Understanding PIM
White Paper

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White Paper
Paul Denisowski
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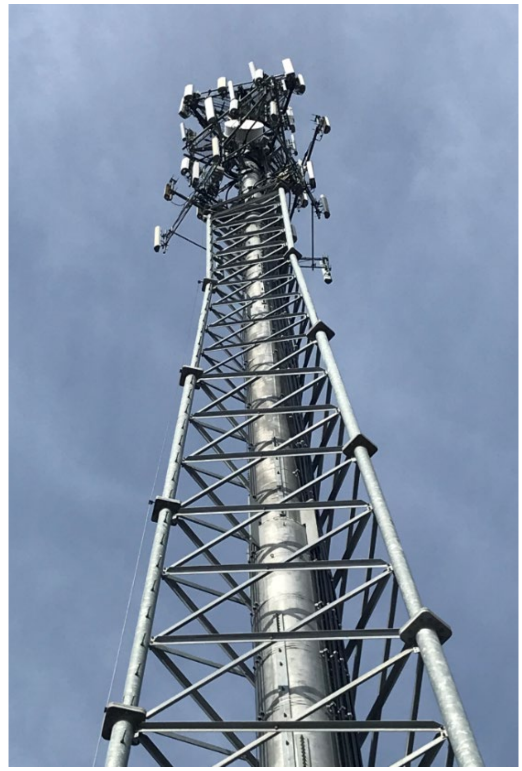
1 Introduction



Radio frequency interference to cellular base stations can take make forms. In some cases, poor frequency reuse planning and/or site selection has created situations in which the base stations themselves create issues for neighboring base stations ("pilot pollution"). Active RF sources whose signals fall within a cellular uplink band are another very common problem. These interferers are typically identified, located, and removed through a process called interference hunting. Interference hunting involves the use of portable spectrum analyzers or receivers and directional antennas to find and deactivate these (usually unintentional) sources of unwanted radio frequency energy. A more subtle, but also widespread, cause of interference in radio frequency networks in general, and cellular networks in particular, is something called **passive intermodulation**, or PIM. This paper explains what PIM is, common sources of PIM, how PIM is identified and tested, and the different ways in which PIM sources can be located in the field.

2 About intermodulation products

2.1 Harmonics

In order to understand passive intermodulation, we first have to start by explaining harmonics and intermodulation products. **Harmonics** are copies of signals that appear at integer multiples of a fundamental frequency. For example, when a signal at 100 MHz (f_1) passes through a so-called non-linear device, this device will produce harmonics at 200 MHz ($2f_1$), 300 MHz ($3f_1$), 400 MHz ($4f_1$), 500 MHz ($5f_1$), etc. Although the original, or fundamental, signal is not commonly referred to as the "first harmonic," the higher order multiples are often called the "second harmonic, "third harmonic," etc. An additional characteristic of harmonics is that the amplitude, or level, of harmonics decreases as the harmonic order, or number, increases: in other words, the amplitude of the second harmonic is lower than the level of the fundamental, the 3rd harmonic is lower than the 2nd harmonic, etc.

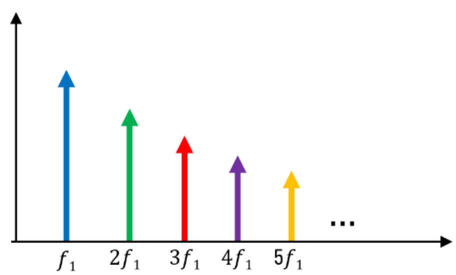


Figure 1 - Harmonics and amplitude

Although there are some applications that use harmonics (e.g. harmonic mixers), harmonics are generally undesired signals, especially in the field.

2.2 Intermodulation products

In addition to harmonics, non-linear devices also create something **called intermodulation products**. Unlike harmonics, which can be created by a single signal, at least two signals are needed for the creation of intermodulation products. When these two signals mix together in a non-linear device, this mixing produces additional signals, or products, at the sum and difference frequencies. For example, two signals, or tones are input to a non-linear device: one at 250 MHz and one at 450 MHz. The output will contain both the original input tones, as well as tones at 700 MHz (the sum of 250 MHz and 450 MHz) and 200 MHz (the difference between 450 MHz and 250 MHz). The amplitude of these intermodulation products is always lower than the amplitude of the fundamental signals.

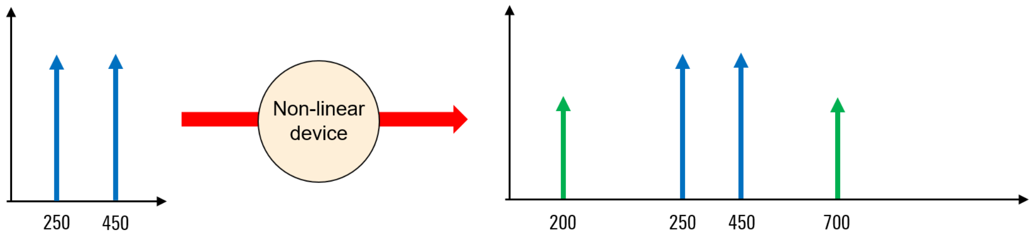


Figure 2 - Intermodulation products

2.3 Higher order products

In the example above, the mixing only occurrs between the two fundamental tones, f_1 and f_2. However, it's also possible for mixing to occur between fundamentals and harmonics. This means that not only will the two fundamental tones, f_1 and f_2, mix with each other, but they will also mix with the second harmonics, $2f_1$ and $2f_2$. This in turn produces additional intermodulation products at $2f_1 + f_2$, $2f_1 – f_2$, $2f_2 + f_1$, $2f_2 – f_1$, etc.

Another important concept is the “order” of harmonics and intermodulation products. “Order” refers to the sum of the (unsigned) coefficients. For example, $2f_1$, the second harmonic of f_1, is "second" order. The sum of the two fundamentals, $f_1 + f_2$ is second order (1 + 1). The third harmonic of f_1, $3f_1$ is third order. And $2f_2 – f_1$ or $2f_2 + f_1$ (2 + 1) are also third order products. These third order intermodulation products are particularly important when it comes to understanding passive intermodulation.

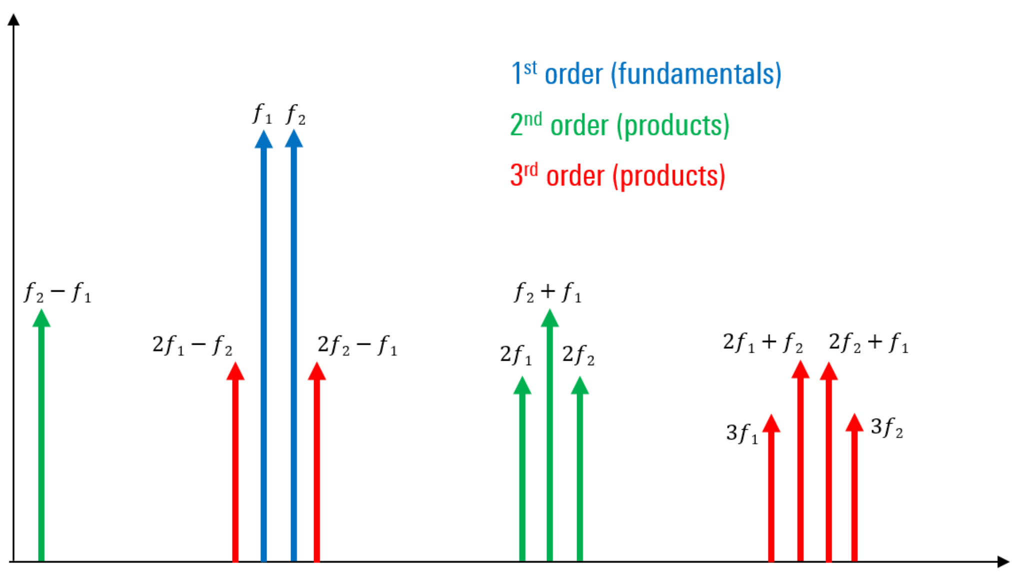


Figure 3 - Fundamentals, harmonics, and products

Mixing occurs between third, fourth, and even higher harmonics as well, producing 5th, 7th, and even higher order intermodulation products. Generally, speaking, the higher the order of an intermodulation product, the lower the relative amplitude of that product. Note also that the spacing between odd-order intermodulation products is always the distance between the two fundamental tones, i.e. $f_2 - f_1$.

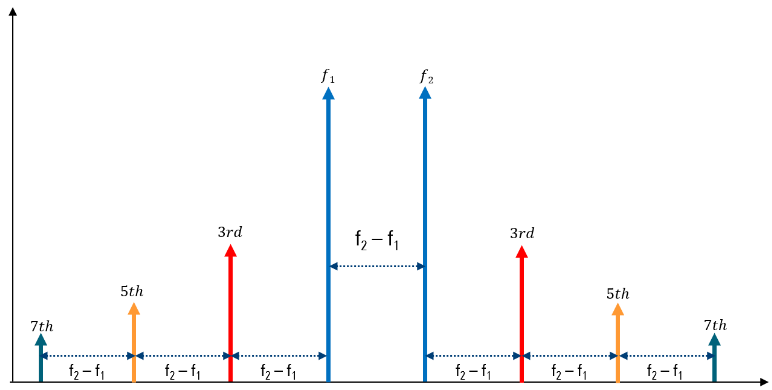


Figure 4 - Spacing of higher order intermodulation products

2.4 Width of intermodulation products

An additional important aspect of intermodulation products is that as the order of intermodulation products increase, the width of these intermodulation products increases. For example, if the fundamentals are 1 kHz wide, the 3rd order products will be 3 kHz wide, the 5th order products will be 5 kHz wide, etc. Depending on the frequency and spacing of the fundamentals, this widening of the signals may be hard to see in spectrum, especially when testing using narrowband or CW tones. However, this becomes much more noticeable if the fundamentals are wider. Cellular downlink signals may be several MHz wide (3G), tens of MHz wide (4G) or even hundreds (5G) of MHz wide.

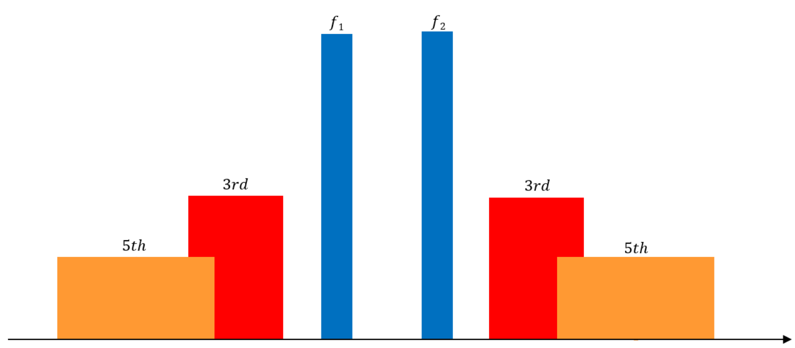


Figure 5 - Width of fundamentals and intermodulation products

3 Passive intermodulation

3.1 About passive intermodulation

As mentioned above, intermodulation products are created in “non-linear” devices or mixers. These non-linear devices can be either active, that is, powered, devices, or passive or unpowered devices. As the name implies, active intermodulation occurs by mixing in active devices. An example of an active device would be a tower mounted amplifier. On the other hand, passive intermodulation, or “PIM,” is created by mixing in passive devices, the classic example being a rusty bolt. PIM is sometimes referred to as the “rusty bolt effect” because corroded metallic junctions are a common source of PIM. Another colloquial terms for PIM is the "diode effect" because these junctions of dissimilar metals have properties similar to some diodes.

3.2 Common PIM sources

The junction of dissimilar materials or metals is the most common source of PIM, and these junctions can be created in various ways. Corrosion or rust is a very common culprit, as are defects during manufacturing or installation. Loose or overtightened connectors are another common source of PIM, and even passive components such as directional couplers can lead to PIM issues.

3.3 Problems caused by PIM

PIM products are almost always undesired signals, especially when it comes to cellular networks. These products can fall into other channels or bands, creating noise, distortion, etc., which in turn can have a strong negative impact on the key performance indications in wireless networks, such as throughput, retainability (or call drops), etc.

In particular, the third order intermodulation products are the most troubling, since they both fall closer to the fundamental signals in frequency and they have greater amplitude than the higher order products. Note however that although these higher order intermodulation products are lower in peak amplitude, they can be very wide, raising the noise floor over a broad spectral range. This higher noise floor is a more serious problem for newer generations of cellular which tend to require a “cleaner” RF environment and lower noise floor due to their higher order modulation schemes. In addition, as spectrum becomes more crowded, there is an increased probability of intermodulation products falling onto occupied frequencies. Intermodulation products generated from the mixing of two cellular downlink carriers is particularly troublesome for several reasons: the carriers are typically very broad (especially in 4G and 5G networks), they have relatively high power, and these signals are "always on."

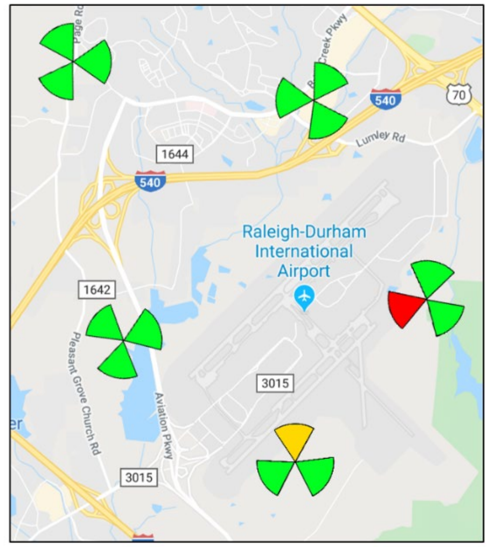


Figure 6 - PIM negatively impacting network KPIs

3.4 Internal vs. external PIM

There is another important distinction that should be made when discussing PIM: namely, the difference between internal and external PIM. In the case of internal PIM, the source of the PIM is between the transmitter and antenna. For example, if PIM is being caused by metal flakes inside of the base station cables or connectors, this would be a case of internal PIM. On the other hand, if a rusty fence were creating PIM, this is an external PIM source – PIM is being generated outside of the base station components. Generally speaking, external PIM sources are much harder to physically locate and remedy than internal PIM sources.

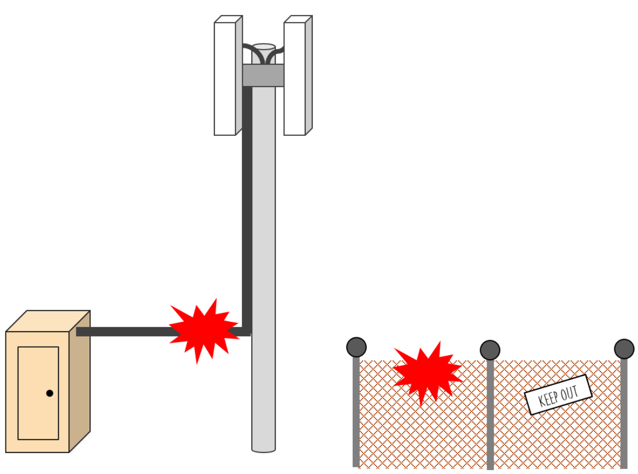


Figure 7 - Internal vs. external PIM sources

4 About PIM testing

4.1 Overview

A person experienced in interference hunting and PIM troubleshooting can sometimes recognize a PIM issue by its spectral signature, so to speak. A broad rise in the noise floor with sharp edges is usually a good visual indication of PIM created by cellular downlink signals. However, in most cases it's very difficult to detect PIM passively, that is, through spectral observation alone. One good first troubleshooting step when diagnosing a potential PIM issue is to turn off one of the suspected contributing components – remember that two or more signals are required to create PIM. But this presupposes that one both knows and can control, that is, turn on and off, at least one of the suspected components, and this frequently is not the case. Therefore, an active PIM test is usually the preferred way of diagnosing, troubleshooting, and resolving PIM issues. A special instrument called a PIM tester is connected to a base station antenna via the transmission line, and two CW tones are generated. The PIM tester knows the frequencies at which third order products would appear given the frequencies of the two tones. If PIM is being generated either internally within the system or externally, one or both of the third order products should be detected by the PIM tester. In a standard PIM test, the third order product is used because this product always has the highest amplitude, but keep in mind that it's also possible for higher order products to cause interference and other issues, especially in the event that very wide higher order PIM products create a broad increase in the noise floor.

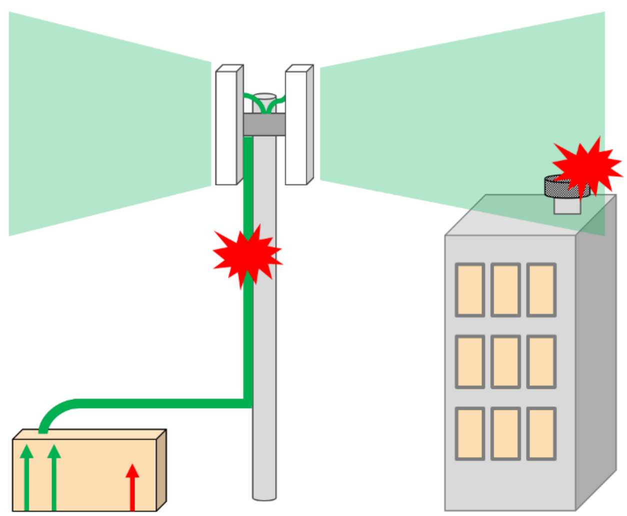


Figure 8 - PIM testing

4.2 Transmit and receive power levels

Most commercial PIM testers have a transmit power in the range of tens of watts per tone, with both tones transmitted at the same power level. There are two main reasons for using relatively high power levels in PIM testing. The first is the need to simulate power that’s close to the actual transmitter power, and modern cellular base stations usually also have transmit powers in the tens of watts. There's also the need to be able to see any generated intermodulation products in the presence of interference or a high noise floor: more power in the fundamentals means more power in the products, making the products easier to detect.

With regards to the measured products, we can express measurement results either as the absolute power of the products, in dBm, or relative to the fundamental, that is, in dBc, or decibels down from the carrier. The latter is the most common way that PIM results are represented. Typical measured PIM levels in the field are around -150 dBc, which means that if the PIM tester is generating tones at 30 to 40 watts, measured PIM levels will be around -105 dBm.

4.3 Distance to PIM

A PIM test can indicate that PIM is occurring, but in order to resolve PIM, it's also necessary to know **where** the PIM is being generated. Some PIM testers can provide something called “distance to PIM” (DTP), or a rough estimate of how far away the PIM source is. Distance to PIM is determined in much the same way as modern distance to fault (DTF) measurements are made on cables – frequency domain data is processed using the inverse fast Fourier transform (IFFT). Given the propagation velocity of the signal through the cable (a function of the construction of the cable), a reasonably accurate DTP can be calculated. In the case of DTP and external PIM sources (i.e. PIM beyond the antenna), both the velocity factor of the cable as well as the distance to the antenna have to be entered, since the fundamentals and products will propagate at different speeds through the cable and through the air. Some instruments can do DTF and DTP simultaneously.

Distance to PIM is useful in both finding so-called internal PIM, as well as finding external PIM sources. In the case of internal PIM, a DTP measurement provides a very good indication of where the PIM is originating. However, in the case of external PIM, this distance to PIM measurement only yields the location of the source on a circle (or rather a sphere) beyond the antenna.

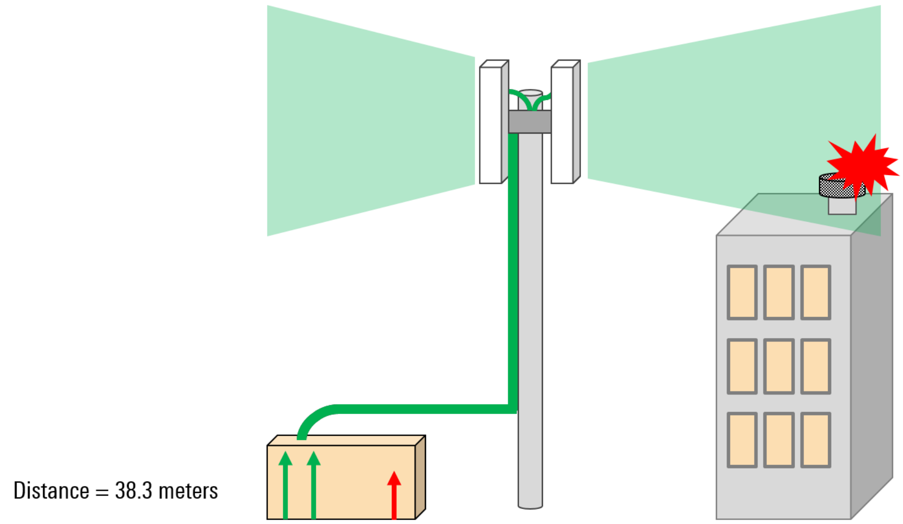


Figure 9 - Distance to PIM (external source)

4.4 Locating and resolving PIM

Figure 10 - Localizing PIM with a portable receiver and directional antenna

There are several different approaches to precisely localizing a PIM source. The “brute force” method of determining a source of PIM is simply replacing parts to see if the PIM goes away. If the PIM is believed to be internal, then visual inspection and “tapping” on connectors and components can help to determine if that component is involved – if measured PIM levels change while an object is being manually manipulated, then it’s likely that object is involved in the production of PIM. For external sources of a PIM, a so-called PIM “blanket” is sometimes used. This is an RF-insulating blanket that can be used to cover suspected sources of PIM. For example, if the measured PIM product disappears or drops in amplitude when a rooftop air vent is covered with a PIM blanket, that vent is a likely source of PIM. Another method is using a portable spectrum analyzer or monitoring receiver and a near-field probe or directional antenna. This technique is very similar to how active, non-PIM RF interferers are located – the “interferer” in this case being the third order product created while our PIM test is active. And like most other interference issues, finding and resolving PIM can be very labor-intensive and time-consuming, so using the proper tools and techniques is crucial in efficient and effective resolution of PIM issues. In many cases, a hybrid approach that combines multiple methodologies is highly advisable.

5 Summary


Figure 11 - External PIM sources are often found on rooftops

In summary, intermodulation is the mixing of two or more signals in a nonlinear device, and this creates both harmonics and products of varying orders. When this mixing occurs in passive, that is, unpowered devices, we refer to this process as passive intermodulation, or PIM. Unintended or undesired intermodulation products are a problem because they can create noise and interference, and this is a particularly common issue in cellular networks. The third order intermodulation product, being the strongest, is the most troublesome, but higher order products are also capable of creating issues, including an overall increase in the ambient noise floor. PIM testing is the active process by which we detect and locate PIM sources, and PIM tesitng is usually performed using two high power, unmodulated RF signals, or “tones”. The PIM tester transmits these two tones into the cable and antenna system, and then checks to see if a third order product appears at the mathematically predicted frequency. If PIM is detected, there are multiple methods of locating and resolving PIM. Classic methods include distance to PIM, which gives us a rough distance to the PIM source, as well as physical manipulation of components or devices to see if PIM levels change while the object is shaken or tapped. So-called PIM blankets can also be used to shield PIM sources. And finally, portable spectrum analyzers or receivers and directional antennas or probes can be used to hunt for PIM sources in the same way active RF interferers are detected and located.

PIM is both a common and a serious issue in wireless communications networks, but the use of proper test instruments and techniques can greatly improve the ability to detect, localize, and resolve PIM issues both effectively and efficiently.

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Regional contact

Europe, Africa, Middle East
+49 89 4129 12345
customersupport@rohde-schwarz.com

North America
1 888 TEST RSA (1 888 837 87 72)
customer.support@rsa.rohde-schwarz.com

Latin America
+1 410 910 79 88
customersupport.la@rohde-schwarz.com

Asia Pacific
+65 65 13 04 88
customersupport.asia@rohde-schwarz.com

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+86 800 810 82 28 |+86 400 650 58 96
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Rohde & Schwarz GmbH & Co. KG
Mühldorfstraße 15 | 81671 Munich, Germany
Phone + 49 89 4129 - 0 | Fax + 49 89 4129 – 13777

www.rohde-schwarz.com