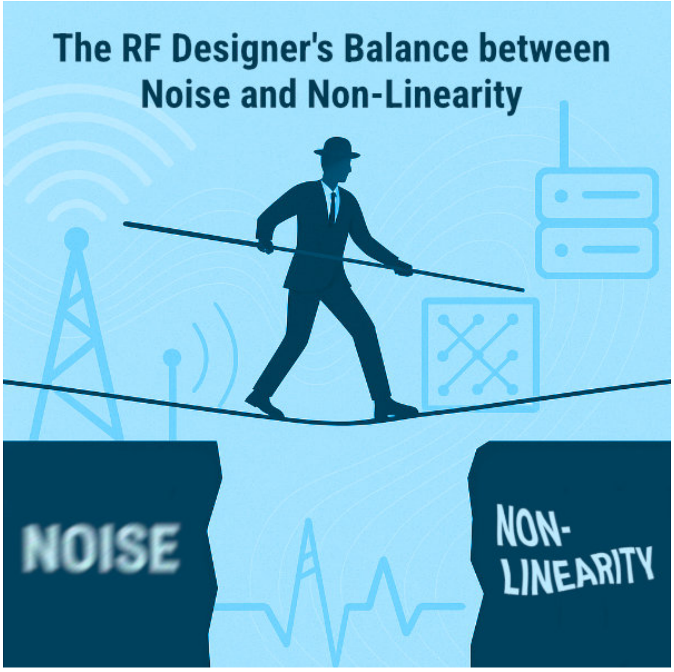
On the Trade-off Between Bandwidth and Dynamic Range in Modern Radio Monitoring Systems

Introduction

This white paper highlights some critical aspects of designing multi-antenna / multi-receiver systems. While a casual first assessment would typically ask for the best super-wideband and super-sensitive general purpose design, a closer look at the RF performance reveals that banded approaches do have significant advantages.



Historical perspective

When wireless communication was in its early stages, the only challenge was to receive a weak signal from far away. This resulted in very good narrowband systems, with antennas and receivers optimized for the desired band. The critical parameter was *sensitivity*. In other words, how weak a signal can be so that it can still be detected and received. Wideband systems were neither cost-effective nor feasible at the time.

Over time, advances in semiconductor components have made it possible to design systems that can cover a wider and wider bandwidth with one hardware. The systems have become more flexible (e.g., through software-defined radio – SDR), and the performance loss intrinsic in moving from narrowband to wideband has been compensated by better receiver components and advanced digital processing of signals, but also by more cost-effective power amplifiers and transmitter systems, which allow transmitting stronger signals.

Nowadays, these wideband systems are widely in use. Civil as well as military applications work with receivers that can process signals from short-wave to several gigahertz. Antennas are designed to be wideband, although not quite as wideband as the receivers, as the physical challenge to channel the energy of propagating waves into a cable is always limiting the bandwidth somehow.

The high frequencies in use in commercial as well as military systems have increased the impact of cable losses as well. This has led to a trend that the first amplification stage has moved from the receiver to the antenna. The typical setup of a simple radio monitoring station is depicted in 1.

Figure 1: Illustration of an one-antenna, one-receiver setup.

For high-performance systems, as they are used by security and defense forces, a single antenna and a single receiver are not good enough. As mentioned above, the physical properties of antennas require using various antenna types for various purposes:

- covering different bandwidths
- having difference coverage (omni-directional, directional)
- installation at different locations

Receivers have become small and are used in groups. Also, receivers may be different according to their task within the overall objective of the installation. One or more operators are using these receivers to perform different kinds of tasks:

- direction finding
- overall spectrum scan
- focusing on a particular communication signal to intercept
- focusing on a particular radar signal for identification and subsequent jamming

An example of such a setup, which is even common in vehicles, looks like in Figure 6.

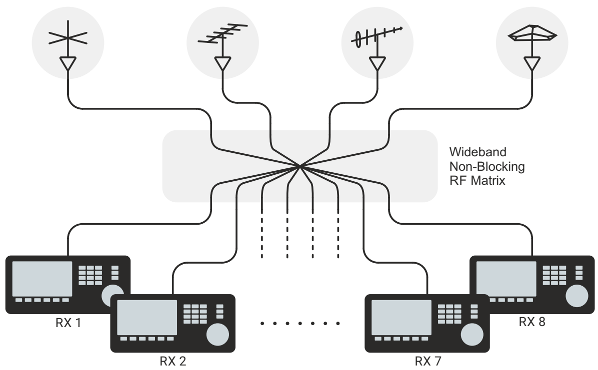


Figure 2: Illustration of a multi-antenna, multi-receiver setup.

Operators appreciate the flexibility to switch to any of the available antennas on their receiver, to have the optimal reception situation. Therefore, a matrix is introduced that allows any receiver to select any antenna arbitrarily, which requires amplification stages in the matrix in order to create identical copies without losing signal power. Sometimes also two or more receivers will analyze the signal of the same antenna. Hence, the matrix is called *non-blocking*. In the case depicted, it will create 8 identical copies of each of the antenna signals and allow any receiver to switch to it.

Today's situation however has led to another important constraint that is getting more and more important: the spectrum is crowded. Everything is wireless: from ISM band usage for consumer applications to cellular everyday use, in any frequency range there are plenty of signals. And on top, the cost and effectiveness of jamming intentionally (as done by the military enemy) make the problem even worse. Agile communication, i.e., the ability to change frequency quickly in order to always use the best (emptiest) portion of the spectrum, is one of the mitigation techniques.

This new situation creates a new requirement for the receiving system: not only must it be *sensitive* to weak signals, it must also be *tolerant* to strong signals present in the signal coming from the antenna. What is worse, as the antenna, matrix, and receiver systems are now all wideband, any strong signal in the entire covered spectrum can saturate the receiving elements and make it impossible to receive correctly the weak signal under scrutiny. E.g., a strong cellular base station nearby will jam the receiving system and make it impossible to receive a remote transmitter arriving with very low signal power.

Technical implications

In technical terms, the dilemma is characterized by the terms

- *noise performance*, impacting sensitivity, and
- *linearity*, impacting the tolerance to unwanted signals.

The term *dynamic range* is used to describe the overall performance limiting the reception. It is the range between the weakest signal receivable (due to noise) and the strongest signal tolerable (due to non-linearity effects, like saturation and intermodulation).

Noise performance

Any active component in the receiving path will add some noise to the incoming signal. The first one is typically the amplifier sitting in or close to the antenna, the so-called *low-noise amplifier* (LNA). This noise is unavoidable and depends on the bandwidth of the system. The performance of active systems with respect to noise is characterized by the *noise figure* (NF), which quantitatively expresses the degradation of the *signal-to-noise ratio* (SNR). LNAs typically have NF values of 3 – 5 dB, meaning the amplifier introduces noise power comparable to the input noise, resulting in the SNR being roughly halved. On one hand only the very first amplifier is critical: once the desired signal has been amplified by some dB, it is sufficiently above the noise that any additional noise from subsequent amplifiers becomes less relevant. On the other hand amplifying the signal will drive the following amplification stages even easier into the non-linear region when strong signals are present. Therefore, the optimum performance depends on a balance between too much and too little amplification at every stage of the chain to balance out additional noise with additional risk of non-linear distortion.

Linearity

Each amplifier can only deliver a certain power at the output. Which means if the input signal level becomes too high, the output will not follow the input signal strength anymore. This is depicted in 3.

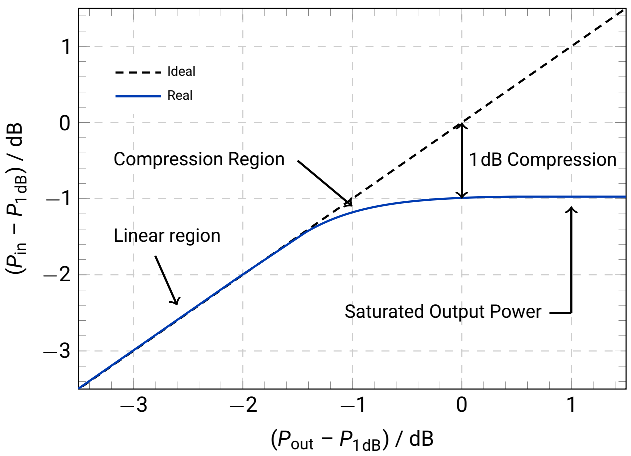


Figure 3: Illustration of an ideal linear output (- - - -) vs. saturated output power (——).

Three regions are visible in the diagram:

- the *linear region*, where the input signal comes out of the amplifier with more power, but almost unchanged in shape
- the *compression region*, where the output signal still gets stronger with increasing input signal, but the non-linearity will modify the shape of the signal and *compress* it.
- the *saturation region*, where the output signal will simply not follow anymore and the signal is *clipped* to the maximum capability of the amplifier

Unfortunately, for a receiving application, good operation requires staying absolutely in the linear region. Since 100s to 1000s of different signals enter the antenna at different frequencies at the same time, any non-linearity will modify the total shape of the received signal and add distortion. The distortion is unfortunately not limited to any particular frequency and cannot be filtered away. It can be located directly inside the band that the receiver wants to look at and thus have a detrimental impact on signal quality, and more importantly, it will reduce the capability to analyze weak signals under scrutiny. The upper limit of the linear region is often defined by either the *1 dB compression point* or by a parameter called *3rd order intermodulation distortion* (IP3). These parameters can be referenced both to the input signal level or to the output signal level, which is equivalent as long as it is clearly defined. The difference between referencing the input or output side of the amplifier is merely the amplifier's gain. A 10 dB gain amplifier will have a 1 dB compression point referenced to the output, which is 10 dB higher than the 1 dB compression point referenced to the input. The same can be applied to IP3. It is convention that the compression point is referencing the output when not specified otherwise. IP3 is normally specified as *IIP3* (IP3 referenced to the input) or *OIP3* (IP3 referenced to the output). In this wirelessly overcrowded world, the antenna (and especially wideband antennas) will receive a weak signal and other strong signals simultaneously. The weak signal will be received properly only if the strong signal is not exceeding the linear region. Imagine the cellular base station tower, which may be much closer to the antenna than the remote soldier trying to send a message. The operator of a receiver system may want to switch off and bypass the LNA at the antenna, in order to avoid its non-linearity. This has the consequences, that

- the cable loss towards the matrix or the receiver will weaken the already weak signal further, bringing it closer or below the sensitivity limit
- and the next amplifier in line (e.g., in the matrix or the receiver) will be the defining element for the *dynamic range*. And it fundamentally has the same problem as the LNA at the antenna.

Finally, the receiver applies its technology to filter out the desired signal in a relatively small band, removing all the unwanted signals from the spectrum. At the same time, it removes all the wideband noise outside the desired signal. But it can perform this task properly only if the unwanted parts have not mixed already with the wanted signal prior to that filtering, as a consequence of intermodulation/non-linearity of the amplification stages.

System design choices

The first important design choice is the selection of the antennas. It is done according to the specific needs of the application. In many cases, there are both omnidirectional and directional antennas. Additionally, some antennas are designed for specific frequency bands (e.g., long-range communication bands like HF or frequencies assigned to an organization), while others cover the lower frequency range (e.g. 20 – 1300 MHz) or offer very wide bandwidths (e.g., 20 – 8000 MHz, 1 – 18 GHz) to enable scanning of the complete wireless spectrum.

The next design choice is the presence of the LNA in the antenna, which can be always on, or can be activated or bypassed.

Then there is the choice of the matrix: how many inputs, how many outputs, and the frequency range? For simplicity, the system designer would want a matrix that covers the entire spectrum on all inputs and outputs. A matrix that is completely "transparent" and has no impact on the signals coming from the antennas. But exactly here starts the dilemma: the most flexible matrix from a bandwidth point of view will be performance-limiting from a *dynamic range* perspective. This aspect will be worked out in more detail in the next section.

The final choice is the receiver topology. Identical flexible receivers or a set of purpose-optimized receivers can be chosen according to the application.

The RF matrix

While this white paper cannot cover all the various application choices, this chapter focuses on the impact of the choice of the RF matrix on the overall performance. The base assumption is that a non-blocking matrix is needed to serve all the receivers in a flexible way. Non-blocking receivers must use active elements, i.e., amplifiers in the signal path, in order to keep the signal at least at the same power level as it is at the input of the matrix. The following paragraphs will highlight the dilemma of choosing between bandwidth and RF performance, and the wide range of choices available to the system designer.

The RF matrix consists of two stages: the first stage creates identical copies of the input signals; the second stage allows selecting which copy is used at which output. In terms of RF performance, the second stage is less critical. The choices of RF switch technology are large, and there are not only electro-mechanical but also solid-state switches, which offer a very high bandwidth, limited insertion loss, good noise performance, as well as good linearity. At least relative speaking when looking at the challenge present in the first stage.

The first stage is about taking the limited energy of an input signal, amplifying it and distributing it to multiple outputs. At its core, there is the amplifier again, with its linearity properties explained in the previous chapters.

Although the choice of semiconductor components for amplification is large, there are physical limits of the technologies that are schematically indicated in Figure 4.

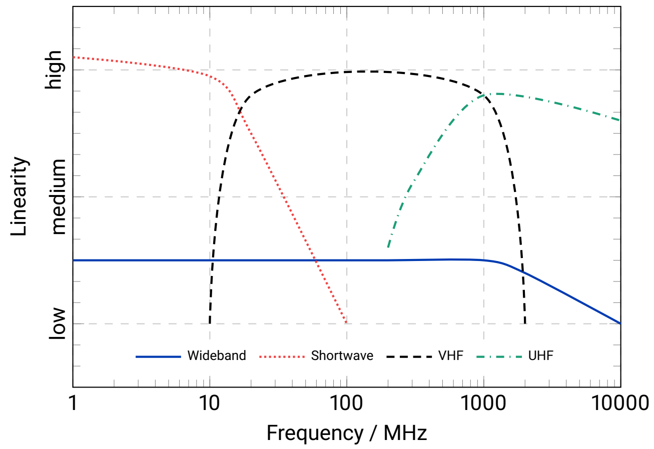


Figure 4: Illustration of the typical linearity of different technologies.

But linearity is only one side of the coin; the other side is the noise performance. Different technologies also have different noise properties, which is illustrated in Figure 5. It can be seen, that specific technologies perform much better in some bands than others.

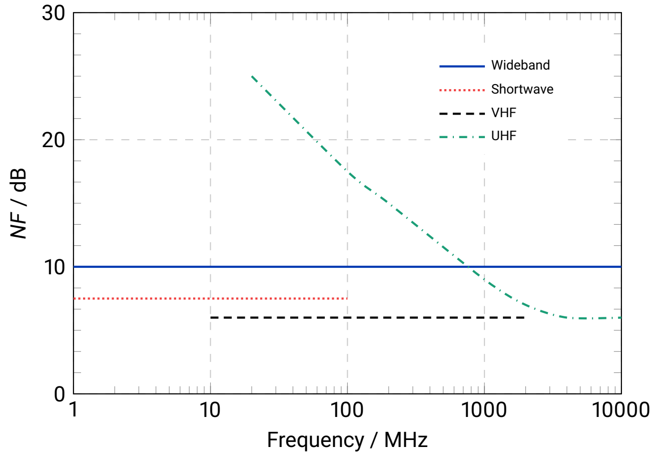


Figure 5: Illustration of the noise performance of different technologies

As previously outlined, both linearity and noise performance are equally important in the design of multi-antenna, multi-receiver systems. The dynamic range – the ability to detect weak signals in the presence of strong interferers – can be described by the gap between the system's linearity and its noise figure. When comparing these parameters, it becomes clear that wideband technologies offer the greatest bandwidth but also the smallest *dynamic range*. In contrast, more band-specific technologies such as shortwave, VHF, and UHF—though still wideband to some extent—achieve significantly higher *dynamic range*. In other words, they are better equipped to handle scenarios involving a weak desired signal alongside much stronger unwanted signals.

Knowing that antennas have similar banded properties, the ideal matrix will be adapted to the antenna connected to its input, as depicted in Figure 6.

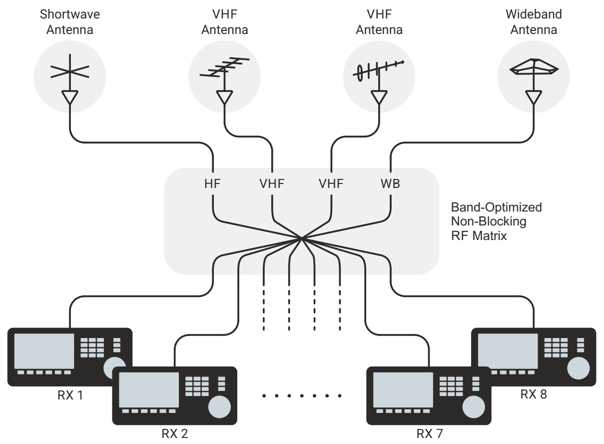


Figure 6: Illustration of an optimized multi-antenna, multi-receiver setup.

Such matrices are feasible and available from specialized vendors.

Conclusion

A receiving chain—from antenna to receiver—requires careful balancing of all elements: the antenna, antenna LNA, distribution matrix, and receivers. The system designer must consider not only the sensitivity, which depends on the noise performance of each component, but also their linearity and dynamic range to optimize overall system performance.

Banded and wideband approaches have substantial advantages depending on the application. A combination of wideband and banded approaches can be integrated in one system to offer the best of both worlds.

- Banded paths offer the biggest dynamic range and sensitivity. This is especially important in the HF/VHF area, where the interfering signals are strongest.
- Wideband paths allow the highest flexibility.

Becker Nachrichtentechnik offers both: banded and/or wideband matrix solutions within a single housing as well as support for overall performance optimization.

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