Optimizing a Wireless Ethernet Radio Network

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by Telemetry & Remote SCADA Solutions

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Summary

Executive summary

When deciding which wireless Ethernet radios to buy, it's tempting to focus on a few key specifications – such as operating distance or data-throughput rate – provided on the product datasheets. However, several factors contribute to overall network performance for Supervisory Control and Data Acquisition (SCADA) – and some of those factors work against one another.

The following discussion helps separate perception from reality, detailing the difference between specified over-the-air speeds and actual data throughput in a SCADA application. Suggested steps for optimizing wireless Ethernet radio networks are also presented, along with several real-world examples. Note: This paper assumes the reader has basic knowledge of radio networks.

Datasheet Specifications Don't Tell the Whole Story

You can have long range or high data-throughput rates, but not both at the same time.

- Speed: Actual data speeds for different wireless Ethernet radios are more functionally comparable than one might expect after taking a quick look at product datasheets. A few key factors determine the throughput of a spread spectrum radio, whether it's being tested in a lab or operating in a real-world environment. Some manufacturers claim their radios achieve data speeds of 512kbps to1Mbps – but often times, radios set to higher speeds will actually communicate much slower. Still others claim unusually high rates of 5–12Mbps. But are they talking about over-the-air, or actual data throughput?

- Distance: Some datasheets describe radios covering very long distances (typically qualified by statements saying actual results depend on things like antenna height and terrain). However, in wireless networks, distance and speed work against each other. To operate at optimum performance levels, a radio is very unlikely to achieve these stated specifications.

Key Factors Influencing Wireless Ethernet Network Performance

- Actual data throughput (including packet retries/ repeats)
- Channel bandwidth
- Message length
- Distance/operating range
- Interference & obstructions
- Signal-to-noise ratio

Optimizing Your System: Trade-Offs Between Speed, Distance, & Performance

Providing substantial channel bandwidth is an essential step when designing a robust wireless infrastructure. But it's important to understand the big picture: An incorrectly designed system can produce a bottlenecked network that performs at what seems like sluggish speeds with poor reliability.

Several things are major contributing factors that determine what you will get from an actual SCADA application, versus what the specifications say on paper.

Best practice: Send shorter messages

The reality is that as soon as data is transferred through the air, successful communication becomes a game of probability – and you want to make sure the odds are in your favor. Best practice is to send more short messages, rather than fewer long ones, to mitigate potential bottlenecking and other negative effects. Smaller data segment packets, coupled with fast hopping times, greatly improve the chances of successful data transfer.

Distance comes at a price

Optimizing a wireless Ethernet radio network doesn't equate to achieving the longest distances possible. Some manufacturers claim operating distances of 20, 40, or even 60 miles. This may be technically correct, but there's a trade-off: Longer operating range (distance between two radios) happens at slower data speeds, while faster speeds are achieved over shorter distances.

Bandwidth also comes at a price

Wider channel bandwidth allows more data transfer. However, keep in mind that wide band can defeat the purpose by allowing more noise, causing system performance to drastically decrease. To counter this situation, a stronger receive signal strength indication (RSSI) and higher signal-to-noise ratio (SNR) will be required, which in most cases means that the radios need to be in closer proximity – reducing the overall operating range of the system.

Real-World Examples

Below are some real-world examples illustrating key points from this discussion. These are not intended to falsify any manufacturer's performance claims. Rather, the idea is to demonstrate the trade-offs between distance, bandwidth, and speed in actual wireless Ethernet networks, and to show how product datasheets don't tell the whole story.

Example: A 512kbps radio can give you 256kbps (or less)

In either a fixed or mobile wireless Ethernet network, if you hard-set a radio to the 512kbps mode, but the RSSI and SNR are not at desired levels, your actual data-throughput speed will be lower than if the radio had been set to 256kbps. Why? Because of TCP data segment retries, which rapidly diminish actual throughput.

- Frequently, an auto-baud rate setting can be selected instead -- but again, if the RSSI and SNR are not at adequate levels, the radio will switch back to 256kbps anyway. In this situation, the radio will de-associate and then re-associate, again slowing your data-throughput speeds.

- Some radios in the field today use a channel bandwidth of 316.5kHz, which is why the 256kbps works well: In conventional 2-level modulation, the data throughput speed is not greater than the allotted bandwidth, so the 316.5kHz allows the radio to perform better (because the 256kbps throughput is lower than the allotted bandwidth). To achieve 512kbps, you would need 4-level modulation, which requires a stronger and more reliable signal.

Example:
Determining actual throughput for a 512kbps radio

Several manufacturers claim their radios cover an extended range at over-the-air throughput of 512Kbps (they qualify that by saying actual performance is influenced by antenna height, obstructions, terrain, etc.).

- To achieve this high throughput, the specifications typically say the radio Bit-Error-Rate (BER @ 1x10^{-6}) is at -92dBm. Real-world experience has shown that an RSSI of at least -77dBm would be required, with an SNR of +26dBm or better. However, even if this was achieved, actual throughput would be 300-380kbps at best. The rest of the so-called 512kbps would be consumed by overhead and retry packets.

- Although it is possible to get RSSI around -70dB, it’s difficult to keep SNR in the +26dBm range. Other 900MHz spread spectrum systems may be nearby, and other in-band and out-of-band noise may be present.

The above example is for a fixed application, such as a SCADA network. In a mobile Ethernet environment, reliably getting SNR at the desired +26dBm is nearly impossible. For instance, in most cases, the radio would be set to 256kbps using 2 level modulation: This would correspond to a Bit-Error-Rate (BER @1x10^{-6}) of 99dBm, which translates to an RSSI of a remote to a master radio no worse than 5dBm. The resulting SNR of +21dBm would net a throughput around 180kbps.

Example: Radios specified at 512kbps–1Mbps with 600kHz bandwidth

Recently, some manufacturers have claimed over-the-air data rates of 512kbps and 1Mbps at 600kHz. This wider bandwidth allows for 2-level modulation that nets an over-the-air data rate of 512kbps, with a resulting actual throughput of 300-380kbps.

Although greater data speeds are possible, this places limits on distance, while increasing the chance of interference because of the larger bandwidth. In addition, more bandwidth means the radio makes fewer hops, decreasing its flexibility. Because operating distances are lower, more investment in infrastructure (master radios) is required to achieve the higher throughput speeds. Therefore in most cases, these radios are set to the 512kbps, especially in mobility situations.

Example: Signal-to-noise ratio with 4-level modulation

Signal-to-noise ratio (SNR) is defined in terms of decibels per milliwatt (dBm). To reliably receive a signal using 4-level modulation, SNR usually needs to be at least +25dBm. So if a receiver is hearing noise at a level of -95dBm, then the receive signal strength indication (RSSI) of the remote radio must be -70dBm (-95 + 25 = -70). If SNR drops below +25dBm, then it may be better to switch to 2-level modulation, because it works adequately in an SNR range of +18dBm. To meet the minimum SNR at 2-level modulation (+18dBm), RSSI should be -77dBm (-95 +18 = 77dBm). Simply by switching the modulation setting, the system has gained +7dBm of signal quality – this can mean the difference between working poorly or working reliably.

Example: Higher-order modulation (64 QAM, 16 QAM, QPSK, BPSK)

Some radios utilize much higher bandwidths and promise much faster data throughput. Instead of the typical 2-level and 4 level modulation discussed earlier, they use 64 QAM, 16 QAM, QPSK, or BPSK (see table below).

However, these radios need a very strong signal, and little noise, or in many instances they will not even connect. Additionally, they're not recommended if more than 100 spread spectrum radios are in the vicinity: The wide bandwidth makes them especially susceptible to interference, limited range (usually less than 1 mile), and degraded throughput due to TCP segment retries.

Generally speaking, a 1.75MHz bandwidth mode (detailed below) is the only suitable higher-order modulation option being deployed today for multipoint systems. However, 1.75MHz is still significantly wider than usual, allowing lots of noise into the system.

- It's unlikely that 64 QAM or 16 QAM will work for anything other than a point-to-point system.
- A 3.5MHz bandwidth is unachievable in most multipoint SCADA systems because of the clear signal that would be required.
- In multipoint applications, QPSK or BPSK modulation can work successfully, although radios tend to operate over a short distance (typically only one mile). In mobile applications, experience has shown that BPSK is usually the only modulation that works reliably.

Example of higher-order modulation specifications

	3.5 MHz bandwidth mode		**1.75 MHz bandwidth mode**	
Modulation scheme	Sensitivity	Raw bit rate	Sensitivity	Raw bit rate
64 QAM	-77 dBm	12.7 Mbps	-80 dBm	6.35 Mbps
16 QAM	-86 dBm	4.8 Mbps	-89.5 dBm	2.4 Mbps
QPSK	-92 dBm	2.4 Mbps	-95 dBm	1.2 Mbps
BPSK	-92 dBm	1.2 Mbps	-98 dBm	600 Kbps

Example: Trio J-Series Ethernet radio

Schneider Elecrtic offers a Trio J-Series Ethernet radio which uses a 360kHz bandwidth and passes 256kbps of data using 2-level modulation. As discussed above, a product with these specifications compares favorably to many radios claiming higher over-the-air data throughputs. (It can also be configured to a 512kbps over-the-air data rate with 4-level modulation.) But in many cases, this radio will face the same issue that others encounter: The speed can't be higher than the allotted bandwidth. Unless a network can achieve the recommended RSSI and SNR levels, a radio set to higher speeds will often end up communicating at 256kbps -- and in some cases even less, because of TCP packet retries.

Key Factors Influencing Wireless Ethernet Radio Network Performance

Channel Bandwidth – The difference between the lowest and highest frequency in which a channel resides during each hop in a frequency-hopping spread spectrum (FHSS) radio system. The wider the bandwidth, the more data can be passed during each frequency hop. Typically, actual data speed is never greater than the channel bandwidth allotted (assuming 2-level modulation). In spread spectrum, you are not restricted to a minimum bandwidth; FHSS allows 100kHz, 200kHz, even 680kHz. However, although more bandwidth allows more data to be pushed through in a given period of time, remember that doing so sacrifices operating distance. And as bandwidth increases, this opens the radio receiver up to allow more noise and/or interference. This is a main factor in decreasing operating distance, and it is where signal-to-noise ratio (SNR) comes into play.

Modulation – RF industry standard has traditionally been 2-level modulation, which gives radios good sensitivity at the receiver, but poor multipath distortion performance. Some radios now accommodate 4-level modulation, allowing up to twice the data-throughput speeds; however, this sacrifices sensitivity, which reduces operating distance. Other types of higher-order modulation, such as GFSK, BPSK QPSK, QAM 16, or QAM 64, allow faster speeds. But as with 4-level, reliably receiving data at higher rates requires much stronger RSSI and SNR. Otherwise, each data packet will need to be sent multiple times, drastically reducing throughput rates. In some cases, actual speeds are slower than if 2-level modulation were being used.

Receive Signal Strength Indication (RSSI) – This is the measurement in decibels per milliwatt (dBm) of the received radio signal strength (not the quality of the signal). This indicates the strength of each remote radio relative to the master radio in a SCADA network. Manufacturers state a recommended minimum RSSI level to achieve reliable radio performance. In terms of actual measurement, this is stated in terms of –xxdBm, where xx is a numeric RSSI reading.

Signal-to-Noise Ratio (SNR) – The ratio of a radio's signal to noise that is corrupting it; for example, SCADA data compared to background noise. In RF, this is defined in terms of +dBm. Example: To reliably receive a signal using 4-level modulation, SNR usually needs to be at least +25dBm. So if a receiver is hearing noise at a level of -95dBm, then the RSSI of the remote radio must be -70dBm (-95 + 25 = -70). If SNR dropped below +25dBm, then it may be better to switch to 2-level modulation, which works adequately in an SNR range of +18dBm. Considering the same example, to meet the minimum SNR requirement at 2-level modulation, RSSI should be -77dBm (-95 +18 = 77dBm): The system has gained +7dBm of signal quality.

Distance – The greater the distance between a master and remote radio, the less likely data will arrive intact. A minimum RSSI and SNR must be maintained between them to ensure reliability and performance. For a 3-mile link with the data rate set to 512kbps, one would expect an actual throughput around 380kbps, which is quite reasonable. But if the same settings were used over 25 miles, the required RSSI and SNR thresholds would probably not be met. The radios may remain linked, and the settings may indicate a data speed of 512kbps, but in reality each packet of data would probably be sent multiple times, reducing actual throughput to only 80–200kbps.

Data Segment Packet – Smaller data segment packets, coupled with fast hopping times, greatly improves the chances of successful data transfer.

Dwell Time – The length of time a radio stays on a given frequency before hopping to the next one in its sequence. Ideally, a radio should be flexible enough to change from short (10ms) to long (200ms) dwell times, allowing operators to fine-tune system performance. A shorter dwell time lowers the chance a radio will incur interference. Longer dwell times can typically be used only for point-to-point systems; in many point-to-multipoint SCADA systems, these longer times will severely cripple system performance.

Radio Sensitivity – The manufacturer's specified radio sensitivity in terms of Bit-Error-Rate (BER = 1x10^{-6} @ -99dBm). This means that in a perfect lab environment the radio will receive (1)-bit error for every (1,000,000) bits passed at an RSSI level of -99dBm. In the real world, if you were to design a radio network to these ideal specifications, that radio would not operate correctly: The rule of thumb is to design a system so the RSSI of the remote back to the master is at least 20dBm higher than the stated BER (for stated BER between -100dBm and 110dBm). For stated BER between -90dBm and -99dBm, design the actual remote RSSI at least 15 dBm higher. This is also commonly referred to as fade margin.

Fade Margin – The measure in dBm between a manufacturer's stated radio sensitivity in terms of BER, and the real-world minimum recommended RSSI of the remote as it relates back to the master. Example: For a radio with stated BER = 1x10^{-6} @ -99dBm, the fade margin would typically be +15dB. Because -99 + 15 = -84dBm, -84dBm would be the minimum recommended RSSI for the remote radio.

Interference – Radio interference comes from other sources using the same frequency band: The greater the amount of interference the less likely data will arrive intact. This is where the quality and performance of the radio comes into play. Most industrial radios design RF filtering into the front-end of the radio receiver to help suppress unwanted signals. This is sometimes not enough, and external reject/notch filters are required.

TCP Packet Retries – As the probability of successful communication decreases, the number of retries increases, resulting in more traffic and data collisions, lower throughput speeds, and possibly failed communications. In a TCP/IP over RF system, flow control, error correction, and congestion control are handled by the TCP/IP layers. But noisy media result in extra traffic due to TCP retries caused by unacknowledged data segments packets.

Physical Obstruction – The more obstructions along the radio path, the less likely it is that data will arrive intact. Again, this is why RSSI and SNR are so important in radio system design. The 900MHz ISM (industrial, scientific, and medical) band is more forgiving to certain obstructions than are the 2.4GHZ and 5.8GHz ISM bands.

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