single antenna equipped in an Angle Diversity setup can sometimes be utilized and may provide some relief. An excellent dissertation on multi-path outage prevention techniques is given by Harris Corporation's Digital Microwave Systems Applications Seminar, Volume 1 "Digital Microwave Link Engineering" manual [3], R.F. White's "Engineering Considerations manual [2]"
4. Make absolutely sure that all viable paths are researched to the degree that a field verification of all potential hazards are visually checked out and documented. **NEVER, NEVER RELY ON USGS MAPS ALONE** as the only source of path detail. The elevation tolerances and details are not sufficient for one to reliably engineer a high availability path. Do your homework here for the fixes are very expensive.
5. When the construction of an antenna support structure is mandated, always engineer more height and strength than would originally thought to be required. Many times space diversity is found to be necessary and changes in antenna placement from original design is the remedy. A 20% to 40% over design usually works (20% on 200ft and 40% on 100ft structures). Normal separation of space diversity antennas is 25 to 40 feet. Separations as much as 60 feet have been known to be implemented to in rare cases to compensate for a few multi-path problems.

   A word about construction standards is warranted. Tower design standards are governed by the American National Standards organization (ANSI). A document by the Electronic Industries Association / Telecommunications Industries Association (EIA/TIA), EIA/TIA-222-F (revision G will be out by the end of 2002) is the bible for all tower construction and includes all the relevant information that needs to be included in tower specifications. This document can be purchased from Global Engineering Corp., Voice # 1 (800) 854-7179, Web page: http://global.his.com. The price is $99.00.
6. Do not power the radio directly from an AC source and try to avoid UPS systems. A simple battery/charger system is simple and has the least number of parts to potentially fail. A control battery 129 VDC to 48 VDC DC to DC converter is minimally acceptable on those systems that have the lower reliability requirements. A separate monitored power supply is preferable and has over the years proven to be the most reliable set up at our company.
7. Always monitor the health of the AC and DC power supply as well as the radios via a separate circuit that is not carrying the traffic unless this communication system is in a ring scenario.
8. Always design for 6 dB more receive margin than is needed to achieve the required reliability to account for electronics degradation over time.

9. Always allow for tree growth over a twenty-year period of 6 inches per year minimally as far as path clearance is concerned.
10. Always ground antenna coax and wave-guide at **least 4 times**, once at antenna, once midway down the tower, once at the control house entrance and finally at the radio so that lightning current can effectively be dissipated. Make sure there are no 90-degree bends in the ground wire from the wave-guide to the ground system.
11. Also **NEVER** use the tower steel as the ground conductor but rather install minimally a 1/0 (preferably 4/0) copper conductor on each leg of the tower from bottom to top, ringing the top of the tower and tie the cable grounds to these leg runs. The bottoms of each copper run should be welded to a 10 to 12 foot copper ground rod. The radio and entire building should be grounded to this ground. The idea is to provide as solid a ground as possible. Refer to appropriate articles on lightning and surge protection.
12. All wave-guides should be secured to the tower guide at 3 to 4 foot intervals when mounted in a high wind prone area.
13. When deploying back-up generation make propane the fuel of choice if possible. Always supply with 50% more capacity than what is initially thought to be necessary both in generation capacity and fuel supply.
14. Always assume it will cost more to construct than one would normally estimate.

v. Rain and Fog

As mentioned in part **ii**. Rain and to a lesser degree fog can adversely affect the receive level of a M/W beam. The amount of loss is directly proportional to the frequency, droplet size, intensity of the rainfall (inches per hour) and the size of the rain cell that crosses the path. Rain and fog will have negligible effects on the paths designed in the above referenced frequency bands. At 5.8GHz only a cloudburst from a large diameter cell will have any noticeable effect.

Table A, Examples A1, A2, A3

Path Calculations A1, A2, A3 based on Paths shown on Examples A1, A2, A3 respectively

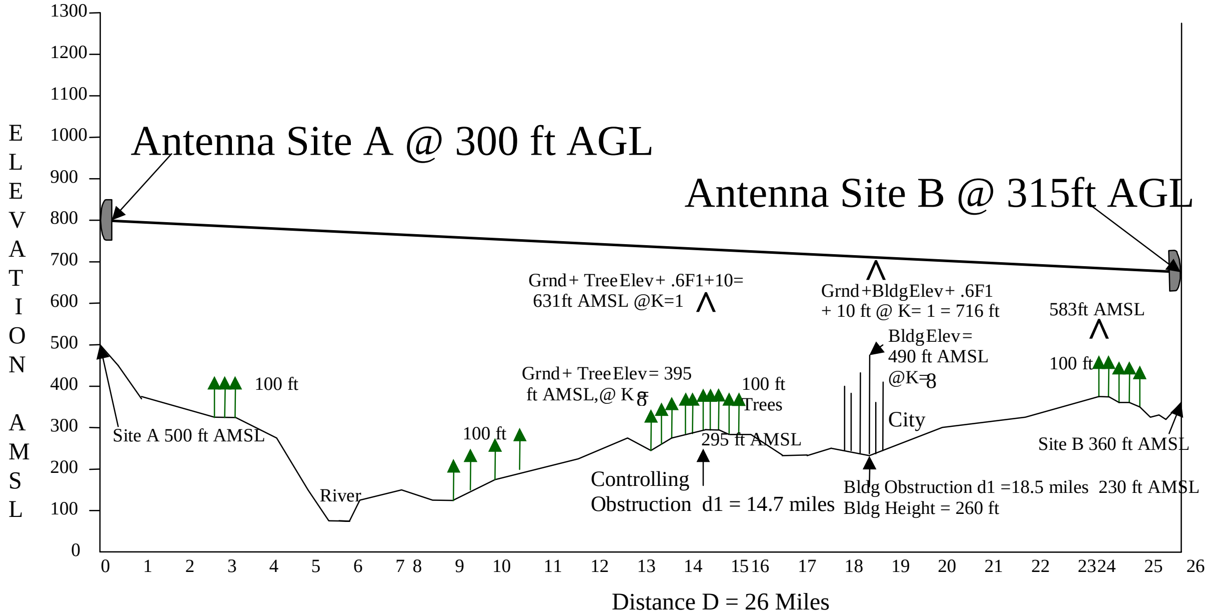
Example	**A1**	**A2**	**A3**			
Operating Frequency, f, GHz	0.9	2.4	5.8			
Information Bandwidth	128Kbps	128Kbps	T1			
Xmit Power Site A	30dBm	27dBm	20dBm	assume 2.4 GHZ operating Full power		
Antenna size	8 ft parabola	8 ft parabola	8 ft parabola	.9GHZ	2.4GHz	5.8 GHZ
Antenna Gain Site A	24.4	32.5	41.2	7/8 foam	1 5/8 foam	EW52
Cable/WG loss Site A	-3.7	-3.5	-2.8	1.28/100ft	1.4/100ft	1.22/100ft
Connector Loss Site A Xmtr	-1	-1	-2			
Path Loss PL Free Space Db	-124.0	-132	-140			
Rain Attenuation (5.8GHz)	0	0	-10	assumes a 10 mile wide cloudburst, 4"/hr		
Antenna Gain Site B	24.4	32.5	41.2			
Connector Loss Site B Rcvr	-1	-1	-2			
Cable/WG loss Site B	-3.8	-3.9	-2.9			
Receive Level	-84.7	-76.4	-77.3			
Receiver threshhold (10-6 BER)	-108	-108	-96			
Path Fade Margin, FM	23.3	31.6	18.7			
Coding Gain (nominal)	9	9	9			
SESR @ 10-6 BER	7.3721E-04	2.9183E-04	0.01375143			
Path Reliability %	99.9760405	99.9905155	99.5530783			
Expected Annual Outage min/yr	29.9877709	11.8708331	559.368432	`@5.8GHZ this design yields>9 hr/yr outage		
`-constant in PL equation	-96.6	-96.6	-96.6			
`-20 logD	-28.2994669	-28.2994669	-28.2994669			
`-20 logf	0.91514981	-7.6042248	-15.2685598			
Path Distance D, miles	26	26	26			
climate c = 4 south, coastal	4	4	4			
Temperature t = 65 F	65	65	65			
Light / Heavy route criteria	Light	Light-Hvy	Unusable			

PLoss = -(96.6 + 20logD + 20logf)
SESR = 2.5 x 10-6 x c x fx D3 x 10-FM/10

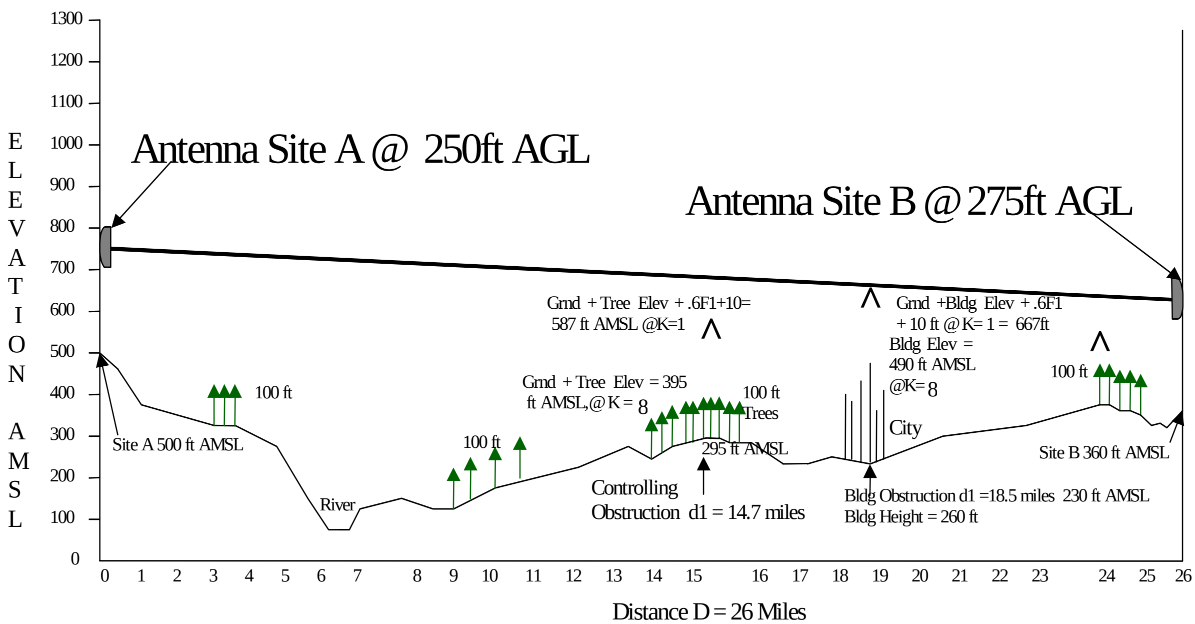
Path Rel = 100 - 100 x SESR/4 x t/50
Ann out (min) = SESR x 13.34 x t/50

Note: 2.4 GHz best frequency to use for this path, 5.8 GHz constrained to T1 therefore threshold high value, path loss too high, making 5.8 GHz a poor choice. 900 MHz could be used if best effort scenario will suffice

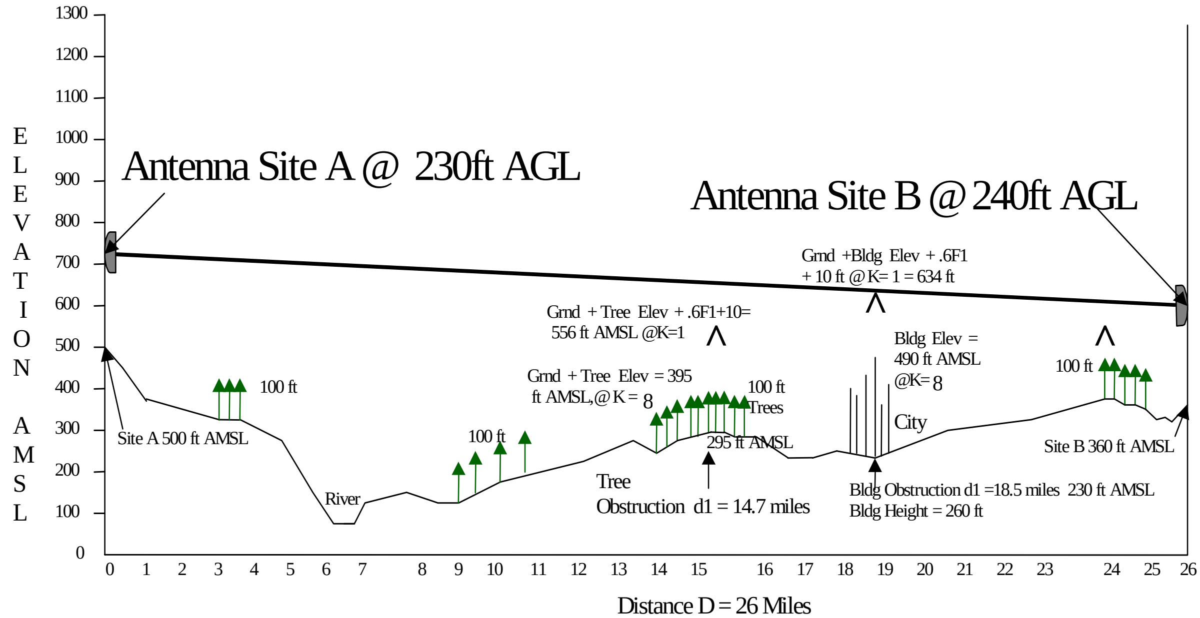
Example A1 Path Profile Operating at 900MHz Under "Light Route" clearance criteria



Example A2 Path Profile Operating at 2.4GHz Under "Light Route" clearance criteria



Example A3 Path Profile Operating at 5.8GHz Under "Light Route" clearance criteria



Appendix A.4 Spread Spectrum Radios for Utility Communications

A.4. 1 Intersubstation Applications

If a Utility Communications Engineer were given the task of providing communications between one substation and another, their choice would most likely be digital technology using either microwave or fiber. The digital technology would consist of a single or multiple T1's terminated in a channel bank at each substation. A T1 (or DS1) consists of 24 voice channels under a standard referred to as the "North American Hierarchy". The reason for choosing this configuration would be due to its ability to accommodate a wide range of channel types including RS-232 and other data configurations, voice, alarm signals, etc. This configuration would accommodate the variety of channels required to support the average substation, including phones, RTU channels, modem connections for DFR's, breakers, etc. The decision to install fiber optics or microwave would depend heavily on economics, but reliability would not be ignored. If the choice was microwave radio, the installation of a spread spectrum radio might be considered. Because of its low cost and ease of installation, it may appear to be an attractive choice if all criteria were met including sufficient reliability to accommodate the traffic.

Reasons for choosing a spread spectrum radio would include; economics, ability to immediately deploy, no licensing required, small antenna size possible, takes up little space and some can have portions installed outside, and low power consumption.

Reasons for not choosing a spread spectrum radio might include; limited RF channel availability increasing the possibility of interference, power output limitation on 2.4 GHz band radios, limited path fading countermeasures, highly susceptible to echo distortion, Radio Frequency Interference (RFI) risk high because unlicensed frequency bands are used, limited monitoring, alarming and control features, no antenna diversity features to protect against path fades, and no receiver switching capability. Most point-to-point microwave radios use sophisticated methodologies such as forward error correcting that improves the operability and reliability of the radio. Spread spectrum radios typically do not have these features.

Well-engineered microwave and fiber optic systems that utilities would normally install to carry protective relaying and other critical traffic would have multiple reliability features that distinguish these installations from the average spread spectrum radio installation. These might include redundant power supplies and other common cards, battery and charger systems to provide continuous power, backup generators to sustain equipment during a long power outage, alarming to a central control desk so the health of the system can be monitored, and control features that allow adjustments or troubleshooting to occur from a central location. Many of these systems also use loop designs or other redundancy techniques to improve availability.

Of the issues above that would most influence the choice of not using a spread spectrum radio to carry protective relaying channels, the risk of RFI would be at the top of the list. Because these frequencies are unlicensed, anyone can use them for any reasonable purpose with the only restraints placed on the transmitter power out by the FCC in Part 15 of their rules. Interference could come from others using similar equipment; specialty uses including portable video feeds for television networks, wireless connections to the Internet, etc. These sources of interference can appear with no notice and disappear just as fast. The interference may last for a few moments, an hour, a day, or continuously. The use of a spread spectrum radio for protective relaying purposes would be at the users risk and is not recommended for high voltage line protection.

The suitability of using a spread spectrum radio instead of a traditional microwave radio other than the problems listed above would be minimal. The inherent delay in a point-to-point spread spectrum radio would be consistent with a traditional point-to-point microwave radio. Spread spectrum devices could be purchased that would carry other than T1 traffic; for example, point-to-point Ethernet radios are readily available on the market. Problems such as susceptibility to interference, lack of error correction, and operating voltage restraints would also apply to these radios. From a delay perspective, an Ethernet radio would be no different than a T1 radio, however, end device protocols and applications may induce delays unacceptable for protective relaying circuits.

A.4. 2 Intrasubstation Applications

There are a wide choice of technologies and an even wider selection of manufacturers to choose from when looking for intrasubstation wireless communications devices. The two primary types of spread spectrum technologies that might be used in substations would be wireless Ethernet and RF telemetry radio modems.

A.4. 2.1 Wireless Ethernet

A Wireless Ethernet installation in a substation would follow the IEEE standard 802.11b. The predominate component would be the access point, which is a device that connects to a wired Ethernet and allow wireless devices like laptops to communicate through them and onto the network. Access points can be strategically located throughout the substation to provide the desired coverage. To convert a PC or laptop to wireless, a wireless LAN client adapter must be installed in the PC or laptop. The client adapters are equipped with antennas that communicate with the access point. The most common protocol used with this equipment would be TCP/IP, which would allow the network at the substation to be interconnected to any other IP network in the company if that were desired. While other protocols will work on Ethernet, they may not be a versatile or as easy to manage. The access points are commonly powered off of 120 VAC or 48 VDC.

A.4. 2.2 RF Telemetry Radios

A large variety of telemetry type wireless modems can be purchased from multiple vendors. These radios are primarily manufactured for SCADA type environments, and can be as sophisticated as a self-contained RTU to a small radio with an RS-232 input for connecting other SCADA type equipment. Various protocols are available including Modbus, serial, and Ethernet. Some of these devices are built for use as a point to point applications where one end would be at a distant part of the substation, a breaker for example, and the other would be in the control house connected to an RTU, computer, or similar device. Other designs would include point-multipoint, where one device in the control house could transmit and receive from multiple devices in the substation. These devices can be powered off of a variety of voltages depending on the manufacturer, but 24 VDC and 120 VAC would be typical voltages.

A.4.3 Using Spread Spectrum Radios for Protective Relaying Purposes

A.4.3.1 Intersubstation

The discussion on the use of spread spectrum radios between substations to carry protective relaying traffic will be limited to radios with T1 interfaces or spread spectrum radios specifically designed to carry protective relaying traffic. Other radios using RS-232, Ethernet, or other techniques, will be discussed under ‘Intrasubstation’, and the same arguments would apply in a long-haul situation as inside of a substation.

Whether a spread spectrum radio or a commercial grade microwave radio is used to carry protective relaying traffic between two substations would be transparent to the relay the majority of the time. However, if proper engineering were done, the reliability of the spread spectrum radio would pale compared to the commercial grade microwave radio. A careful engineering study would discover that the spread spectrum radio would not meet the same reliability figures as a commercial grade microwave radio. The spread spectrum radio will most likely be more vulnerable to fading, outages and errors because of the low cost design, lack of redundancy resulting in a higher Mean Time Between Failures (MTBF), and devoid of features found on more expensive radios. In addition to these differences, the spread spectrum radio will inherently be more susceptible to interference than its commercial grade cousin. Licensed radios from time to time experience interference that can be devastating to protective relaying circuits. Because the most likely source of interference will be some other licensed transmitter, the search can be quickly narrowed down to likely suspects, and usually the culprit can be determined. Because the interfering party is operating by the same FCC rules, the problem can be quickly sorted out. Not so with the spread spectrum radios. The interference that would be affecting protective relaying signals could be coming from a wide variety of sources, could be present for only for a short duration, or be intermittent. If the interfering party is discovered, there is little recourse because the frequencies are not licensed and the offending party is well within his rights to use the frequency band.

While using an off-the-shelf spread spectrum radio for high-voltage protection channels may prove to be too risky, there are spread spectrum radio designs that could prove to be adequate for lower voltage transmission lines. Specially designed spread spectrum radios are on the market that are specifically designed for certain types of protective relay outputs. While matching the spread spectrum radio to the relay eliminates many of the problems that less rigorous designs might encounter, it does not make the installation as sound as the more traditional designs. Areas of risk the user still must contend with would include a reliable power source, redundant components, and the ever-present threat of interference that may be reduced, but not completely eliminated. These radios may also introduce delays if built with internal intelligence that can determine if messages have been received, or interference is present.

So using spread spectrum radios as a medium to carry protective relaying circuits between substations comes down to a decision of risk. If all the facts have been gathered, and it is agreed that the risk is acceptable, then spread spectrum radios might be a plausible solution.

A.4.3.2 Intrasubstation

The use of spread spectrum radios inside of a substation brings about a whole different set of problems than when using the same technology between substations. Interference would be less of a problem inside of a substation. The phenomena referred to as the “Near-Far effect” involves the susceptibility of a radio receiver to be interfered with by a foreign transmitter located closer than the intended transmitter. This phenomena is more likely to occur with Direct Sequence spread spectrum than Frequency Hopping, however, the likelihood of an interfering transmitter being closer or having a stronger signal than the intended transmitter right there within the parameter of the substation would be remote.

To properly analyze the use of spread spectrum radios for protective relaying, a discussion of functionality is required. In almost all cases, protective relaying information is either the conveyance of a contact closure from one location to another as is the case with Direct Transfer Trip (DTT). Or, the information is the duplication of a waveform or similar information as is required for pilot wire relaying, and would also be true for a differential scheme. In traditional DTT schemes, the contact information is transmitted to the far end using tones (a change is frequency defines a change in state) or the setting of bits in a data stream. Both of these methods have safeguards to ensure that reliability and dependability are optimum for the design. Multiple tones are used, for example, to make certain that anomalies in the system do not falsely imitate a trip signal. When digital technology is used, a Cyclic Redundancy Check (CRC) or similar method checks the message for accuracy, and repetitive signals may be required to fulfill 2 out of 3 or 3 out of 4 algorithms for example. To transmit a change in state of a contact, high speed is not necessarily required, more importantly; safeguards must be in place to ensure reliability and dependability. Delays in a DTT scheme are acceptable if known. Change in delay can be detrimental to relay coordination, and care must be taken to ensure that the trip signal is received with the same amount of delay every time.

Transmitting waveforms is considerably different than contact information. The transmitting of waveforms requires higher bandwidths because more information must be sent, a change in delay would be devastating to the process, and end-to-end delay if great enough would make the information useless. Therefore, the equipment used to transmit these types of signals must be high-speed, high-bandwidth, and substantially delay free. Relay and communications engineers have collaborated over the years to develop techniques to reduce some of these parameters to make it easier to transmit waveforms, but the fundamentals still pretty much hold true.

When attempting to use spread spectrum technology to transmit either contact information or waveforms inside of a substation for relaying purposes, the underlying methodologies must be examined. If a wireless Ethernet were designed to carry information within a substation and protective relaying made up part of this information, would the technology be able to support it? As mentioned earlier, the spread spectrum radio would be essentially transparent to the technology, and it would be the technology that would determine suitability. So the question that needs to be posed is, is Ethernet capable of carrying relaying traffic? The short answer is yes, but must be qualified. Delays must be checked. Delays will be found, for the most part, in the software, not in the hardware. The hardware including the spread spectrum radio will be reasonably consistent at delivering the packets of information with some increased delay noted as the system becomes more heavily loaded. Contention for processor time or similar can be detrimental to relaying traffic unless Quality of Service (QoS) is implemented and enforceable on the relaying data stream. Ethernet is quite capable of carrying contact information even at 10 Mb/s if other factors do not impose excessive delay or change in delay on the data. For the transmission of true waveform information, it has been recommended to use Fast Ethernet (100 Mb/s) to ensure adequate bandwidth and speed. However, the same applies that QoS must give relay information priority over other information, and software processes must not present an undue burden on the relay information.

Similar to attempting to use Ethernet for protective relaying purposes, problems must be overcome if attempting to use a SCADA system to transmit relaying information. Many SCADA type devices utilizing spread spectrum as their transmit medium will carry both discrete (contact information) and analog (waveform information). Again, the spread spectrum radio will be, for the most part, transparent to the process and only add a minimal amount of delay. Polling schemes, information processing times, and other processes will have much more influence on the successful outcome of the transmittal of relaying information. Attempts to use this type of equipment for protective-relaying purposes would require a through engineering study to ensure its adequacy for the task.

A.4.4 OSI Reference Model

Another approach to view the feasibility of the use of spread spectrum technology for protective relaying purposes would be to use the OSI 7-layer reference model. In the model, layer 1 is the physical layer. This is the layer that the spread spectrum radio resides. This layer makes no decisions, only takes what is given to it at one end of the medium and puts it out at the other. Layers 2 and 3 are concerned with getting the information to the proper location. At layer 4, the transport layer, decisions about re-transmitting come about. Layer 4 checks to see if packets received from layer 3 have been received in the correct order and if they are all there. If not, then a retransmittal is requested. The request would flow back down through layers 3 and 2 to layer 1, the physical layer, which could be a spread spectrum radio, and back to the transmitter that originally sent the information. An engineering study of the use of spread spectrum radios for protective relaying should then take into account the various layers, what they do, and what effect they would have on a protective relaying scheme. While this model is specifically for Ethernet, it would have its uses in analyzing SCADA type applications also.

Appendix A.5 Code of Federal Regulations (US)

[Code of Federal Regulations]
[Title 47, Volume 1]
[Revised as of October 1, 2001]
From the U.S. Government Printing Office via GPO Access
[**CITE**: **47CFR15.247**]

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TITLE 47--TELECOMMUNICATION

CHAPTER I--FEDERAL COMMUNICATIONS COMMISSION

PART 15--RADIO FREQUENCY DEVICES--Table of Contents

Subpart C--Intentional Radiators

Sec. 15.**247** Operation within the bands 902-928 MHz, 2400-2483.5 MHz, and 5725-5850 MHz.

(a) Operation under the provisions of this section is limited to frequency hopping and direct sequence spread spectrum intentional radiators that comply with the following provisions:

(1) Frequency hopping systems shall have hopping channel carrier frequencies separated by a minimum of 25 kHz or the 20 dB bandwidth of the hopping channel, whichever is greater. The system shall hop to channel frequencies that are selected at the system hopping rate from a pseudorandomly ordered list of hopping frequencies. Each frequency must be used equally on the average by each transmitter. The system receivers shall have input bandwidths that match the hopping channel bandwidths of their corresponding transmitters and shall shift frequencies in synchronization with the transmitted signals.

(i) For frequency hopping systems operating in the 902-928 MHz band: if the 20 dB bandwidth of the hopping channel is less than 250 kHz, the system shall use at least 50 hopping frequencies and the average time of occupancy on any frequency shall not be greater than 0.4 seconds within a 20 second period; if the 20 dB bandwidth of the hopping channel is 250 kHz or greater, the system shall use at least 25 hopping frequencies and the average time of occupancy on any frequency shall not be greater than 0.4 seconds within a 10 second period. The maximum allowed 20 dB bandwidth of the hopping channel is 500 kHz.

(ii) Frequency hopping systems operating in the 2400-2483.5 MHz and 5725-5850 MHz bands shall use at least 75 hopping frequencies. The maximum 20 dB bandwidth of the hopping channel is 1 MHz. The average time of occupancy on any frequency shall not be greater than 0.4 seconds within a 30 second period.

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(iii) Frequency hopping systems in the 2400-2483.5 MHz band may utilize hopping channels whose 20 dB bandwidth is greater than 1 MHz provided the systems use at least 15 non-overlapping channels. The total span of hopping channels shall be at least 75 MHz. The average time of occupancy on any one channel shall not be greater than 0.4 seconds within the time period required to hop through all channels.

(2) For direct sequence systems, the minimum 6 dB bandwidth shall be

at least 500 kHz.

(b) The maximum peak output power of the intentional radiator shall not exceed the following:

(1) For frequency hopping systems in the 2400-2483.5 MHz band employing at least 75 hopping channels, all frequency hopping systems in the 5725-5850 MHz band, and all direct sequence systems: 1 watt. For all other frequency hopping systems in the 2400-2483.5 MHz band: 0.125 watts.

(2) For frequency hopping systems operating in the 902-928 MHz band: 1 watt for systems employing at least 50 hopping channels; and, 0.25 watts for systems employing less than 50 hopping channels, but at least 25 hopping channels, as permitted under paragraph (a)(1)(i) of this section.

(3) Except as shown in paragraphs (b)(3) (i), (ii) and (iii) of this section, if transmitting antennas of directional gain greater than 6 dBi are used the peak output power from the intentional radiator shall be reduced below the stated values in paragraphs (b)(1) or (b)(2) of this section, as appropriate, by the amount in dB that the directional gain of the antenna exceeds 6 dBi.

(i) Systems operating in the 2400-2483.5 MHz band that are used exclusively for fixed, point-to-point operations may employ transmitting antennas with directional gain greater than 6 dBi provided the maximum peak output power of the intentional radiator is reduced by 1 dB for every 3 dB that the directional gain of the antenna exceeds 6 dBi.

(ii) Systems operating in the 5725-5850 MHz band that are used exclusively for fixed, point-to-point operations may employ transmitting antennas with directional gain greater than 6 dBi without any corresponding reduction in transmitter peak output power.

(iii) Fixed, point-to-point operation, as used in paragraphs (b)(3)(i) and (b)(3)(ii) of this section, excludes the use of point-to-multipoint systems, omnidirectional applications, and multiple co-located intentional radiators transmitting the same information. The operator of the spread spectrum intentional radiator or, if the equipment is professionally installed, the installer is responsible for ensuring that the system is used exclusively for fixed, point-to-point operations. The instruction manual furnished with the intentional radiator shall contain language in the installation instructions informing the operator and the installer of this responsibility.

(4) Systems operating under the provisions of this section shall be operated in a manner that ensures that the public is not exposed to radio frequency energy levels in excess of the Commission's guidelines. See Sec. 1.1307(b)(1) of this chapter.

(c) In any 100 kHz bandwidth outside the frequency band in which the spread spectrum intentional radiator is operating, the radio frequency power that is produced by the intentional radiator shall be at least 20 dB below that in the 100 kHz bandwidth within the band that contains the highest level of the desired power, based on either an RF conducted or a radiated measurement. Attenuation below the general limits specified in Sec. 15.209(a) is not required. In addition, radiated emissions which fall in the restricted bands, as defined in Sec. 15.205(a), must also comply with the radiated emission limits specified in Sec. 15.209(a) (see Sec. 15.205(c)).

(d) For direct sequence systems, the peak power spectral density conducted from the intentional radiator to the antenna shall not be greater than 8 dBm in any 3 kHz band during any time interval of continuous transmission.

(e) The processing gain of a direct sequence system shall be at least 10 dB. The processing gain represents the improvement to the received signal-to-noise ratio, after filtering to the information bandwidth, from the spreading/despreading function. The processing

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gain may be determined using one of the following methods:

(1) As measured at the demodulated output of the receiver: the ratio in dB of the signal-to-noise ratio with the system spreading code turned off to the signal-to-noise ratio with the system spreading code turned on.

(2) As measured using the CW jamming margin method: a signal generator is stepped in 50 kHz increments across the passband of the system, recording at each point the generator level required to produce the recommended Bit Error Rate (BER). This level is the jammer level. The output power of the intentional radiator is measured at the same point. The jammer to signal ratio (J/S) is then calculated, discarding the worst 20% of the J/S data points. The lowest remaining J/S ratio is used to calculate the processing gain, as follows: Gp = (S/N) o + Mj + Lsys, where Gp = processing gain of the system, (S/N) o = signal to noise ratio required for the chosen BER, Mj = J/S ratio, and Lsys = system losses. Note that total losses in a system, including intentional radiator and receiver, should be assumed to be no more than 2 dB.

(f) Hybrid systems that employ a combination of both direct sequence and frequency hopping modulation techniques shall achieve a processing gain of at least 17 dB from the combined techniques. The frequency hopping operation of the hybrid system, with the direct sequence operation turned off, shall have an average time of occupancy on any frequency not to exceed 0.4 seconds within a time period in seconds equal to the number of hopping frequencies employed multiplied by 0.4. The direct sequence operation of the hybrid system, with the frequency hopping operation turned off, shall comply with the power density requirements of paragraph (d) of this section.

(g) Frequency hopping spread spectrum systems are not required to employ all available hopping channels during each transmission. However, the system, consisting of both the transmitter and the receiver, must be designed to comply with all of the regulations in this section should the transmitter be presented with a continuous data (or information) stream. In addition, a system employing short transmission bursts must comply with the definition of a frequency hopping system and must distribute its transmissions over the minimum number of hopping channels specified in this section.

(h) The incorporation of intelligence within a frequency hopping spread spectrum system that permits the system to recognize other users within the spectrum band so that it individually and independently chooses and adapts its hopsets to avoid hopping on occupied channels is permitted. The coordination of frequency hopping systems in any other manner for the express purpose of avoiding the simultaneous occupancy of individual hopping frequencies by multiple transmitters is not permitted.

Note: Spread spectrum systems are sharing these bands on a noninterference basis with systems supporting critical Government requirements that have been allocated the usage of these bands, secondary only to ISM equipment operated under the provisions of part 18 of this chapter. Many of these Government systems are airborne radiolocation systems that emit a high EIRP which can cause interference to other users. Also, investigations of the effect of spread spectrum interference to U. S. Government operations in the 902-928 MHz band may require a future decrease in the power limits allowed for spread spectrum operation.

[54 FR 17714, Apr. 25, 1989, as amended at 55 FR 28762, July 13, 1990; 62 FR 26242, May 13, 1997; 65 FR 57561, Sept. 25, 2000]