Industrial Wireless Systems - Application Considerations

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ABSTRACT
Presented here are tools and techniques to plan and design a wireless communication system for an industrial control application. Basic concepts of signal gain, radio transmission and transceiver hardware components are discussed as a foundation. A functional approach to system design based on the assessment of the application requirements with practical examples is offered. The importance of a site survey in the system design is presented along with useful methods of site terrain and energy spectrum analysis. System gain calculations and the final hardware selection process are described. Application examples are given.

1. INTRODUCTION

As control engineers, we're often guilty of assuming that information exchange between systems in an industrial setting is a given. The proliferation of Ethernet in manufacturing automation has greatly enhanced our ability to design communication architectures that include programmable controllers and I/O devices at the plant floor level, PC's and data loggers at the supervisory level, servers and business systems at the Enterprise level. How quickly we forget that era (expensive and painful by today's standards) when communication technologies such as Allen Bradley Data Highway, Modicon Modbus, to name a few, were the state of the art.

Data exchange over a distance presents an added set of challenges that have been addressed with a range of solutions for the extension of Ethernet networks, point to point protocols such as RS-232, and legacy technologies such as those mentioned above. These are of particular interest to the coal mining and processing industry. In general, where no hard communication path exists wireless transmission systems are an extremely cost effective method of bridging the distance.

GCI has deployed several remote monitoring and control systems for the mining and coal processing, water utility, and waste water processing industries using wireless and other technologies. Attaining a level of experience and proficiency hasn't, admittedly, come without a learning curve and some pain. As spoiled as we've become with the ease of Ethernet, we discovered that implementing a robust remote monitoring/control system using wireless or other long haul technology requires more than setting up two radios and crossing your fingers. The upside presented here is what we've learned of tools and techniques that allow for better planning and implementation of a wireless control system.

2. THE BASICS

2.1. Gain

An important concept to grasp when involved with the design or implementation of a wireless communication system is Gain, which is used to quantify the transmission and reception characteristics of radio components. For amplified transmitters and receivers, the simplified explanation is that gain is a ratio of actual power to a theoretical reference power of 0.001 Watts or 1mW[1]. Since gain is a ratio,.the engineering units cancel out to yield a dimensionless value. As a matter of practicality, gain is usually expressed in decibels (dB) as a logarithmic relationship with the dimensionless ratio using the formula –

[1] Banner Engineering Corp , 2010, *Antenna Performance* , Minneapolis MN, Publication Number 135765, pg 5

$Gain_{dB}$ = 10 log_{10} (device $power_{mW}$ /1_{mW}) or 10 log_{10} (device power)[2].

2.1.1. Amplifier Gain

When comparing the relative power or sensitivity of a radio amplifier, the term Gain expressed as dBm (decibel relative milliwatt) is used.

Example 1 – A radio device transmits an amplified signal with a power output of 1W at the antenna connection. What is the radio transmitter's gain in dBm?
Using the formula above:
Gain = 10 log_{10} (device $power_{mW}$ / 1_{mW}) = 10 log_{10} (1000_{mW} / 1_{mW}) = 10 log_{10} (1000) = 10*3 = 30dBm

Example 2 – A radio receiver circuit is sensitive to an incoming signal with a power level of 10pW. What is the receiver's gain in dBm?
Gain = 10 log_{10} (10pW/1mW) = 10 log_{10} (0pW/1000000000pW) = 10 log_{10} (.000000001) = 10(-9) = -90dBm

2.1.2. Antenna Gain

When comparing the focusing characteristics of an antenna, the gain is the measure of the power that its electro-magnetic field can generate in a conductive surface at a given distance, relative to the power generated by a theoretical device at the same distance. The theoretical device is described as an Isotropic Radiator which is a point in space that radiates a uniform electro-magnetic field in all directions[3]. Its power level at the reference distance is 0.001 Watts or 1mW. So the gain is the ratio of the antenna's power to the theoretical 1mW. The same formula is used convert the dimensionless gain value to decibels (dB).
$Gain_{dB}$ = 10 log_{10} (device $power_{mW}$ /1_{mW}) or 10 log_{10} (device power).
When comparing antenna characteristics using the 1 mW Isotropic reference, the term GAIN expressed as dBi (decibel relative to Isotropic) is used. Using the decibel formula, the theoretical gain of an isotropic antenna = 10 log_{10} (1) = 10*0 = 0dBi.
The closest real antenna that exhibits isotropic characteristics is a simple dipole. The dimensionless gain of a dipole relative to an isotropic reference is 1.64mW / 1mW = 1.64[4]. Using the decibel formula, the gain of a dipole antenna = 10 log_{10} (1.64) = 10*0.2.15 = 2.15dBi.
When comparing antenna characteristics using the dipole antenna as a reference, the term Gain expressed as dBd (decibel relative to dipole) is used. The decibel gain of a dipole is = 10 log_{10} (1.64/1.64) = 10 log_{10} (1) = 10*0 = 0dBd. So, 0dBd = 2.15dBi, or gain dBi = gain dBd + 2.15. Antenna gain specifications will typically use decibel dBi or decibel dBd.

2.2. Radio Frequency Transmission

A wireless system in its simplest form uses a pair of digital radios equipped with an antenna to achieve communication between two physical locations that are separated by air space. These systems use electro-magnetic energy in the Radio Frequency range of 3 Hz (Extremely Low Frequency) to 300 GHz (Extremely High Frequency) to exchange information[5].
In the United States, the Federal Communications Commission regulates the use of RF bands by licensing entities using devices that produce EM energy in this range. The FCC allocates a range of frequency

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[2] http://en.wikipedia.org/wiki/Decibel
[3] http://en.wikipedia.org/wiki/Isotropic_radiator
[4] http://en.wikipedia.org/wiki/Dipole_antenna
[5] Weidner, R & Sells, R., 1975, *Elementary Physics Classical and Modern*, Allen and Bacon Inc, Boston MA, **III**, pg. 480 - 501

bands designated Industrial, Medical, and Scientific (ISM) that do not require licensing. These bands are @ 900 MHz (902 – 928), 2.4 GHz (2.400 – 2.483), and 5.8 GHz (5.725 – 5.850).

2.3. Transceiver and Components

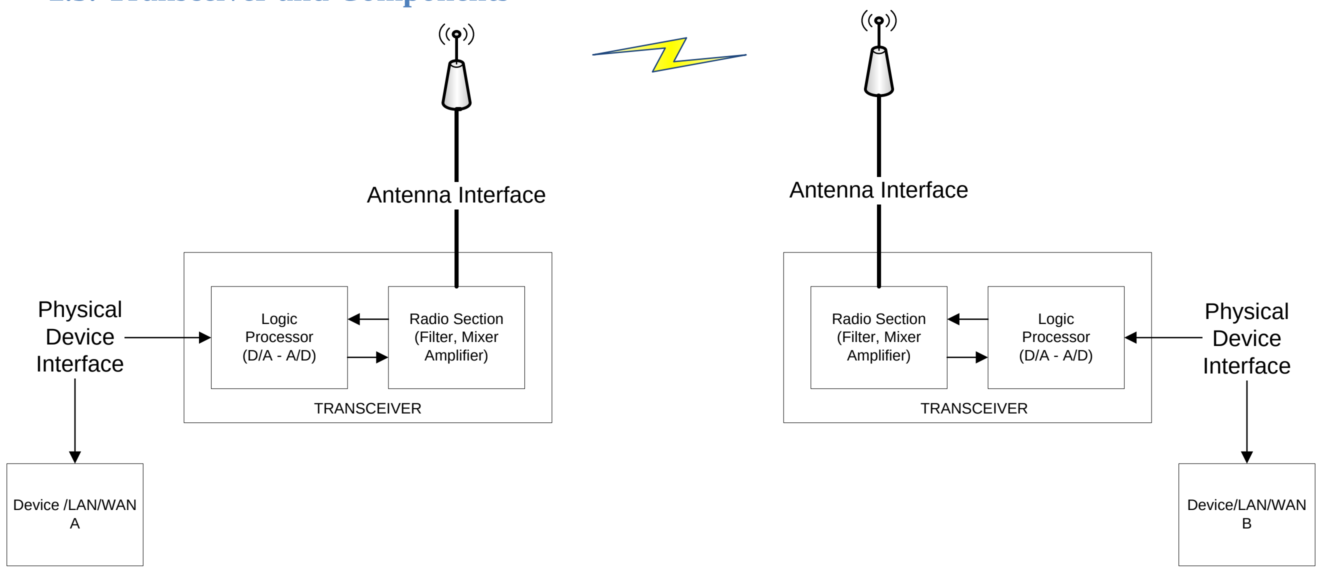


Figure 1 - Block Diagram of Basic Radio Components

2.3.1. Physical Device Interface

Wireless systems are available to provide seamless hardware interface connectivity to one or more devices, local area networks (LAN) or wide area networks (WAN) using similar communication protocols. The interface normally provides the physical connection based on the specific protocol. Mature independent protocols examples:

- Ethernet (Device/LAN/WAN)
- EIA RS-232-C (Device)

Common open industrial communication protocols:

- Profibus
- ControlNet

Vendor specific protocols:

- Modbus (Modicon)
- Data Highway (Allen Bradley)

2.3.2. Logic Processor

The logic processing unit converts protocol specific data between digital and analog domains. Digital to analog information encoding is accomplished by modulating the amplitude (AM), frequency (FM), or phase (PM) of the analog signal. More sophisticated methods such as spread spectrum, encode information across multiple frequencies within a band. Data encryption for security and channel multiplexing for multi-use are performed here as well. Since modulation, encryption, and multiplexing will be specific, their definition will be designed by an equipment vendor into a matching set of hardware or set as a general standard such as the IEEE 802.11[6] specifications that will allow interoperability between multiple vendors.

2.3.3. Radio Section

The radio hardware circuits use one or more filters and amplifiers to produce/receive encoded RF signals between antennas over one of the available frequency bands. Filters such as high pass, low pass, and band pass are used to isolate specific frequencies. Amplifiers increase the gain of analog signals betweens circuits within the transceiver and provide the gain between two or more transceivers separated by air space.

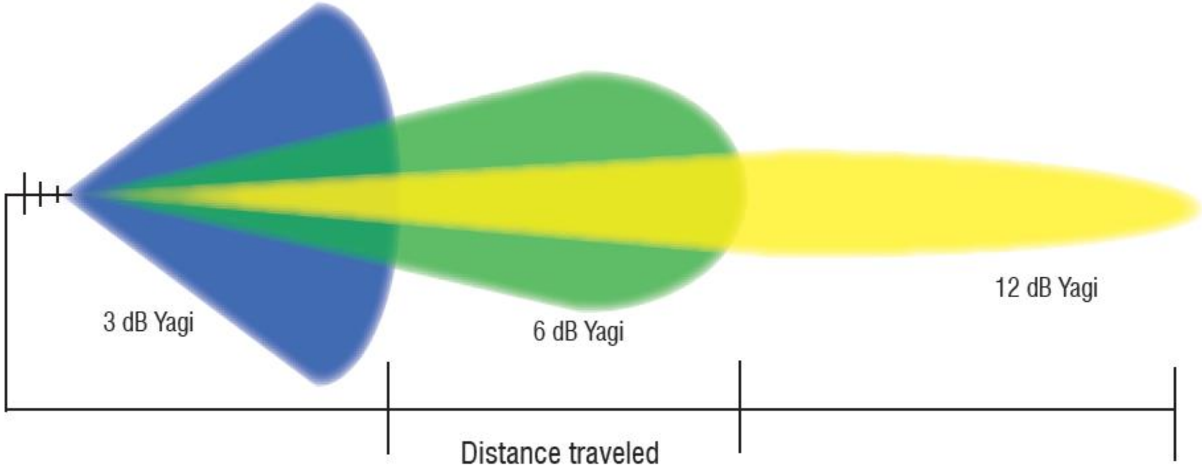
2.3.4. Antenna and Interface

Antennas transmit and receive the RF energy in free space. The antenna's physical interface to the transceiver is a critical component as each connecting device (cable, adaptor, etc) will attenuate or decrease the overall gain of the antenna system.

Antennas are typically designed to provide either uniform or directional sensitivity. A Yagi antenna design will generate and be sensitive to RF energy in a focused pattern which is parallel to the direction and in the same plane as the antenna is mounted.

Figure 2 - Yagi Antenna

A Yagi designed to have an increased gain will have a narrower focus, illustrated as follows.



[6] IEEE Computer Society, 2007, *Wireless LAN Media Access Control (MAC) and Physical Layer (PHY) Specifications*, Institute of Electrical and Electronic Engineers, New York NY, IEE Std 802.11-2007

Figure 3 - Energy Dispersion Pattern vs. Antenna Gain[7]

An Omni-directional antenna is designed to provide sensitivity that is in a uniform radial pattern in the plane perpendicular to the direction the antenna is mounted.

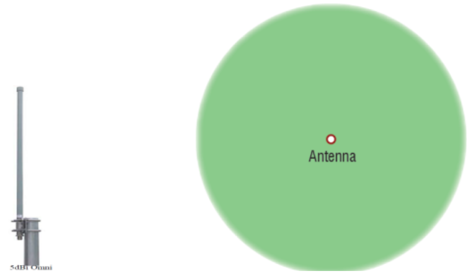


Figure 4 - Omni Directional Antenna with Top Dispersion View

A higher gain Omni antenna will have a narrower sensitivity in the vertical plane.

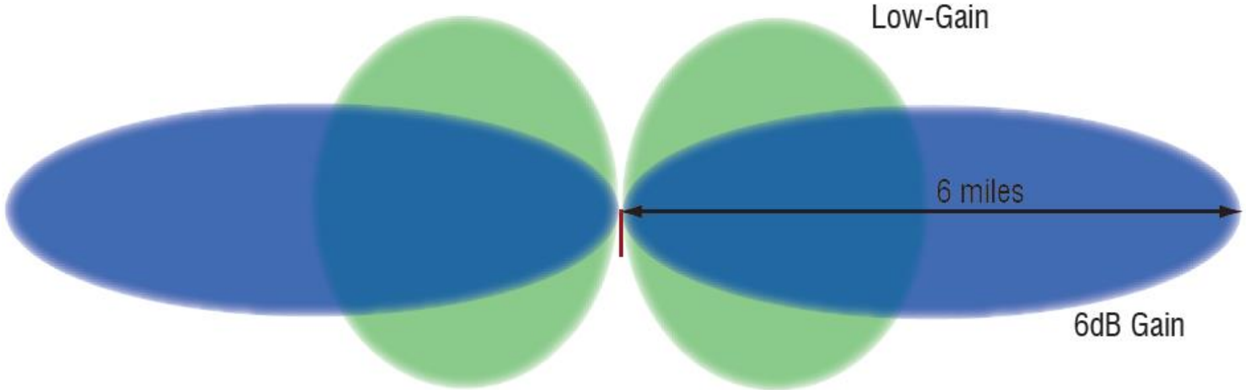


Figure 5 - Omni Directional Antenna Vertical Dispersion Pattern vs. Gain[8]

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[7] Banner Engineering Corp , 2010, *Antenna Performance* , Minneapolis MN, Publication Number 135765, pg 7
[8] Banner Engineering Corp , 2010, *Antenna Performance* , Minneapolis MN, Publication Number 135765, pg 6

3. WIRELESS APPLICATION PLANNING

Many factors influence the overall design strategy and consequently the choice of communication technologies. As with any engineered system for industrial applications, good planning will save time, effort, and dollars when the design evolves from the drawing board to full implementation.

3.1. Functional Design Considerations

Primary considerations are the functional requirements of the system.

- How many remote locations must be connected?
- What protocols are already in use?
- Will this system be attended or unattended/fully automated?
- Does this system require high bandwidth?

3.1.1. Equipment/Process Monitoring and Control

Process monitoring/control applications typically involve communication between PC workstations or servers and programmable controllers (PLC's) or distributed control systems. Most human machine interface (HMI) software packages such as Wonderware® provide configurable communication poll rates that can be adjusted to make the best use of available bandwidth. In a new installation, the designer has the luxury of selecting Ethernet as a communication protocol, which provides the widest range of hardware support. If there is an existing control system or communications infrastructure, the designer must also factor the use of the current technology vs. the cost of upgrading to Ethernet. The choice of wireless solutions should be prioritized based on:

- Matching the existing protocol or upgrading to Ethernet
- Robust radio connectivity and immunity from interference
- Strong data encryption
- System can be configured to use available bandwidth

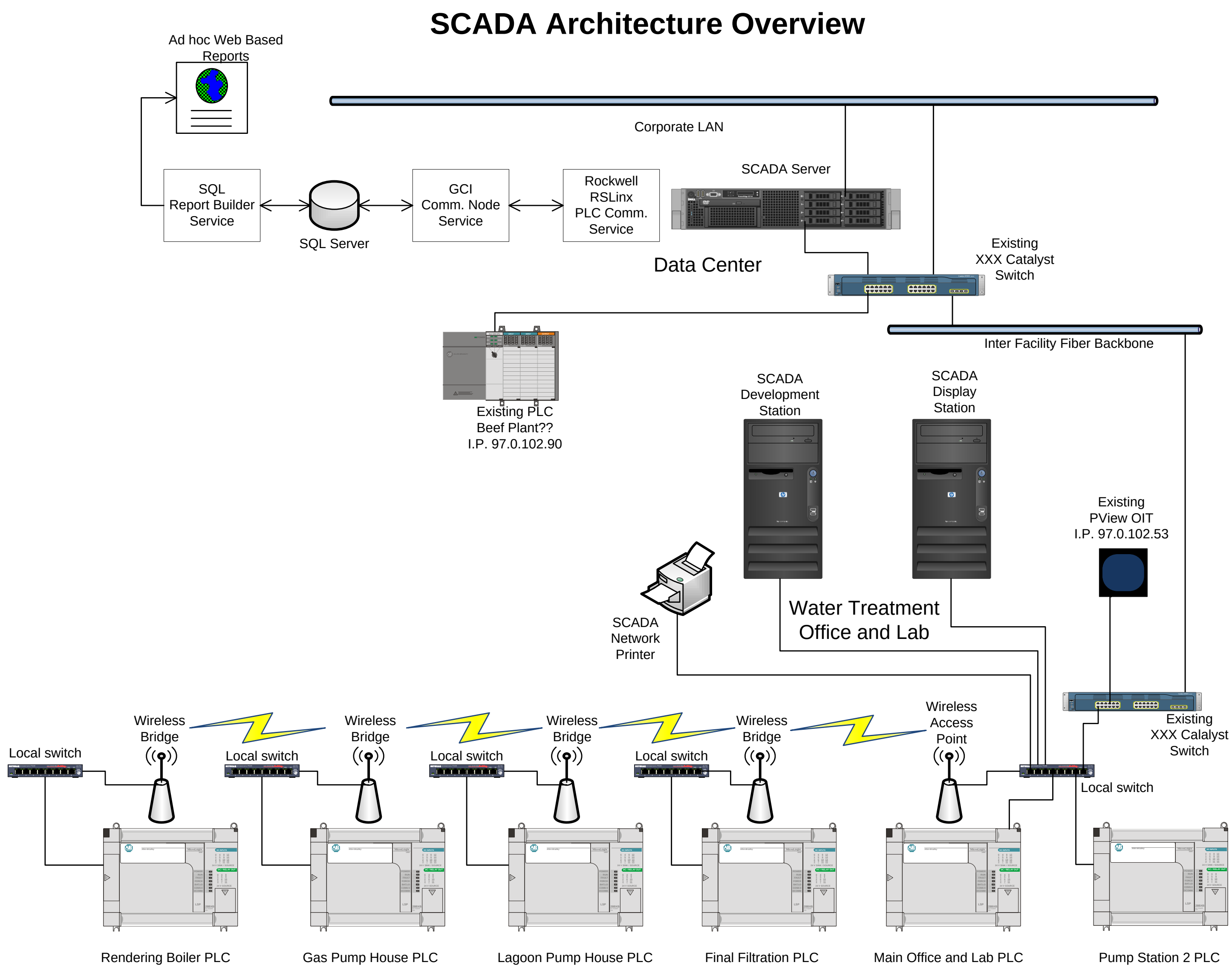

Figure 6 - Supervisory Control and Data Acquisition System with Wireless Architecture for Waste Water Treatment Facility

3.1.2. Unattended Equipment/Process Control

Unattended industrial control applications that span distances typically involve data exchange between a fixed number of devices. There are wireless systems that are designed specifically to provide very reliable connectivity for the limited bandwidth that's required for discrete and analog control. These systems typically include a discrete status in a form-C contact or solid state output that can be hardwired to a master control circuit. This would be used to place the remote system in a safe state in the event of communication failure. If the nature of the control application is mission critical, there are systems that provide hardware redundancy over an alternate radio path. There are also a number of wireless systems that support control architectures based on legacy technology such as serial over RS-232/422, Allen Bradley Remote I/O, Modbus, etc.

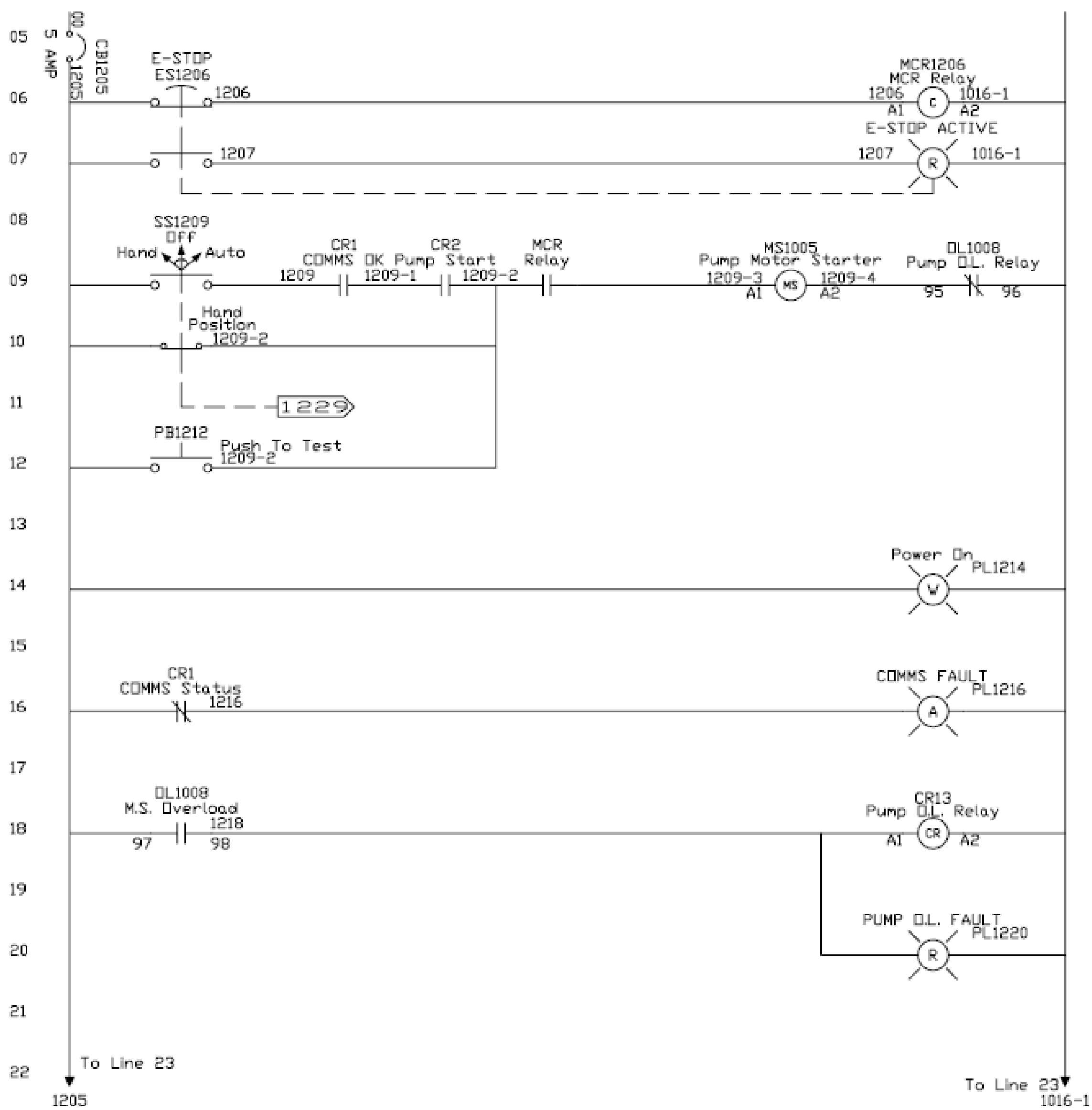

Figure 7 - Hardware Design with Communication Status Interlocked for Safe Operation

3.1.3. Attended Mobile Systems

Control applications that require a mobile wireless connection generally fall into an operator attended class. Attended mobile systems can benefit from simple wireless platforms that utilize hand held remote push button devices communicating with a fixed receiver. These are designed to exchange a small data set.

Figure 8 - Mobile Remote Push Button Transmitter with Matching Receiver

At the other extreme, mobile PC workstations can implement an HMI application to provide a range of control and monitoring functions in a facility. In either case, it's difficult to plan for 100% radio coverage since interference from obstacles may not be predictable. The system designer is responsible to ensure that equipment operation is safe if there is a loss of communications.

Figure 9 - Mobile PC Workstation with Wireless Ethernet Interface

3.1.4. Bandwidth Intense Applications

Remote applications that may require high bandwidth include:

- On-line PLC programming (100 – 500 Kb)
- Video surveillance (800Kb w/MPEG4 compression)
- LAN/WAN bridging (10Mb – 100 Mb)

Systems such as these that must operate together on the same wireless system may require a transceiver set operating at the 5.8 GHz frequency range. There are some tradeoffs that the designer must weigh when considering a higher frequency/bandwidth system.

- RF energy at 5.8 GHz suffers more free air signal loss than RF energy at 900 MHz for a given distance. A comparably equipped 5.8 GHz system has a shorter usable range than a system operating at the lower frequency.
- 5.8 GHz systems are less immune to interference from other sources of RF energy in the same frequency. These systems are best deployed where no radio signatures currently exist. This is typically not the case in an industrial environment.
- 5.8 GHz systems are less immune to signal loss due to physical obstructions. A 5.8 GHz system therefore requires clear line of site between the two transceiver antennas (no trees, buildings, etc). Again, this is typically not the case in an industrial setting.
- Due to the high gain antennas and higher elevation required for reliable transmission, these systems tend to be more expensive to deploy.

Based on the limitations and expense associated with high bandwidth transceiver systems, most industrial applications should be engineered to maximize efficiency so they can be implemented with the lower bandwidth hardware. PLC programming is an intermittent activity such that it can be coordinated with periods of reduced control system activity. A LAN bridge or video surveillance system might require separate, independent sets of wireless hardware. The rule of thumb is to use the lowest frequency transceiver set whenever possible.

3.2. Site Survey

In our experience, a site survey is an important task to complete before a wireless hardware solution can be finalized. The site survey should allow the designer to evaluate:

- System topology based on number and location of communicating devices
- Distance and clarity of sight between communicating devices/systems
- Existing wireless systems and or other RF sources at the site

3.2.1. Point to Point Topology

An Access Point is a transceiver set that can communicate with multiple transceivers on the same frequency. These secondary transceiver sets are referred to as Remote Subscribers. A Remote Subscriber can only communicate with one Access Point. The role selection on the transceiver is normally a hardware switch or software configuration. Most wireless hardware platforms that are currently available use the same transceiver hardware to function as either an Access Point or a Remote Subscriber.

A communication system that can be satisfied with a single connection between two locations can usually be implemented with a point – to – point design where two transceivers with properly selected antenna systems provide a wireless bridge between the communicating devices thus extending the protocol. This is conceptually similar to extending the cable media between the two devices. One of the transceivers will be configured as the Access Point, and one will be configured as the Remote Subscriber. In this arrangement, the available communication bandwidth between the two locations is equal to the bandwidth of the transceiver hardware.

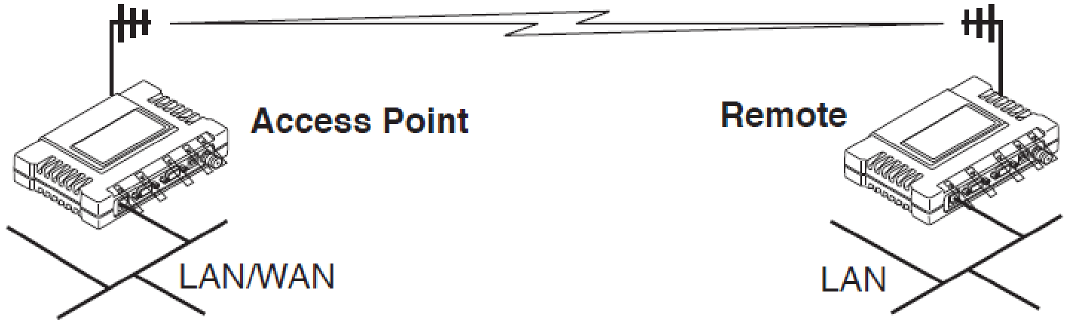

Figure 10 - Point to Point Topology[9]

3.2.2. Point to Multipoint Topology

A system that requires connectivity between multiple devices in different locations could be implemented with a point – to – multipoint topology where one of the locations is outfitted with a transceiver system configured to be a common Access Point. This is typically and most practically the device or LAN connection that is centrally located relative to the entire installation. The remaining locations are implemented with a transceiver set configured to be a Remote Subscriber. **A drawback of this solution is that the available communication bandwidth is shared among all of the locations, reducing the effective bandwidth at any one location.**

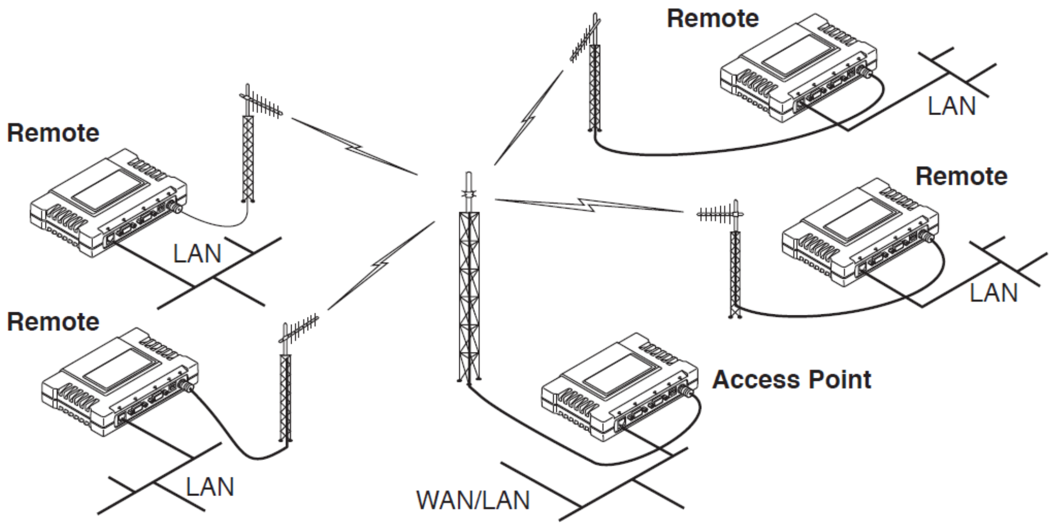

Figure 11 - Point to Multi Point Topology[10]

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[9] GE MDS LLC, *iNET Series Reference Manual*, Rochester NY, MDS 05-2806A01, Rev. H, pg. 8
[10] GE MDS LLC, *iNET Series Reference Manual*, Rochester NY, MDS 05-2806A01, Rev. H, pg. 8

3.2.3. *Point to Multipoint Alternative Topology*

If the reduction in bandwidth associated with a point – to – multipoint topology cannot be tolerated based on the application requirements, it is possible to design multiple point – to – point systems where the central location includes a separate Access Point transceiver set and antenna arrangement for each Remote Subscriber. This is a more expensive solution but maximizes the bandwidth at any one location.

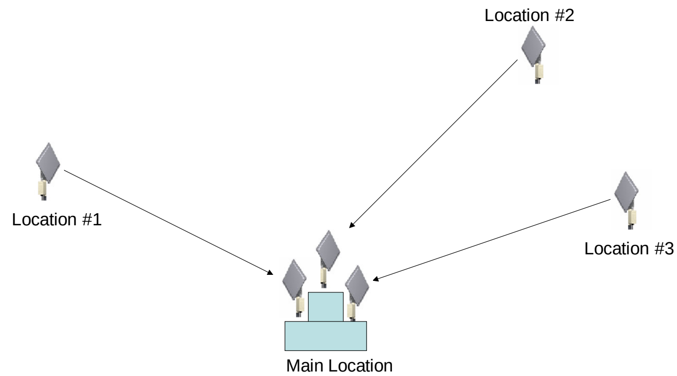

Figure 12 - Alternative Multipoint Topology to Preserve Bandwidth

3.2.4. *Distance and Terrain*

The distance and terrain between device locations is an essential component in the evaluation of a wireless solution. A portable global positioning system can aid in identifying the map coordinates of each proposed antenna location. An extremely useful tool to assist in this task is Google Earth, which can be downloaded from the internet site http://www.google.com/earth/index.html.

Start the Google Earth application, which will open an aerial view of the planet Earth in a web browser. On the top menu, click on the **View** pull down and select **Status Bar** so that it's checked. This will provide the longitudinal and lateral coordinates and the elevation of the pointer on the bottom of the display.

The mouse can be used to pan and zoom to display an aerial view of the target location. Alternatively, the location can be entered in the **Fly To** tab located on the side bar.

With the location in the map window, use the **Add** drop down and select the **Path** tool to create a linear path between the desired points on the map. Each path requires a name to be saved. Once these paths are created, select a path, use the **Edit** drop down and select **Show Elevation Profile**. An elevation window will provide a graphic representation of the surface topology. The path properties window contains a measurement tab that shows the distance between the path end points in user selectable miles or kilometers.

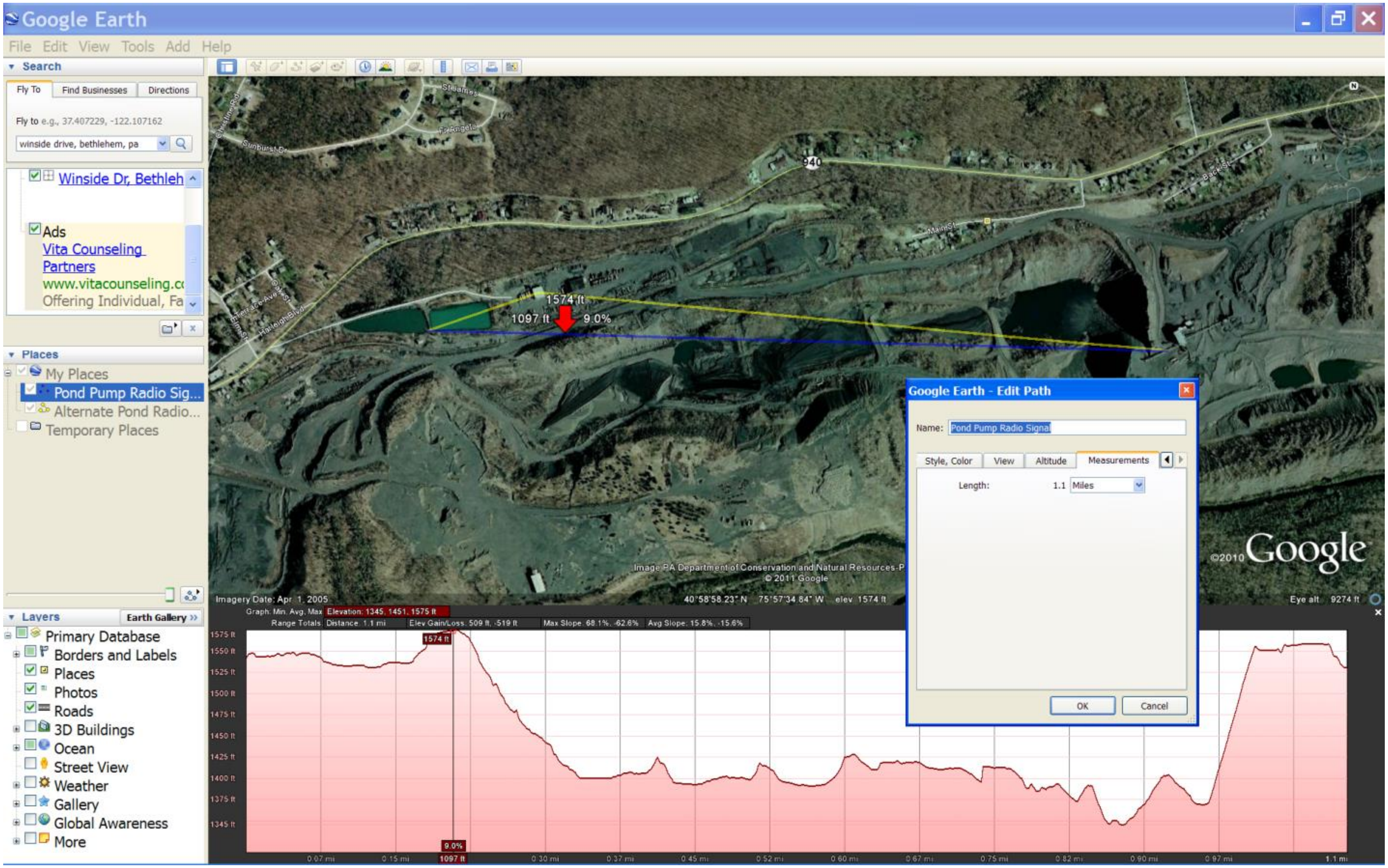

Figure 13 - Use of Google Earth to Evaluate Site Surface Terrain

3.2.5. Spectral Evaluation of Existing RF Interference

It is useful to know if there are any existing sources of energy in the RF band that will potentially be used. Many consumer and residential wireless devices occupy the 2.4 GHz and 5.8 GHz frequency bands. Cell towers also contribute to the background near the upper end of the 900 MHz spectrum.

There are wireless systems that provide utilities to measure the power spectrum of a given frequency band as well as the surrounding frequencies.

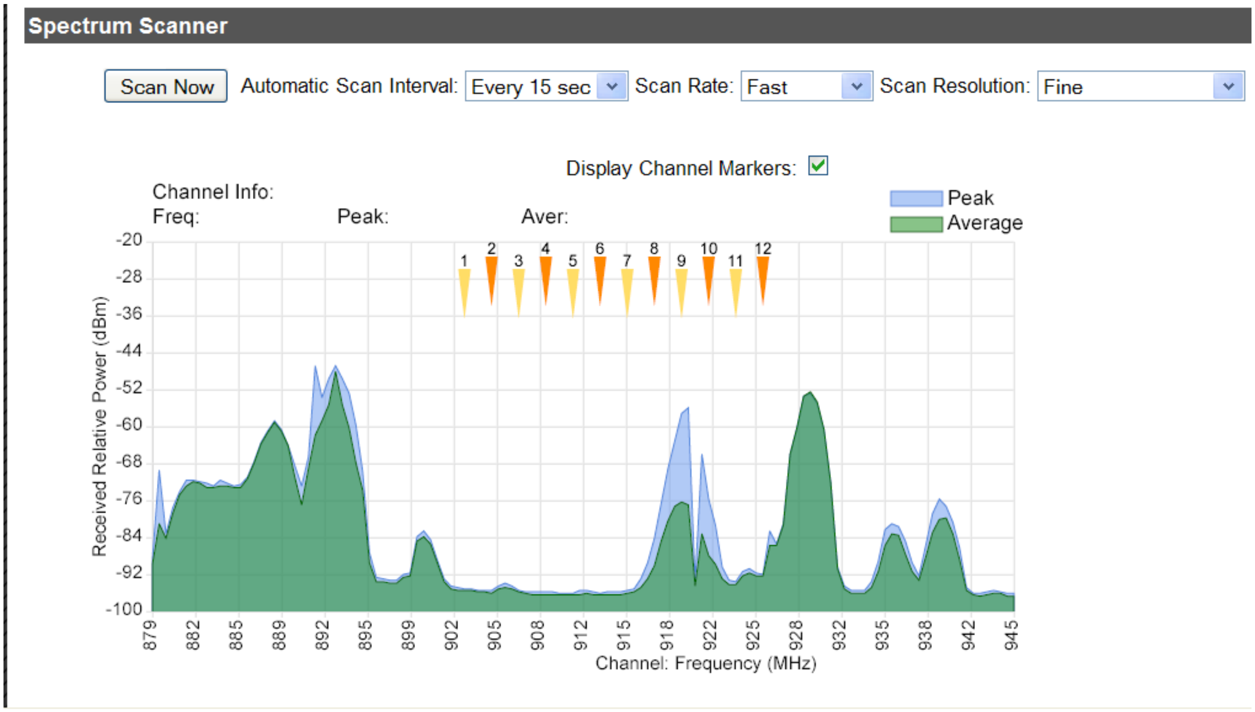

Figure 14 - RF Spectrum Display for Proposed Installation Site[11]

In the 900 MHz spectrum shown above, the usable band between 902 MHz and 928 MHz contains a noise signature at 920 MHz and a radio signature at 928 MHz. These frequencies should be avoided when deploying a new 900 MHz system.

[11] Spectrum Analyzer Utility, AvaLAN Wireless Systems Incorporated,

3.3. System Hardware Selection

3.3.1. Link Budget Calculations

Once the overall design strategy has been determined, selection of radio hardware requires an estimation of the overall wireless system gains and losses. Each component of the system will be accounted for in a Link Budget calculation.

Theoretical Received Gain = Transmitter Gain + Antenna 1 Gain + Antenna 2 Gain – Free Space Loss – Component Loss

Where:

- Transmitter gain is the power output of the transmitter section. This will be specified by the manufacturer.
- Antenna gain is the focusing characteristic. This will be specified by the manufacturer for a given antenna design in either dBi or dBd. Remember that if a dBd gain is provided, the value 2.15 dB must be added to yield an equivalent dBi gain.
- Free space loss is a physical loss of EM energy due to propagation. One accepted equation for free space loss between two isotropic antennas is $L = 20 \text{ Log } (4\pi d/\lambda)$[12]. L is the power loss in dBi. The equation simplifies to
  L = 20 Log (Freq in MHz) + 20 Log (Distance in Miles) + 36.6
- Component loss is the sum of all components that reduce or attenuate the radio signal. These include antenna connectors, antenna cabling, lightning arrestors, etc. The manufacturer will specify the loss associated with each component in dB.

Once the theoretical Received Gain is calculated, it is compared to the radio receiver sensitivity specification, which is supplied by the radio manufacturer. The Safety Margin = Calculated Received Power – Receiver Hardware Sensitivity. The safety margin will be specified by the radio manufacturer in order to guarantee stable performance.

3.3.2. Transceiver and Antenna Set Selection

The results of the Link Budget calculation will dictate the maximum distance between any two antennas at a given radio frequency. The distance can be increased by selection of a higher gain antenna. There are transceivers that provide a user selectable power output up to 29 dBm.

Obstacles such as trees and buildings can drastically increase the free space loss component of the link budget. In general, penetration of trees limits the distance between two high gain Yagi sets operating at 900 MHz to 1500 ft. 2.4 GHz and 5.8 GHz systems should not be used to penetrate trees. A method of obstacle avoidance between two locations is to design a system with an Access Point and two Remote Subscribers such that avoid the obstruction completely.

It is important to note that FCC regulations restrict the maximum forward gain of any unlicensed radio transmitter at 30 dBm. A combination of radio amplifier power and antenna gain that exceeds 30 dBm violates federal regulations. It is the responsibility of the designer to ensure that these rules are enforced.

[12] http://en.wikipedia.org/wiki/Path_loss

4. APPLICATION EXAMPLES

4.1. Waste Water Site Data Monitoring around Cellular Towers

System Description:

- 2 existing dedicated I/O transceiver systems @ 900 MHz
- 1 new local PLC and Ethernet transceiver @ 900 MHz with 5dBi Onmi Antenna in Access Point role.
- 5 new remote PLC systems outfitted with Ethernet transceivers @ 900 MHz with 9 dBi Yagi in Remote Subscriber role
- 2 LAN connected SCADA workstations with Rockwell RSView HMI application for monitoring and control
- 1 server class PC with data collection subsystem and SQL database
- Time stamped data collection mandated by DEP

Application Challenges:

i. Point to Multipoint configuration reduced overall bandwidth for each remote PLC system
ii. Large cellular array on the site premises caused interference
iii. Existing I/O telemetry system caused interference
iv. Resulting communication errors further reduced overall system bandwidth

Solution:

- Background noise and number of radios hampered the throughput of the system.
- Configured the sever PC to provide a clock synchronization update event once per day for all PLC’s and workstations.
- Used each PLC system to pre-process data and events to be collected by creating a time stamp and storing data entries in a logical memory stack. These stacks were unloaded to the server database when bandwidth conditions were favorable.

4.2. Remote Pump Control around Shale Hills on Coal Processing Site

System Description:

- Coal processing facility
- Replaced legacy PLC system with Ethernet based CPU
- Replaced remote pump control PLC system with Ethernet based fixed unit
- Replaced legacy point – to – point serial radio with newer 900 MHz Ethernet transceivers.
- 9 dBi Yagi and 11 dBi yagi with minimal antenna cabling operating over a distance of 1.1 miles
- LAN in facility connects control room workstations with HMI application to ISP hosted Internet access

Application Challenges:

i. Cell tower in plain sight of the facility
ii. System performance erratic, particularly after precipitation.
iii. Suspected a shale hill was obstructing the radio path
iv. Not practical way to measure elevation of hill due to inaccessibility
v. Spectrum analysis revealed a second radio system operating @ 900 MHz.

Solution:

- Used Google Earth to do an elevation analysis of the line between the two antenna installations.
- Found the suspected hill was the obstruction.
- Retrofitted the site with a third radio to act as a repeater, located around the hill obstacle.
- Re-configured the radio roles such that end units were Remote Subscribers

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http://en.wikipedia.org/wiki/Isotropic_radiator

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