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Factors Contributing to Sensor Density

The Underappreciated Impact of Noise Figure on System Performance

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Abstract

This white paper is written for system designers developing or optimizing an in-place monitoring system (IPMS) supporting technical surveillance countermeasures (TSCM), cybersecurity, electronic device policy enforcement, spectrum management, and similar critical missions. By providing insight to questions such as "How many sensors do I need?" and "How far apart can they be spaced?", this white paper assists designers with understanding how key factors, such as receiver noise figure (NF), directly influence the density and distribution of sensors within the total system deployment.

Frequency range, instantaneous bandwidth, and sweep speed are typically understood with respect to their value to an IPMS designed for detection and analysis of anomalous signals. By understanding the approach and techniques presented in this white paper, designers should be capable of evaluating receiver performance against particular threat characteristics that are all too often overlooked, such as signal strength, possible transmitter and receiver locations, and directionality.

This white paper demonstrates that, for an effective IPMS, sensor density is primarily dictated by the specifications and performance of its sensors — most especially the sensor's noise figure. In specifying and designing an IPMS, selection of the most cost-effective and mission-effective sensor requires a judicious examination of sensor performance and mission objectives — a low-cost sensor with poor noise figure may likely result in a high-cost IPMS with performance limitations, versus fewer high-performance sensors with excellent noise figures.

Contents

1. Introduction

In-place monitoring systems (IPMS) can offer an effective and efficient method to monitor designated spaces for incidental or nefarious activity. IPMS solutions offer extensive benefits over isolated, often intermittent, detection and monitoring solutions, as they are networked, share resources, omnipresent in each deployed space, and offer continuous (24/7/365) detection and monitoring capabilities. Radio frequency (RF) IPMS solutions far outpace traditional RF survey solutions — leveraging multi-sensor deployments to effect multiple mission objectives simultaneously, perform automated inside/outside determinations, calculate geolocation estimations of emitters, and much more.

When considering implementation of an IPMS, the system designer must consider a multitude of factors such as sensor performance, perceived threat, unique mission objectives, existing RF environment, variable site conditions, etc. Sensor performance specifications such as frequency range, sweep speed, signal-to-noise ratio, and instantaneous bandwidth are critical to meeting mission objectives, but so is sensor density — the number of sensors in a defined area. Too few sensors (too low of a density) and signals will go undetected. Striking the right balance of sensor number and sensor spacing can be counterintuitive and complex. This white paper focuses on sensor density requirements as they correlate to specific sensor performance specifications and is intended to help system designers determine the optimum number of receivers, and their best layout, when designing an IPMS.

To accomplish this, it is important to first determine how near or far and how strong or weak a transmitter needs to be so it can be reliably detected by a single receiver. This understanding will help develop the concept of detection radius to express how much area a single sensor can survey. Building on this foundation, this white paper will consider a collection of receivers and investigate the requirements for efficient spacing within a defined area of interest.

Given these building blocks — detection radius and efficient receiver spacing — examples are provided to illustrate how a system designer can best choose the number of sensors and sensor spacing to optimally craft an effective and efficient IPMS. Note that these illustrations are designed with *detection* in mind. A designer may also wish to design a system not just for detection but also for demodulation and/or higher resolution location estimation. Although not illustrated in this white paper, these same principals can be applied to design a system that produces location estimation with increased resolution or that is better suited for demodulation of detected signals.

2. Detection Radius

First, it is important to develop the concept of detection radius. This is essentially a detection range issue, but when placed at the center of a space, detection range becomes detection radius. That is, given a sensor location, how far away can a transmitter of a given signal strength and frequency be and still be detected. However, before examining range, the topic of thresholding must first be evaluated.

2.1. Detection Threshold

To detect the presence of a transmitter, it is not sufficient for the transmitted signal to simply "reach" the receiver; it must arrive at the receiver with enough strength to be perceived above the noise floor[1]. Moreover, in practical implementations, to reliably discriminate a signal from the background noise, the signal must also have sufficient power to exceed a given detection threshold. In a manner of speaking, the signal must stand distinctly above the noise.

Furthermore, the threshold should be high enough above the noise floor so as not to overwhelm the system by false detections. Neither should a threshold be set so high that signals of interest are often ignored. One could easily dedicate volumes solely to the topic of setting proper detection thresholds. However, this paper is concerned with the phenomena and analytics leading to optimized sensor density. Nevertheless, setting a threshold is necessary to develop the concept of detection radius.

Consider Figure 1, below. The spectrum depicts a brief survey of the 5 GHz unlicensed band (conventionally populated by Wi-Fi signals). In this amplitude vs. frequency graph, the green trace shows the result of a "max hold" operation, whereas the blue trace depicts the average signal power across the band. When a device transmits during this survey, the max hold trace clearly depicts signal energy above the noise floor (parts of the spectrum without active transmitters).

An unoccupied region of the spectrum shows a noise floor of roughly −116 dBm. As illustrated by the blue trace, this is calculated by taking the average power at the receiver. When a signal is not present, this average is equivalent to the noise floor as indicated by the cursor at 5.57 GHz. A "max hold" operation shows the maximum power during the survey for the same spectral region was −116 dBm, as indicated by the green trace. Given the spectrum shows only background noise energy at this frequency, it is safe to conclude the noise floor is about −128 dBm. Seeing as the max hold energy is −116 dBm, it is evident that a threshold too close to the noise floor would overrun the system with far too many false alarms.

1 Note: This statement is not strictly true for direct-sequence spread-spectrum signals. Nevertheless, the principal remains the same: One cannot simply require the signal to "reach" the receiver; it must arrive with enough power to be differentiated from noise.

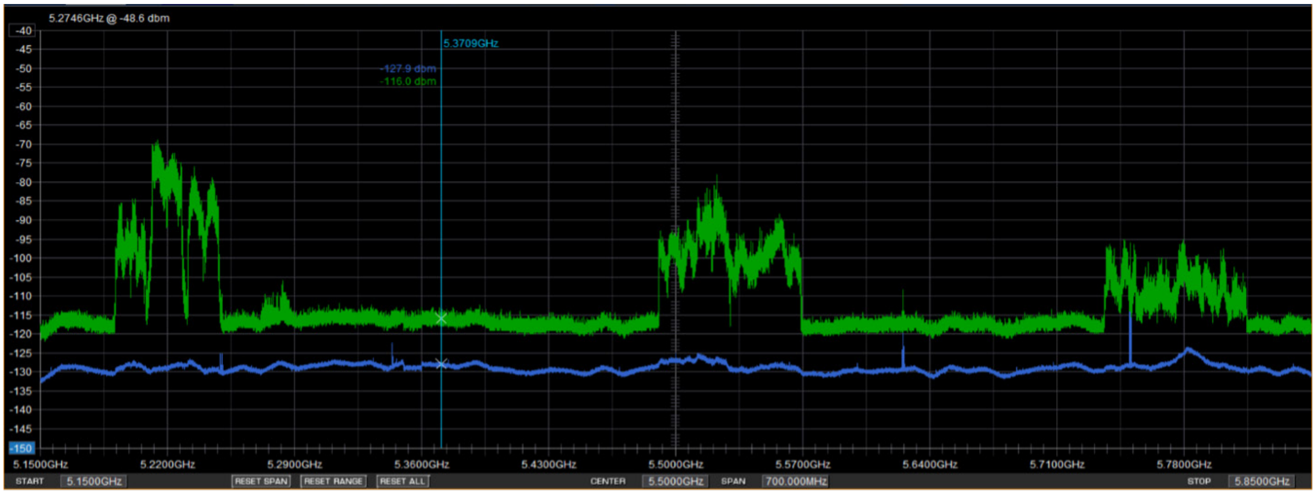


Figure 1: *Typical max hold (in green) and average (in blue) power spectrum of the 5 GHz unlicensed band collected with receiver of 5 dB noise figure and 16.2 kHz resolution bandwidth (RBW).*

To reduce false alarms, it is a reasonable practice to set a threshold 10 dB above the maximum noise level (e.g., max hold) of an unoccupied region. For the survey data of Figure 1, this would suggest a threshold of –106 dBm. Note this is about 20 dB above the noise floor. Thus, for the purpose of this white paper, a signal to be detected by an IPMS must arrive at the receiver at least 20 dB above the average noise power. (It is worth noting that if the intent is not only to detect a signal of interest but also to demodulate it, then an even greater threshold margin is not only advantageous, but necessary.)

2.2. Noise: The Inescapable Enemy of Detection

In the discussion of detection thresholds above, this paper introduced a few terms related to noise — specifically “noise floor” and “noise figure.” The performance of a receiver, or of a system, to detect signals of interest cannot be understood without also considering noise.

Noise is always present; there’s no escaping it. The “noise floor” in any given part of the spectrum describes the average power from all noise sources inside and outside of the receiver. Sources of noise outside the receiver are largely composed of unwanted or interfering transmissions (so-called “man-made noise”) as well as atmospheric (e.g., lightning) and even extraterrestrial sources. Mitigating these external sources of noise is almost always beyond control and must often be taken as a natural part of the environment.

Conversely, noise within the receiver can be attributed to a variety of internal electronic processes such as thermal noise, shot noise, flicker noise, intermodulation, etc. The best-built receiver cannot be noise-free. Each of the electrical components in the signal chain — even a simple resistor — always contributes noise to the signal path through the receiver.

But not all receiver designs are equal. The art of engineering is tradeoff, and engineers are faced with thousands of tradeoffs when designing a receiver as they try to balance performance against the constraints of size, weight, power, and cost. As the engineer considers the pros and cons of each choice, the receiver’s noise figure should be a driving factor in the design of any IPMS receiver because it weighs so heavily in the architecture of the overall system. But what exactly is noise figure, and why is it a crucial element for an IPMS?

In simple terms, noise figure quantifiably describes the level of noise the radio itself contributes to the noise floor. Therefore, the noise figure of a radio expresses how the receiver may push the noise level up, thereby obscuring a signal. A lower noise figure means the system is better able to detect signals of interest.

Examples below illustrate how seemingly small differences in noise figure can have significant impact on the overall system design.

2.3. Path Loss

As stated above, the concepts explored thus far have been working toward developing the concept of detection radius. Signal power is an important element to consider, but this is in the context of detection range (or radius). How close must a transmitter of a given strength be for reliable detection? The combined attributes of transmit power and distance determine the reliable detectability of a given signal.

As signals propagate, they lose power. A portion of this phenomenon is attributable to the well known inverse square law. But equally important is the loss of energy as frequency increases. The free-space path loss (FSPL) equation for isotropic antennas is given as[2]:

$$FSPL \ = \ \left(\frac{4\pi df}{c}\right)^2$$

Where d is the distance between transmit and receive antennas (in meters), f is the frequency (in Hz) of the transmission, and c is the speed of light.

Expressed in dB, this is:

$$FSPL \ (dB) = 20\log_{10}(d) + 20\log_{10}(f) - 147.55$$

From the FSPL equation (in either form), it is evident that signal power loss between transmit and receive antennas increases as the square of distance and as the square of frequency. That is, four times as much power is lost when the transmit/receive distance doubles. Similarly, four times the power is lost when the transmit frequency doubles. This last point is particularly relevant to IPMS deployments. For example, as seen in Figure 2, below, a 20 GHz signal will arrive at the example receiver with 60 dB less power than a signal at the same range transmitted at 20 MHz.

Above about 1 GHz, path loss is even more severe indoors when the path from transmitter to receiver is affected by interior walls, office furniture, a variety of materials (absorptive and/or reflective), and more. When considering path loss for indoor radio propagation, many factors must be weighed, and an exact determination is usually impractical. However, the International Telecommunication Union (ITU) has published excellent recommendations[3] that enable a system designer to accurately estimate path loss for interior spaces. To model typical path loss for an indoor IPMS, this paper will draw from the ITU recommendation for a transmitter–receiver pair located on the same floor, separated by 4 to 30 meters, with non-line-of-sight (NLoS) RF propagation. Thus, taken from the referenced ITU recommendation, path loss is expressed as:

2 See, for example, Free-space path loss - Wikipedia (https://en.wikipedia.org/wiki/Free-space_path_loss)

3 See ITU Recommendation ITU-R P.1238-12, *Propagation data and prediction methods for the planning of indoor radiocommunication systems and radio local area networks in the frequency range 300 MHz to 450 GHz*, 08/2023

$$PL_{Indoor}\ (dB) = 10\alpha \log_{10}(d) +\ \beta\ + 10\Upsilon log10(f)$$

Where d is the distance between transmitter and receiver (in meters), f is the frequency (in GHz), α, β, and Υ are transmission loss coefficients given in the ITU recommendation for indoor, office space, for frequencies between 300 MHz and 82 GHz and distances between 4 and 30 m. Specifically, $\alpha = 2.46$, $\beta = 29.53$, and $\Upsilon = 2.38$.

Given the path loss for indoor NLoS propagation, Figure 2 shows that a 20 GHz indoor signal will arrive at the example receiver with 67 dB less power than a signal of the same range transmitted at 20 MHz. Recall that this loss was 60 dB for the FSPL condition. Therefore, indoor NLoS propagation loses at least an additional 7 dB at 20 GHz when compared with FSPL.

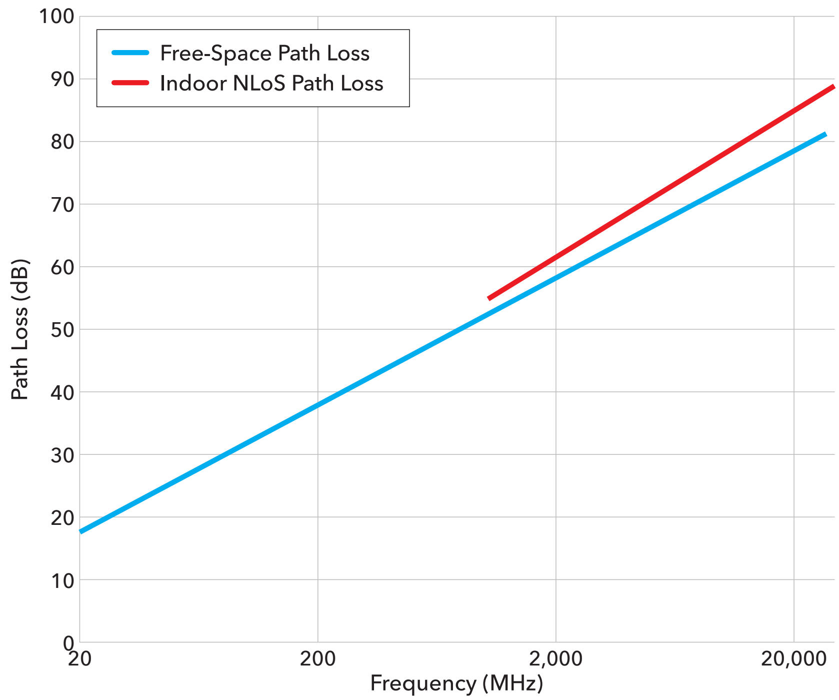


Figure 2: *Free-space path loss and indoor non-line-of-sight path loss as a function of frequency for an emitter–receiver pair separated by a fixed distance of 10 m. This figure illustrates the increased path loss as signal frequency increases.*

In the end, reliable detection is often dominated by signal-to-noise ratio (SNR) — the power of the signal relative to the noise power. Any phenomenon that drives signal power down, such as path loss, makes a signal more difficult to detect. Similarly, any phenomenon that contributes to noise, such as noise figure, also makes a signal more difficult to detect. When these two factors combine, there is a profound impact on system design. This is most easily seen when considering the spacing distance between receivers in an IPMS.

With an understanding of path loss, noise floor, noise figure, and threshold values, detection radius can be illustrated for a specific emitter–receiver pair. The following example guides the reader through the computations necessary to calculate such path losses.

2.4. Example 1 – Calculating Detection Radius

Assume a Wi-Fi transmitter with center frequency 5.2 GHz, signal bandwidth of 40 MHz, and signal power of +23 dBm. Given a receiver with 5 dB noise figure, 16.2 kHz RBW, average noise floor of –126.9 dBm, and a threshold 20 dB above the noise, determine the range that the signal can be detected.

First, the signal strength must be determined. It is not simply +23 dBm; rather, it is +23 dBm spread over 40 MHz of bandwidth. Because the receiver has 16.2 kHz RBW, it is possible to determine how many bins the signal occupies:

$$Number\ of\ Bins = \frac{40\ MHz}{16.2\ kHz\ per\ bin} \approx 2,469\ bins$$

Given that the power is expressed in dBm, this power must first be converted to watts, and then the number of watts per bin can be determined by dividing the total power by the number of bins.

$$P\ \ (watts) = \frac{10^{\frac{P(dBm)}{10}}}{1,000} = \frac{10^{\frac{23}{10}}}{1,000} \approx 0.1995\ watts$$

$$P\ \ (watts/bin) = \frac{0.1995\ watts}{2,469\ bins} \approx 8.081\ \times\ 10^{-5} watts/bin$$

The power per bin can then be converted back to dBm.

$$P\,(dBm/bin)\ = 10\ log_{10}\ \ (P\,(watts)) + 30\ \approx\ -10.9\ dBm/bin$$

The criteria of a threshold 20 dB above the noise floor implies the signal loses 96 dBm and arrives at the receiver at –106.9 dBm per bin. To find the distance in meters for this power loss, use the indoor NLoS path loss equation and solve for *d* — distance — as follows:

$$96 - (\beta + 10\Upsilon log_{10}(f)) = 10\alpha \log_{10}(d)$$

$$\frac{96 - (\beta + 10\Upsilon \log_{10}(f))}{10\alpha} = \log_{10}(d)$$

$$10^{\frac{96-(\beta+10\Upsilon \log_{10}(f))}{10\alpha}} = d \approx 101.9\ meters$$

Therefore, for the given signal and this transmitter-receiver pair, the receiver has a detection radius of 101.9 m.

Note that if all other factors remain constant and the receiver has a noise figure of 15 dB, the detection radius will be decreased. With the increased noise figure, the signal can now only lose about 85.98 dBm of power and still be detected. Thus, the detection radius becomes:

$$10^{\frac{85.98-(\beta+10\Upsilon \log_{10}(f))}{10\alpha}} = d \approx 40\ meters$$

3. Receiver Spacing

As expressed earlier in this paper, an understanding of detection radius will help inform the number of receivers required for an indoor IPMS. To work toward that answer, it is important to understand how tightly arranged an efficient distribution of receivers can be.

Suppose there is a radio with radius of detection[4] *R*. That means the receiver will reliably detect all signals (of the appropriate frequency and SNR) located within a circle of radius *R* as illustrated below.

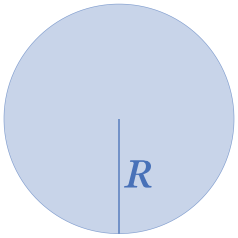


Figure 3: *Illustration of the radius of detection, R*

Putting this in terms of everything discussed to this point, a signal transmitted from *R* meters away will lose power from path loss and must arrive at the receiver at least 20 dB above the noise (composed of noise inside and outside of the receiver).

If a network of receivers is arranged such that the radius of detection for one receiver begins where another receiver leaves off (i.e., receivers are spaced a distance 2*R* from each other), it would result in a grid similar to the one illustrated below:

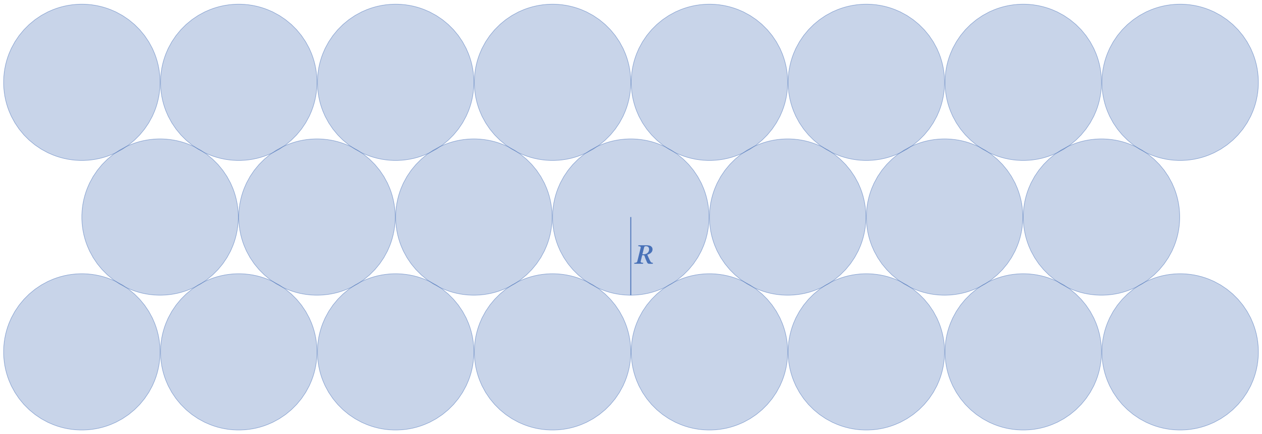


Figure 4: *Receivers arranged in an array with 2R distance between elements.*

However, this pattern clearly reveals that emitters located within the interstitial spaces would go undetected by the network of receivers. To ensure that every location within the network is detectable, the receiver spacing must be tighter. Because the hexagon is the optimum shape to achieve the greatest coverage with the least number of receivers, the size of a hexagon completely enclosed by the radius of detection can be determined, as illustrated in Figure 5.

4 Note that as developed in the previous section, the radius of detection is a function of frequency, SNR, and noise figure.

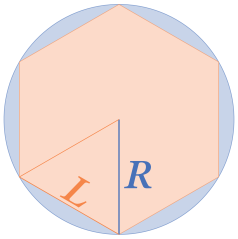


Figure 5: *Hexagon enclosed by a circle of radius R.*

Given that a hexagon can be composed of six equilateral triangles, it is readily evident that L, the length of the side of the hexagon, is equivalent to R, the radius of detection of our receiver.

If the network of receivers is then arranged for 100% coverage of the area of interest, it would result in a grid as follows:

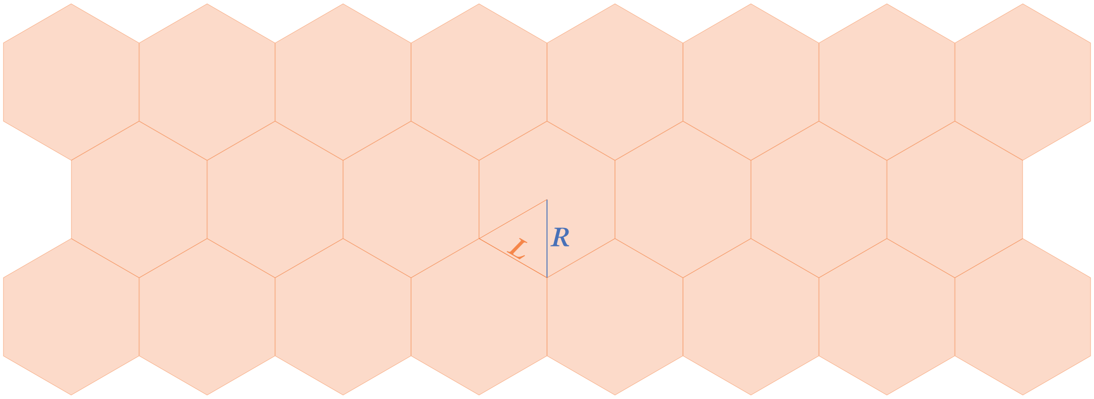
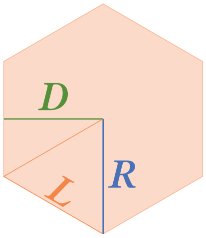


Figure 6: *Receivers arranged in an array with no gaps in coverage.*

In the first attempt, with receivers spaced $2R$ from one another the grid contained spaces, or gaps, in coverage. How far are the receivers spaced in the "no gaps" grid? This distance, D, from the center of one hexagon to the boundary of an adjacent hexagon is given by the following equation and is illustrated in Figure 7, below:



$$D = \frac{\sqrt{3}}{2}R;\ therefore,\ D\ \approx 0.866R$$

Figure 7: *Distance from the center of a hexagon to its neighbor.*

Note that this is simply the equation for the height of an equilateral triangle with sides of length R, and the receiver-to-receiver spacing is about 86.6% of what it was before.

Given this geometry, it is possible to approximate how many receivers are required to cover an area of a given length and width. First, determine the square footage of the area of interest. Thus, the total area of the area of interest = *length* × *width*. Next, determine the area of coverage of one hexagon with radius of detection R. This is given by the following equation:

$$A = \frac{3\sqrt{3}}{2}R^2$$

Therefore, the number of required receivers, N, is given by: $N = (length \times width)/A$

This can best be illustrated by a few examples.

3.1. Example 2 – Calculating Required Number of Receivers

Receiver 1, NF = 5 dB

- **Facility Dimensions:** 300 × 75 meters (facility size 22,500 m^2).
- **Emitter Characteristics:** 5G NR Femtocell Uplink 24.25 GHz, 50 MHz BW, +20 dBm power.
- **Detection Characteristics:** 5 dB noise figure, 20 dB SNR detection threshold, 16.2 kHz RBW.

Given these parameters and RF indoor NLoS path loss, the radius of detection is 15.86 m for this receiver. So, R = 15.86.

Area of coverage of a hexagon with detection radius of 15.86 meters = 653 m^2.

Therefore:

$$\frac{22,500}{653} = 34.5$$

Therefore, about 34 or 35 receivers are required to cover this facility with the 5 dB NF receiver and the given Femtocell Uplink signal.

Receiver 2, NF = 15 dB

NOTE: The only value changed in this illustration is the noise figure of the receiver.

- **Facility Dimensions:** 300 × 75 m (facility size 22,500 m^2).
- **Emitter Characteristics:** 5G NR Femtocell Uplink 24.25 GHz, 50 MHz BW, +20 dBm power.
- **Detection Characteristics:** 15 dB noise figure, 20 dB SNR detection threshold, 16.2 KHz RBW.

Given these parameters and RF indoor NLoS path loss, the radius of detection is 6.22 m for this receiver. So, R = 6.22.

Area of coverage of a hexagon with detection radius of 6.22 meters ≈ 100.5 m^2.

Therefore:

$$\frac{22,500}{100.5} = 224$$

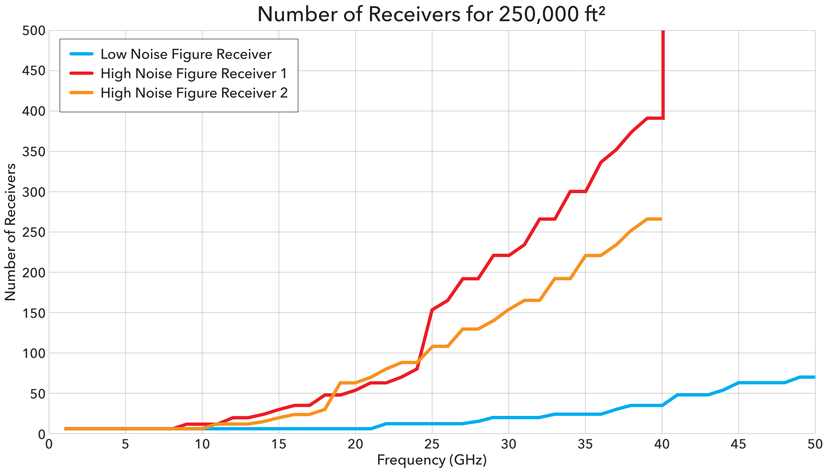
Therefore, about 224 receivers are required to cover this facility with the 15 dB NF receiver and the given Femtocell Uplink signal.

4. Conclusion

From these calculations, it is evident that even seemingly small differences in noise figure can have a profound impact on the number of receivers required to protect a facility with an indoor IPMS. Given the nature of the path loss and its sensitivity to frequency as well as distance, the significance of noise figure is even more profound at higher frequencies.

To illustrate this point, three receivers of varying design were compared. Performance of the receivers was evaluated (using NF as a function of frequency), and a detection-only analysis was conducted to plot the number of receivers required for the specified frequency range in a representative IPMS composed of each type of radio.

The figure below illustrates that at 15 GHz, six receivers having a low noise figure would provide detection for the entire 250,000 ft^2 facility, while utilizing the high noise figure receivers would require 30 radios to provide the same level of coverage. Similarly, if a system designer wanted to cover the facility at 20 GHz, still only six of the low noise figure receivers would be required, while it would require 54 of the high noise figure receivers to achieve comparable results.



Freq.	Low NF Rx	High NF Rx 1	High NF Rx 2
12 GHz	6	20	12
15 GHz	6	30	20
18 GHz	6	48	30
20 GHz	6	54	63

Number of nodes required for reliable detection for radios of differing noise figure.

Figure 8: *As a function of frequency, the number of low noise figure receivers compared with the number of receivers required for two different types of higher noise figure receivers. These results predict the number of IPMS nodes required for reliable detection in a 250,000 ft² facility. Note: To perform reliable location estimation or demodulation, the difference in receiver count would be more extreme. (Values for select frequencies are illustrated in the table above.)*

This illustration demonstrates that scalability is inseparable from performance. Moreover, the astute designer cannot overlook the additional infrastructure and maintenance required to support 54, or even 63, receivers compared with the needs of a six-receiver IPMS.

Following the principles and guidelines outlined in this white paper can be a distinct aid for system designers as they judiciously select appropriate resources and determine the location of these resources within the protected facility.

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