Case Study: Radio Application in a Smart Grid System for a Brownfield Onshore Dispersed Oil Field

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CASE STUDY: RADIO APPLICATION IN A SMART GRID SYSTEM FOR A BROWNFIELD ONSHORE DISPERSED OIL FIELD

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Abstract – Smart grid systems for onshore oil fields use real-time, high-speed field data from intelligent electronic devices (IEDs) to make fast and intelligent decisions that increase power system reliability and minimize power outages. For an efficient smart grid system, a reliable communications network to the IEDs and centralized controllers is critical for high-speed control and data collection. Communications networks that use conventional fiber networks are not always cost-effective for large dispersed oil fields, which have hundreds of miles of medium-voltage overhead distribution systems. This paper discusses the implementation of a smart grid system for a large dispersed oil field using radios as its communications network. The solution includes high-speed load shedding, online monitoring, event reporting, oscillography, and engineering access. This paper also discusses the process used to design and test the radio technology, including the evaluation of its success metrics, network security, radio path study, and optimization.

Index Terms — Radio networks, radio link design, link budget, path studies, load shedding, high-speed control.

I. INTRODUCTION

Implementing a smart grid system for a geographically spread out oil production brownfield has unique challenges. The goal of the implementation described in this paper was to improve the reliability and workflow optimization of a brownfield oil electric power system (EPS) to reduce power outages and downtime and minimize oil production interruptions. This onshore dispersed oil field is powered by utility power and multiple cogeneration facilities across the field. The power is distributed using hundreds of miles of overhead lines, reclosers, and capacitor banks. An efficient and high-performance smart grid system requires a solid network backbone that connects electrical components in the system for high-speed operations and data collection. The conventional system design is a dedicated fiber network; however, getting fiber to the equipment when an oil field is spread out across many miles is expensive.

Today, wireless communications systems, or radio systems, provide the best alternative to fiber-optic communications for many reasons. First, they are more economical. A pair of radios is quite affordable, and the cost of establishing a link for a pair of unlicensed radios is only the cost of the radio equipment and installation. Second, the maturity of radio technology provides a wide range of options, including public or private networks, licensed or unlicensed bands, and standard-based or proprietary systems. Lastly, advancements in signal processing techniques have made it possible for radio systems to support higher data speeds, improve immunity to noise, and more effectively reject interference. These signal processing techniques include multiple antennas and are known as multiple input, multiple output (MIMO) and orthogonal frequency-division multiplexing (OFDM).

Although radios provide many benefits, they also have certain limitations. Choosing the right radio for an application is a matter of matching the radio technology capabilities to the requirements of the application. This paper describes the smart grid application requirements for a dispersed onshore oil field and discusses the radio communications system options that met the system requirements. The paper also describes the methodical process used to design the radio communications links and implement the selected radio system. A pilot project was initiated to design and validate the radio communications links and ensure that they were reliable for this smart grid application. Because it is critical for the radio communications network to operate effectively for high-speed load shedding, key success metrics were defined. Once the radio communications network was proven to meet the metrics, it was likely to meet all communications requirements.

II. THE DISPERSED OIL FIELD EPS

Fig. 1 shows a simplified one-line diagram of the dispersed oil field EPS at the beginning of the project. The EPS consists of three 12.47 kV feeders that receive power from a 115 kV utility overhead power line and eight cogeneration facilities. The feeders share a transformer and a 12.47 kV bus. Cogenerators G1 through G4 are located close to the end of Feeder A, and G5 through G8 are at the end of Feeder B. Each feeder has several branches that tap off of the main feeder.

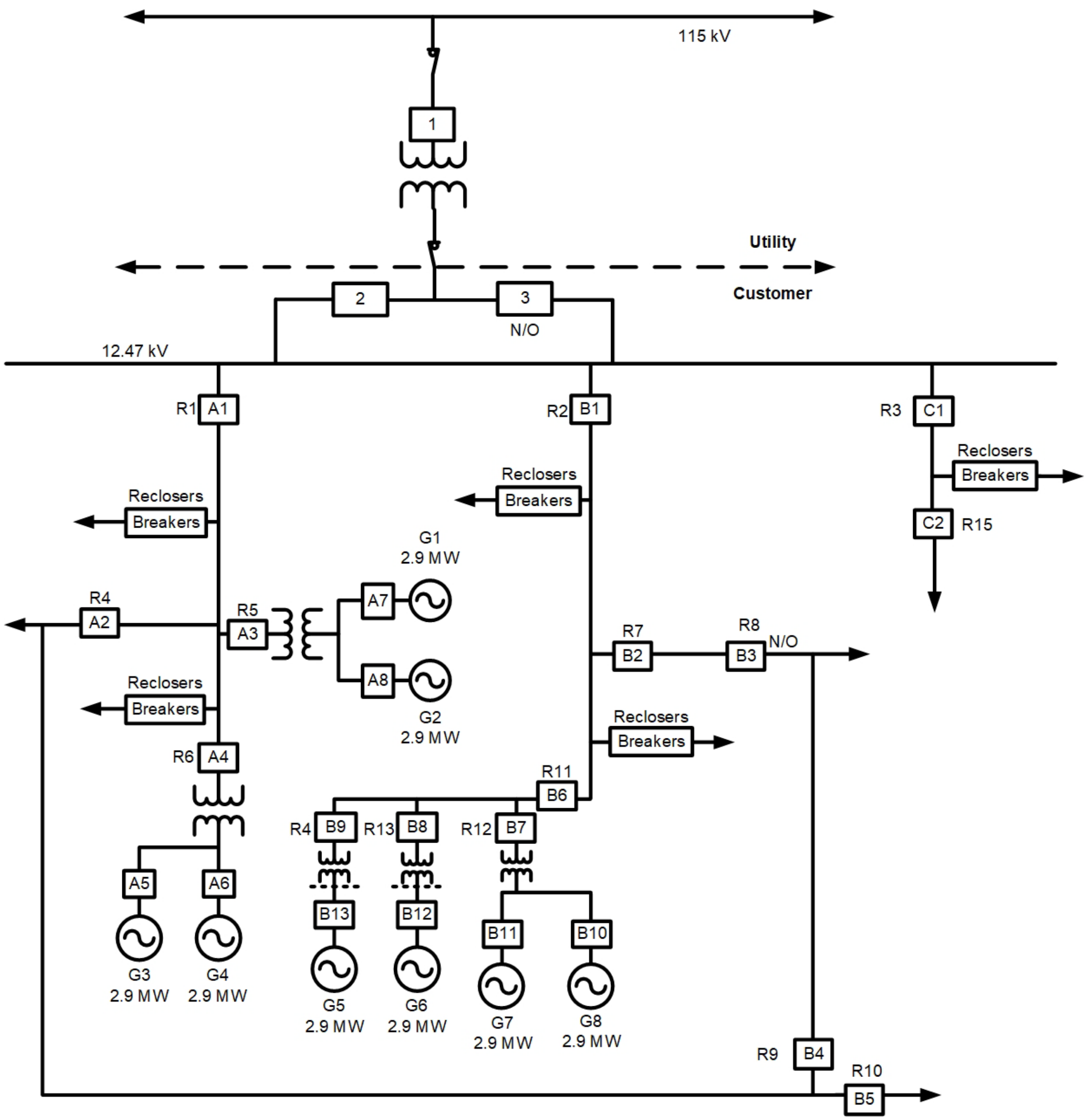

Fig. 1 Simplified One-Line Diagram

During normal operations, the utility lines enter the oil field through Breaker 1 and are then transformed to 12.47 kV. Normally, Breaker 3 remains open and Breaker 2 remains closed. Most of the time, local cogenerators produce more power than required; hence, the oil field exports power to the utility. When the system is islanded from the utility, G5 through G8 run in isochronous mode and G1 through G4 run in droop mode. These cogenerators are connected through Reclosers R1 and R2.

In the event of unbalance between generation and load while islanded, the smart grid system must perform high-speed load shedding to maintain the balance between generation and power consumption. The speed requirements of the radios were analyzed for various equipment variations, such as recloser operating time, to meet the high-speed load-shedding requirements. Note that the reclosers do not perform any reclosing. The radio links were then designed and validated to ensure that they effectively met the requirements.

III. SMART GRID RADIO COMMUNICATIONS REQUIREMENTS

This oil field has three distinct data communications requirements for smart grid operations. Table I summarizes these requirements and lists their key attributes.

TABLE I
KEY ATTRIBUTES FOR DATA COMMUNICATIONS

Data Communications Requirements	Latency	Bandwidth	Distance	Availability
High-speed load shedding	Approximately 50 milliseconds (ms)	Low: small packets with time determinism	Approximately 10 miles	High: requires high-speed control action
SCADA	2 to 5 seconds	Medium: steady operational data and occasional large file transfers	Wide variation	Medium to high: needs reliable access; transport protocols retransmit lost data
Engineering access and event collection	5 to 10 seconds	Medium: command interaction and large file transfers	Approximately 10 miles	Low to medium: can tolerate dropouts

A. High-Speed Load Shedding

Load shedding is the processes of tripping breakers to remove load from the power system in order to maintain the balance between generation and demand. The load-shedding scheme used in this oil field is contingency-based. An underfrequency-based load-shedding scheme and a progressive overload-shedding scheme are also used for backup [1]. In contingency-based load-shedding schemes, the smart grid system constantly monitors contingency breakers. Once a contingency breaker opens, the smart grid fast load-shedding system must operate in less than 130 milliseconds (approximately 8 cycles) according to the stability study. This is the round-trip communication time that includes contingency breaker open detection, transmission time from the signal to the controller, controller processing time, transmission time from the radio communications signal to the recloser that needs to operate, and recloser opening time. Fast- and slow-opening reclosers are available in the field. The fast-opening reclosers operate in 32 milliseconds (approximately 2 cycles). The slow-opening reclosers operate in 80 milliseconds (approximately 5 cycles). If the recloser opening time is subtracted from the latency requirement, the radio communications must operate in less than 50 milliseconds for slow-opening reclosers and 98 milliseconds for fast-opening reclosers.

Fiber-optic communications undoubtedly meet these speed requirements. Radio communications need to be evaluated, validated, and verified to ensure that they meet the requirements. Radio communications link delays are typically longer than those of fiber-optic communications links, especially when the radios use encryption. The fiber-optic links are immune to electromagnetic interference and operate at a higher bandwidth. Electromagnetic interference, bandwidth, and line of sight are a few challenges with radio communications systems in terms of speed and availability. Section IV addresses some of these challenges.

B. Supervisory Control and Data Acquisition (SCADA)

SCADA communications links connect remote IEDs, substation front-end processors, and controllers in control centers. Remote IEDs are typically installed inside recloser cabinets. SCADA systems require periodic data inquiries from field IEDs and manage smart grid control operations. The inquiry period is approximately 2 to 5 seconds [2]. The smart grid system constantly monitors the oil field power system status by collecting data, processing the collected data, and performing control operations and load shedding. Operational data include voltages, currents, and device status. When digital inputs change state, the system often uses report-by-exception messages.

Although the majority of radio technologies meet these data communications requirements, the challenge with this project was that the radio had to meet all three data communications requirements simultaneously. It was crucial that the selected radio system meet all the data communications requirements and be able to perform high-speed load shedding while collecting SCADA data and/or allowing engineering access. It also had to support high-speed communications protocols.

One key decision when selecting a radio system is whether to use a single radio or multiple radios. If selecting a single radio, that radio must support either three different channels with at least one of those channels supporting a high-speed communications protocol or a single channel supporting different communications protocols simultaneously. Using multiple radios for a link at the same location can lead to radio interference issues and higher equipment and maintenance costs. Using a single radio may avoid these issues, but one disadvantage of using a single radio is the single point of failure. Therefore, radio selection (single or multiple radio and single channel or multiple channels) is a key component that designers must consider.

C. Engineering Access and Event Collection

Engineering access allows users to communicate with a field device from a central location. This is often achieved through a fiber-optic or hardwired backbone infrastructure. When radios are used, the radio communications channel dedicated to this function is mostly idle. The data transfer typically consists of short commands and responses for engineering access and sporadic file transfers, such as event reports, oscillography, settings, or firmware files.

Depending on the speed of the radios, transferring large files can take much longer with radio links than with fiber-optic links. Large file transfers should not degrade the performance of high-speed load shedding and SCADA data collection. If a single radio and a single channel are selected as the radio system, then the designer must validate and ensure that the data file transfer time will not affect the other requirements.

D. Latency

Latency is the delay between the input to a radio system and the desired output. A key requirement for high-speed load shedding for a dispersed oil field is that the radio system latency must be constant with minimal variation. When evaluating radio system latency, it is important to know the minimum and maximum latency variations for the radio links. These variations must be considered in the radio network design, and it must be determined whether or not the variations are acceptable for the smart grid high-speed load-shedding scheme. The radio link latency depends on the protocol, technology, and type of communications used. Serial radios often experience less variation than Ethernet radios. To ensure proper radio system operation, it is critical to determine the expected average, minimum, and maximum latency for a given operation.

E. Availability

Availability is the ratio of time that a system is functional to the total time it is required to function; a high availability is desired. For instance, a 99.95 percent availability implies 263 minutes of outage time per year, and a 95 percent availability implies 438 hours of outage time per year. For smart grid oil field applications, the widely accepted radio link availability requirement is 95 to 99.95 percent [2]. Availability and latency are used to calculate the overall system performance.

Even though fiber-optic links have less availability concerns, there are other challenges when using fiber in large, open onshore oil fields. Most fiber-optic cables are installed on fiber poles or power poles and can be subjected to vandalism, vehicle accidents, lightning, storm damage, and wildfires. These issues can have a negative impact on fiber link availability.

F. Encryption

It is important that the selected radio system and network provide wireless link encryption capabilities. Data must be encrypted before exiting the wireless radio channel. Encryption adds confidentiality to the radio communications network so that only the intended recipient can decipher the information. One popular method of encryption is the Advanced Encryption Standard (AES). This method uses a secret key and breaks the plain text into blocks. It operates on blocks of data and scrambles the blocks using different transformations, including substituting bytes, shifting rows, and mixing columns. AES uses several rounds of these transformations to encrypt the plain text [3]. Encryption typically adds latency to communications systems.

IV. RADIO COMMUNICATIONS SYSTEM DESIGN

When the project team began the business review for the brownfield project based on an approved fiber design, it was discovered that one recloser was not in the fiber plan and that a special run to that recloser would be required. This particular recloser supports the sheddable load. Laying dedicated fiber for this remote recloser would have been very expensive. Based on the financial analysis, the project team decided to use radio communication for that recloser because the system had a dedicated fiber network for other loads that would support the system if the radio link failed.

Another consideration for the team was that if this pilot project was successful, then other sites with similar types of reclosers could also use the design.

The design processes began with the radio system selection. The radio communications system was evaluated and validated with the following process:

1. Determine if the radio communications link has direct line of sight.
2. Perform a link budget analysis.
3. Conduct a path study of the link.
4. Perform an onsite survey.
5. Perform optimization.
6. Perform validation.

A set of success metrics was defined to determine if the radio system would be adequate for the smart grid application.

After analyzing the data communications requirements, the possible options were Ethernet radios or serial radios. Based on the security requirements, the project team decided to use a serial radio system with encryption and multiple channels. The following is a list of the characteristics and specifications for the selected radio system:

1. Three independent serial ports with three different protocols for high-speed load shedding, SCADA, engineering access, and event collection.
2. Standard communications protocols, such as DNP3, and a serial high-speed communications protocol.
3. A maximum transmit power of 30 dBm.
4. Receiver sensitivity of –97 dBm and –104 dBi with automatic repeat request.
5. Channel bandwidth of 250 KHz.
6. Three-element Yagi antennas with 8.5 dBi gain.
7. AES 128-bit encryption.

A. Line of Sight

Although a direct line of sight does not guarantee that the radio communications link will work, it is one of the first considerations for a designer. In a radio communications system, there is a distinction between visual line of sight and radio line of sight. Radio line of sight is typically 30 percent longer than visual line of sight because of bending in the earth’s surface [3]. Designers often use radio line of sight for radio system design. Using visual line of sight is possible for shorter ranges, but additional design steps will be necessary to determine the link quality.

Radio line of sight is determined by the Fresnel zone. Fig. 2 shows the maximum Fresnel zone diameter between two antennas. Obstruction within the Fresnel zone can reflect radio signals and cause interference [3]. The formula to compute the Fresnel zone is shown in (1).

$$r = 17.32\sqrt{d/(4f)} \qquad (1)$$

where:

r is the radius of the Fresnel zone in meters.

d is the distance between the transmitter and receiver in kilometers.

f is the frequency carrier in GHz.

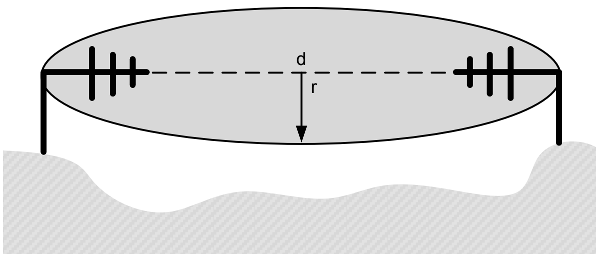

Fig. 2 Maximum Fresnel Zone Diameter Between Antennas

Table II shows the diameter of the Fresnel zone for various distances between antennas for a 900 MHz radio system.

TABLE II
DIAMETER OF FRESNEL ZONE

Distance Between Antennas	Fresnel Zone Diameter
304.8 meters (1,000 feet)	4.9 meters (16 feet)
1.6 kilometers (1 mile)	11.6 meters (38 feet)
8 kilometers (5 miles)	25.9 meters (85 feet)
16 kilometers (10 miles)	36.6 meters (120 feet)
24 kilometers (15 miles)	44.8 meters (147 feet)
32 kilometers (20 miles)	51.8 meters (170 feet)
40 kilometers (25 miles)	57.9 meters (190 feet)

Based on the GPS site location for this project, there is a clear visual line of sight if the antenna heights are above 40 feet. The Fresnel zone diameter for this link is 38 feet. This implies that the antenna heights for the transmitter and receiver must be at least 38 feet to avoid any obstacles and be within the Fresnel zone for a flat surface.

B. Link Budget Analysis

A link budget analysis helps designers determine if a communications system meets range requirements. The range is often referred to as the line-of-sight path. In a brownfield, the distance between the transmitter and receiver is often known. The design is used to determine the maximum transmitted power within the allowed limit for a given receiver sensitivity to ensure reliable communication. For a greenfield or unknown distance, designers use the maximum transmitted power in conjunction with the receiver sensitivity to specify the maximum range for the radio system. The following subsections describe the terms used in the link budget analysis.

1) *Transmit Power:* Transmit power is typically expressed as a ratio with a known reference. A power ratio reference of 1 mW is commonly used and often expressed in the logarithmic quantity dBm. A transmit power of P is given by (2).

$$dBm = 10\log(P/1\,mW) \qquad (2)$$

2) *Antenna Gain:* Antenna gain is the ability of an antenna to radiate radio frequency in a particular direction for a given transmit power. Antennas are passive devices and do not amplify or alter the radio frequency power of the radio. The gain is typically expressed in dB, which is a logarithmic ratio of two power quantities and given by (3).

$$dB = 10\log(P_2/P_1) \qquad (3)$$

where:

P1 is the input power.

P2 is the output power.

This power ratio in dB is a unitless quantity.

a) *Directional Antennas*. Directional antennas, or Yagi antennas, are designed to radiate most of their power in one direction. Because of this radiation pattern, directional antennas have higher gains in one particular direction than in any other direction. Directional antennas are typically used for point-to-point communications.

b) *Omnidirectional Antennas.* Omnidirectional antennas have equal radiated power in all directions. They are generally used for point-to-multipoint communications.

3) *Radio System Path Loss:* The attenuation of the radio signal in a line-of-sight path is referred to as path loss. Designers typically use path loss in free space to estimate the path loss and received power. For the free-space path loss, the attenuation of the transmitted signal is a function of distance and frequency and is given by (4) [4].

$$L_p = 20\log(4\pi d/\lambda) \qquad (4)$$

where:

L_p is the path loss in dB.

d is the distance between the transmitter and receiver.

λ is the wavelength of the radio frequency carrier in the same unit as the distance and is given by $\lambda = c/f$, where *c* is the speed of light and *f* is radio frequency carrier.

The path loss equation, as shown in (5), can be rearranged to provide path loss as a function of distance in miles between the transmitter and the receiver and the radio frequency carrier in MHz [5].

$$L_p = 36.57 + 20\log\left(d_{(miles)}\right) + 20\log\left(f_{(MHz)}\right) \qquad (5)$$

Equation (5) is often used to estimate the maximum line-of-sight range for the given transmit power and receiver sensitivity or to estimate the required transmit power and receiver sensitivity for a radio link over a known distance.

By using the terms in dB and dBm, the received power can be expressed as the addition or subtraction of the two and is given by (6) [4].

$$P_R = P_T + G_T + G_R - L_p \quad (6)$$

where:

P_R is the receive power in dBm.

P_T is the transmit power in dBm.

G_T is the transmit antenna gain in dB.

G_R is the receive antenna gain in dB.

L_p is the path loss in dB.

Fig. 3 shows an example of the components described in (6). Note that the free-space path loss does not consider interference from terrain, buildings, climate conditions, multipath fading, or other factors that may adversely affect radio propagation. The free-space path loss model provides the best-case scenario (or lowest propagation loss) by ignoring these factors. To ensure that the radio system works reliably, the designer must perform a path study and onsite survey, which are described in Subsections C and D.

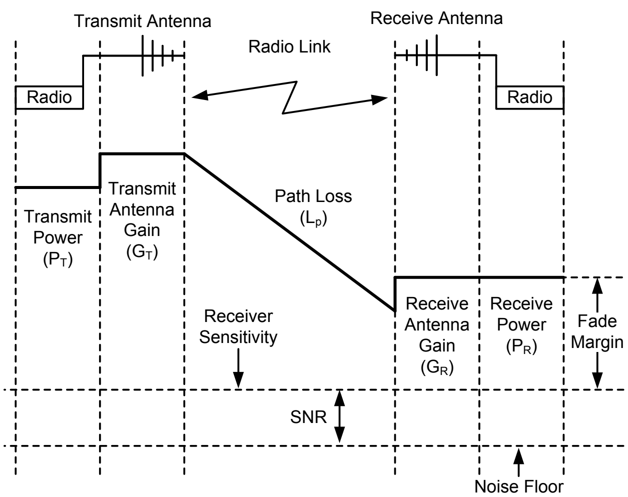

Fig. 3 Example of Components Described in (6)

4) *Receiver Sensitivity:* The receiver sensitivity indicates whether the receiver can decode the received signal or information. The receiver sensitivity defines the lowest received signal that can be detected or decoded and still provide a reliable communications link. Sensitivity is often defined in terms of Bit Error Ratio (BER) at the sensitivity threshold. The BER limits are typically between 10^{-3} and 10^{-6}. A lower sensitivity means that less transmit power is needed for a reliable link over a specified distance.

In general, the receiver sensitivity is a function of the thermal noise, bandwidth, bit rate, modulation type, and noise figure of the receiver.

5) *Signal-to-Noise Ratio (SNR):* The SNR is the ratio of the received power to the noise power in the communications channel. It is a key quality measurement for the received signal. A higher SNR often indicates a higher-quality link. However, the SNR often does not consider interference signals. The SNR is usually given in dB.

6) *Noise Figure:* The radio noise figure is a measure of how much the radio circuitry degrades the SNR of an incoming signal and impacts the sensitivity of the radio.

7) *Fade Margin:* Fade margin is the difference between the received signal and the maximum sensitivity of the radio. It determines the allowable signal loss between the transmitter and receiver. At least 20 dB of margin is recommended to maintain a good link while minimizing radio interruption. This margin reduces the possibility that the received signal will degrade below the receiver sensitivity due to variable environmental effects, such as variations in temperature and humidity or radio interference.

8) *Link Budget Analysis:* Putting all these concepts together, a link budget example is given by (7) [6].

$$P_T + G_T - L_p + G_R - M_F \geq R_S \quad (7)$$

where:

P_T is the transmit power in dBm.

G_T is the transmit antenna gain in dB.

L_p is the path loss in dB.

G_R is the receive antenna gain in dB.

M_F is the fade margin.

R_S is the receiver sensitivity.

Therefore, the P_T, G_T, L_p, G_R, and M_F calculation must be greater than or equal to the receiver sensitivity to establish a reliable radio link.

The link budget analysis for this project shows that transmitting 30 dBm is sufficient for the link. The path loss is 99.9 dB, and the received power is 30 + 8.5 – 99.9 + 8.5 = –52.9 dBm.

If a fade margin of 20 dB is used, the link budget is 30 + 8.5 – 99.9 + 8.5 – 20 = –72.9, which is larger than the specified receiver sensitivity of –97 dBm. Based on this link budget analysis, this radio system meets all of the data communications requirements. It is not guaranteed, however, and additional analysis must be performed for greater confidence in the system.

C. Path Study

After the link budget analysis is complete, a path study typically follows. The path study, similar to the link budget analysis, does not guarantee that the link will work but helps designers determine if the link is viable.

Path study software uses terrain and clutter data, radio-specific information, antenna design, and antenna tower height to compute the path study. These elements are not considered in the link budget analysis and may degrade the communications link and affect the performance of the radio system. However, most path study software does not consider buildings and man-made obstacles. To ensure that these obstacles will not affect the link quality, they must be added to the path study manually or ignored in this step and then verified during the onsite survey.

Most path study software uses the GPS coordinates of the transmitter and receiver. Based on these coordinates, the path study software loads environmental data, such as terrain, to perform the path study. Some parameters that are required in the path study include antenna heights and gains, receiver sensitivity, transmit power, and other parameters, depending on the software. It is important to properly configure the software, correctly set the parameters for the site under study, and use up-to-date data.

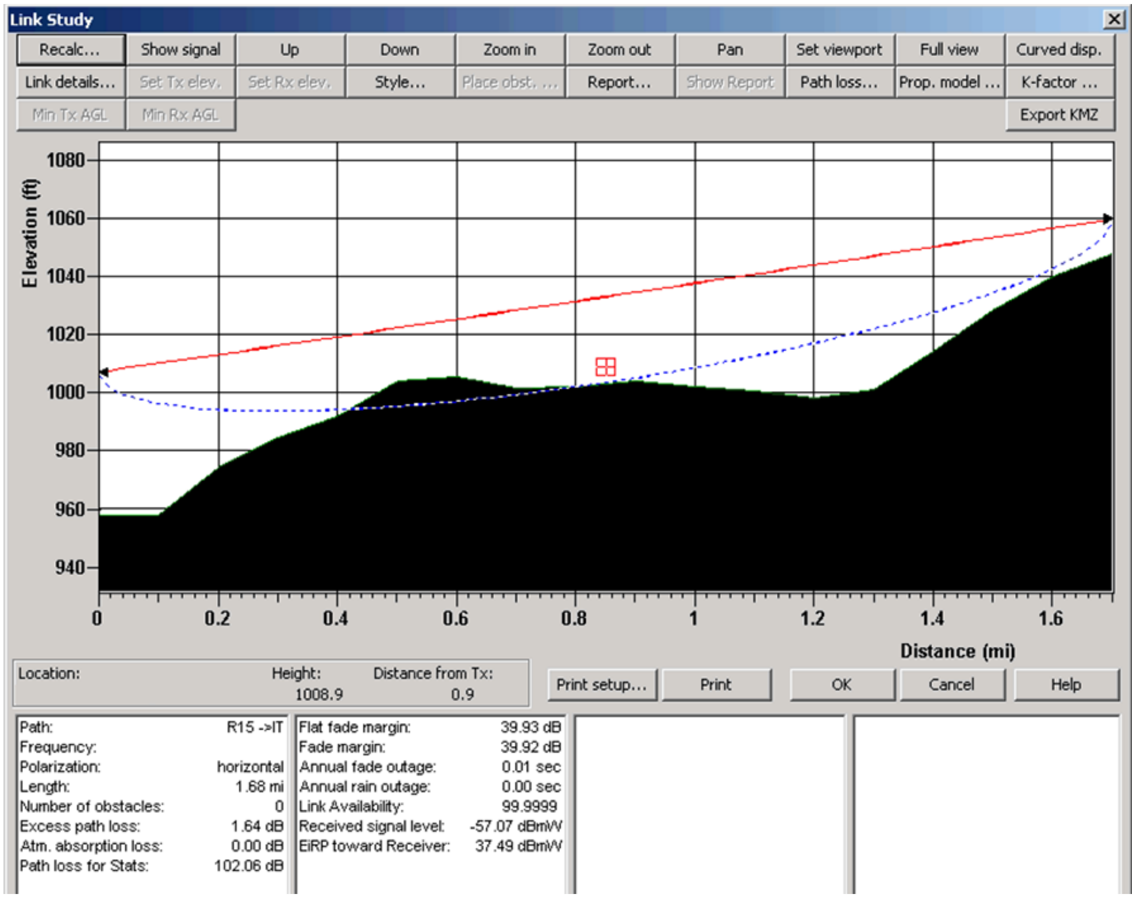

Fig. 4 Path Study

The output of the path study includes a diagram showing a line-of-sight line, the Fresnel zone, and any obstacles between the transmitter and receiver. In addition to the diagram, most path study software provide a list of calculated data based on propagation through the obstacles and multipath effects.

Fig. 4 shows the path study for the link in this project. It clearly indicates that a small portion of the Fresnel zone is blocked by the peak of a small hill. However, the received power is –57.07 dBm, and the fade margin is almost 40 dB. Note that the key difference between the analytical values and the path study is that the analytical computation does not account for the loss of cables and connectors. These values along with the link availability of 99.999 percent strongly suggest that this link is quite reliable and adequate for the smart grid application.

D. Onsite Survey

The onsite survey is used to verify the link and ensure that it will work properly. A path study may show that the received signal is adequate for the link, but unexpected details discovered in the onsite survey, such as sources of radio interference not considered in the path study, moving objects in the surrounding areas, or an inability to install the antenna at the desired location, can significantly impact the radio system performance [7]. An easy way to perform an onsite survey is to install temporary radios at the desired locations and measure the received signal strength and spectrum characteristics of the environment to ensure that any interference does not exceed the expected level.

For this project, the project team installed the selected radios at the recloser cabinet and IT control room and performed optimization and validation using defined metrics to validate the link quality.

Fig. 5 shows a simplified diagram of the devices and radio communications setup. The distance between the recloser cabinet and IT control room is 1.6 miles.

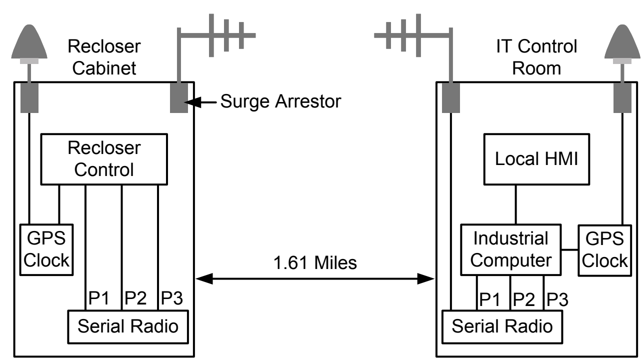

Fig. 5 Simplified Diagram of Devices and Communications

The three ports on the radios are configured as follows:

1. Serial Port 1 (P1) is configured for high-speed load shedding using a serial high-speed communications protocol. The front-end processor converts the serial high-speed protocol to a User Datagram Protocol (UDP)-based Ethernet packet, which is transmitted to the load-shedding processor. The same rule is then applied when the front-end processor receives the load-shedding trip command from the load-shedding processor using a UDP-based Ethernet packet and converts it to a high-speed serial command.
2. Serial Port 2 (P2) is configured for SCADA data collection and control using DNP3. The front-end processor converts the serial-based DNP3 to Ethernet-based DNP3 IP and sends the data to SCADA I/O Server 1 and I/O Server 2 (redundant).
3. Serial Port 3 (P3) is configured for engineering access, event collection, and oscillography using a serial communications protocol. The front-end processor converts the serial-based protocol to an Ethernet-based Telnet protocol and sends the data to a dedicated server, which collects sequence of events and oscillography data.

E. Optimization

Optimization includes adjusting antenna positions and antenna polarization to account for local interferences, transmit power, communications parameter adjustments, and specific data transfer tests that are relevant to the applications.

F. Validation

For specific applications, designers create success metrics to verify and validate that the radio communications network meets the application requirements. The tests can be specific data traffic with specific properties or characteristics. It is important that the metrics are clearly defined and that the tests can determine whether or not the radio network is adequate for the application using these metrics.

This project site was first commissioned in December 2016 with basic parameters; however, inconsistent SCADA data transmission and delays were observed. After some tuning onsite, Table III summarizes the major settings established as an acceptable communications mechanism.

The SCADA data, remote engineering access, and oscillography event collection worked very well. The next task was to establish an algorithm or mechanism to test the high-speed communication.

TABLE III
MAJOR SETTINGS

	P1	P2	P3
Application	Load shedding	SCADA	Engineering access and event collection
Protocol	Serial high speed	DNP3	Serial slow speed
Speed	9,600 bps	9,600 bps	9,600 bps
Type	EIA-232	EIA-485	EIA-232
Hardware Flow Control	False	True	True
Transmit Min. Delay (ms)	NA	10	NA
Transmit Max. Delay (ms)	NA	15	NA

Because high-speed load shedding is critical for smart grid operations, one way to validate the communications link is to send data and messages and measure the round-trip delays in the high-speed load-shedding channel while the other channels are performing their functions. The transmitter test sent a square wave at minimum 50 milliseconds and maximum 50 milliseconds. This test occurred once every hour for three months. Each test lasted for 5 seconds with 50 pulses of the square wave. The industrial computer compiled the round-trip statistics, including the maximum, minimum, and average round-trip time values. The test results showed that no packets were dropped during the testing period and that the average round-trip time was 39.46 milliseconds. Table IV shows the test summary data.

TABLE IV
TEST SUMMARY DATA

	Results From Original Settings	Results After First Tuning	Results After Second Tuning
Dates	2/2/2017	2/27/2017	4/4/2017
Number of Tests	1,246	1,862	2,717
Number of Pulses	24,920	37,240	54,340
Number of Pulses > 50 ms	1,333	1,738	2,300
Percentage at > 50 ms	5.35%	4.67%	4.23%
Link Availability	94.65%	95.33%	95.77%

Based on the test results, this radio link is adequate for smart grid operations for dispersed oil field sites.

V. CONCLUSIONS

The use of radio networks for dispersed oil fields is critical for reaching remote IEDs. By reaching these remote sites, the smart grid system can reduce power outages and downtime and minimize oil production interruptions. If a radio network system meets the communications requirements of a smart grid application, it provides an economical substitute for hardwired or fiber-optic networks.

The processes discussed in this paper have proven to be effective in designing radio links for smart grid applications. Success at each stage of the process does not guarantee that the radio system will work, but success at all stages of the process provides confidence that the link is adequate for the application. For this project, the high-speed load-shedding requirement was less than 50 milliseconds for slow-opening reclosers, and the tested radio system took less than 40 milliseconds on average. Because the spread of the system latency was very small, the radio system meets the high-speed load-shedding requirements.

VI. REFERENCES

[1] K. Hao, A. R. Khatib, N. Shah, and N. Herbert, "Case Study: Integrating the Power Management System of an Existing Oil Production Field," proceedings of the 63rd Annual Petroleum and Chemical Industry Technical Conference, Philadelphia, PA, September 2016.

[2] E. Sagen and H. Loehner, "Evaluation of Wireless Technologies for Power Delivery Automation," proceedings of the 14th Annual Western Power Delivery Automation Conference, Spokane, WA, March 2012.

[3] L. Rogers, T. Bartman, and B. Rowland, "Expanding Protection and Control Communications Networks With Wireless Radio Links," proceedings of the 44th Annual Western Protective Relay Conference, Spokane, WA, October 2017.

[4] T. S. Rappaport, *Wireless Communications: Principles and Practice*, 2nd Edition, Prentice Hall, Upper Saddle River, NJ, 2002.

[5] "Overview of Propagation Theory," adapted from L. E. Miller Propagation Model Sensitivity Study, J. S. Lee Associates, Inc. Contract Report, July 1992.

[6] L. W. Couch, *Modern Communications Systems: Principles and Applications*, Prentice Hall, 1995.

[7] B. Flerchinger, J. Knapek, R. Ferraro, C. Steeprow, and M. Mills-Price, "Field Testing of 3G Cellular and Wireless Serial Radio Communications for Smart Grid Applications," proceedings of the IEEE Rural Electric Power Conference, Westminster, CO, May 2016.

VII. VITAE

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