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OVERVIEW OF PASSIVE INTERMODULATION (PIM): BEST PRACTICES ON PREVENTING PIM

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LETTER FROM THE EDITOR

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Welcome to our first guide focusing on passive intermodulation (PIM), a growing concern for cellular network operators. PIM, which is also known as the "rusty bolt effect," is a form of radio interference due to interactions of the radio waves with dirty connections or corroded parts, and with the advent of 5G, it will be an issue for various technologies.

PIM has been around for decades and often comes from two or more strong signals and a nonlinear junction. The signals are typically from transmitters sharing an antenna run, or transmitters using adjacent antennas or nearby towers with conflicting antenna patterns. Damaged or poorly torqued RF connections, contamination, fatigue breaks, cold solder joints, and corrosion can create nonlinear junctions.

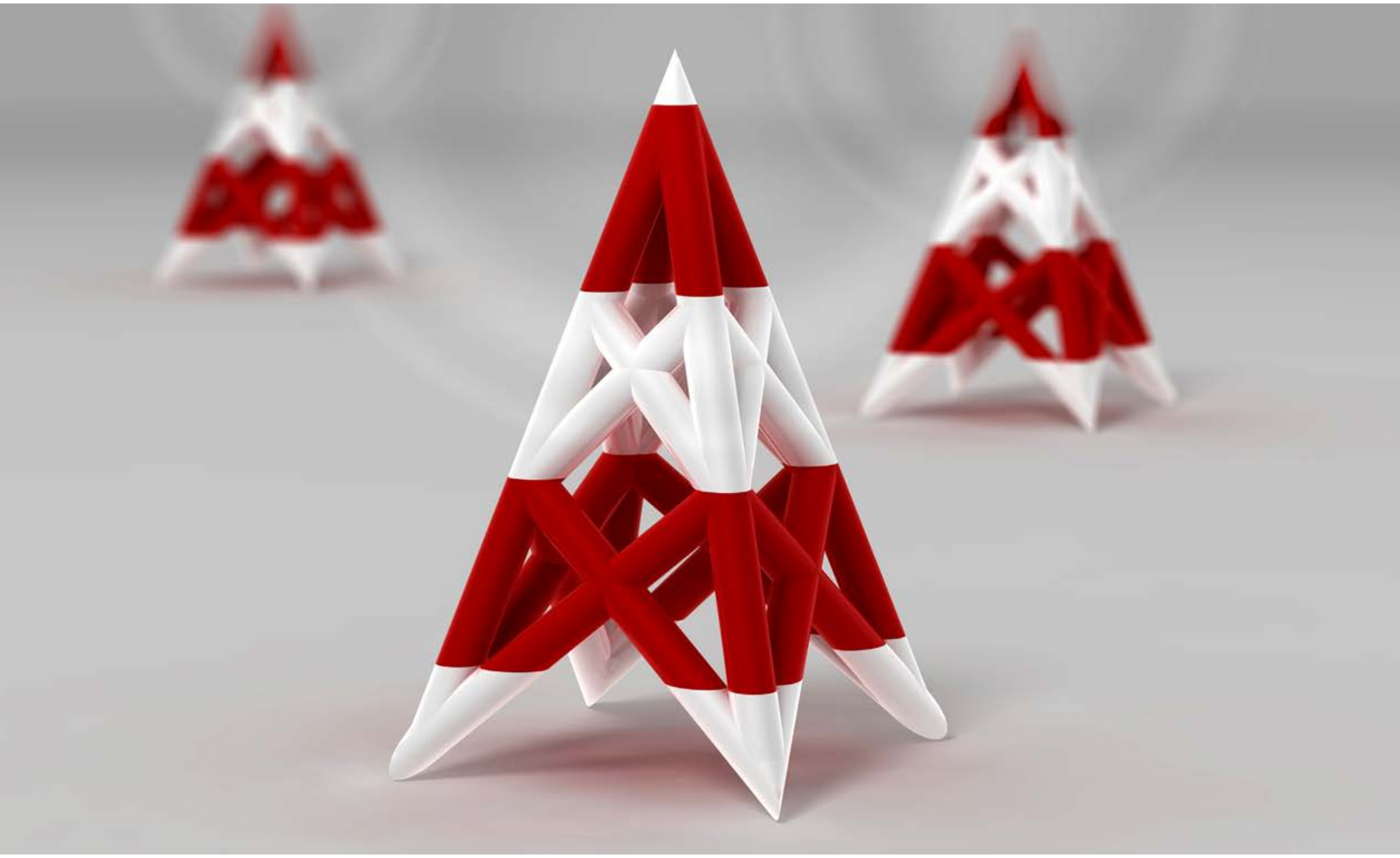
This interference can either impede calls from going through or block them altogether. PIM is especially important for high-speed data connections and applications. As cell usage and throughput grows, the peak power produced by the new digital modulations increases dramatically, contributing heavily to PIM problems.

We have gathered the content of this guide together with Anritsu, a leading test and measurement instrument manufacturer, and it includes an "Introduction to PIM," which lays out some of the ways to test for PIM and techniques to prevent PIM from occurring. This guide also contains an interview from *Interference Technology* Editor John Blyler with Emilio Franchy, Sr. Product Manager at Anritsu, that provides some insights on the new spotlight on PIM, and who will most likely be affected by PIM.

Cheers,
Jenn

INTRODUCTION TO PIM

Jennifer Arroyo
Editorial Director, *Interference Technology*



INTRODUCTION TO PIM

Passive intermodulation (PIM) is a growing issue for cellular network operators. PIM issues may occur as existing equipment ages, when co-locating new carriers, or when installing new equipment. PIM is a particular issue when overlaying (diplexing) new carriers into old antenna runs.

PIM can create interference that will reduce a cell's reception or even block calls. This interference can affect both the cell that creates it, as well as other nearby receivers. PIM is created by high transmitter power, so on-site PIM testing needs to be done at or above the original transmitter power levels to make sure that the test reveals any PIM issues.

PIM is a serious issue for cellular operators wanting to maximize their network's reliability, data rate, capacity, and return on investment. It is worth noting that PIM testing does not replace impedance-based line sweeps; rather, it complements line sweeping, which is now more important than ever.

Impedance Versus Linearity
The PIM test is a measure of system linearity, while a return loss measurement is concerned with impedance changes. It is important to remember that they are two independent tests, consisting of mostly unrelated parameters that are testing opposite performance conditions within a cellular system.

It is possible to have a PIM test pass while return loss fails, or PIM fail while return loss passes. Essentially, PIM testing will not find high insertion loss and return loss will not find high PIM. Line sweeps and PIM testing are both important.

Some cable faults show up best with a PIM test. For example, if an antenna feed line has a connector with metal chips floating around inside, it is highly likely that it will fail a PIM test while the line sweep passes. The antenna run most certainly possesses nearly ideal impedance characteristics, but the presence of metal flakes bouncing around will cause the PIM test to fail. It is also an indication that the connector was not fitted correctly.

Another possible cause of PIM test failure is braided RF cables. These cables will test perfectly in a Return Loss or VSWR test, but generally possess only average PIM performance. The braided outer conductor can act like hundreds of loose connections that behave poorly when tested for PIM, particularly as they age. For permanent installations, braided cables are not recommended.

With the rollout of spread-spectrum modulation techniques, such as W-CDMA, and OFDM technologies like LTE and WiMAX, it has become essential to test both PIM and impedance parameters with total accuracy.

Testing for PIM
PIM lowers the reliability, capacity, and data rate of cellular systems. It does this by limiting the receive sensitivity. In the past, RF engineers could select channel frequencies that would not produce PIM in the desired receive bands. However, as cellular usage grows, the licensed spectrum has become crowded. Engineers must often select less desirable RF carrier frequencies and accept potential PIM issues. Compounding this problem, existing antenna systems and infrastructure are aging, making any PIM that does occur stronger.

When PIM products fall within the receive band of a cell site radio, they make the receiver less sensitive to weak signals that limit receive coverage. This increases the bit-error-rate (BER) and creates more dropped calls. If the connection is for data, interference from PIM creates more error protection bits and resends, which causes a lower overall data rate. In some cases, PIM can even cause receiver blocking, shutting down the sector.

Signs of PIM problems include receive-noise-floor-diversity-imbalance and high noise floors. Other signs include shorter average call duration, higher dropped call rates, lower data rates, and lower call volume.

Defining PIM
PIM is a form of intermodulation distortion that occurs in components normally thought of as linear, such as cables, connectors, and antennas. However, when subject to the high RF powers found in cellular systems, these devices can generate intermodulation signals at -80 dBm or higher.

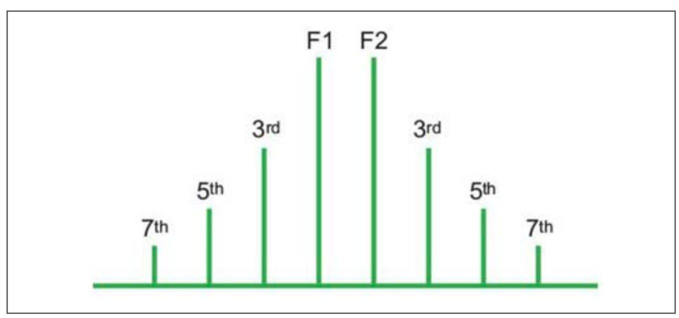


Figure 1. Carriers F1 and F2 with 3rd through 7th order products.

Intermodulated (IM) signals are generated late in the signal path; they cannot be filtered out and may cause more harm than the stronger, but filtered, IM products from active components.

An on-site PIM test is a comprehensive measure of linearity and construction quality.

PIM shows up as a set of unwanted signals created by the mixing of two or more strong RF signals in a nonlinear device, such as a loose or corroded connector, or nearby rust. Other names for PIM include the diode effect and the rusty bolt effect.

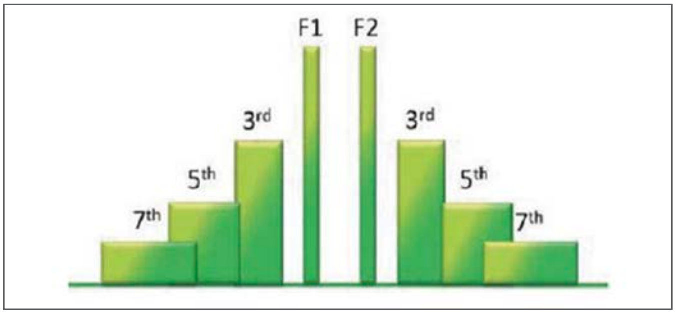


Figure 2. PIM bandwidth increases with the order of the product.

This pair of formulas can predict PIM frequencies for two carriers:

$$nF1 - mF2 \quad (1)$$

$$nF2 - mF1 \quad (2)$$

F1 and F2 are carrier frequencies, and the constants n and m are positive integers.

When referring to PIM products, the sum of n + m is called the product order, so if m is 2 and n is 1, the result is referred to as a 3rd-order product (*Figure 1,* see page 6). Typically, the 3rd-order product is the strongest, causing the most harm, followed by the 5th- and 7th-order products. Since PIM amplitude becomes lower as the order increases, higher order products typically are not strong enough to cause direct frequency problems, but usually assist in raising the adjacent noise floor (*Figure 2*).

It is unlikely that a 3rd-order product will fall directly into a designed cellular receive band. It is highly likely that energy from other external transmissions will mix within the nonlinear transmission line causing many smaller PIM levels to mix over and over, resulting in a wideband raised noise floor that usually spans all operators' licensed spectrum. Once this raised noise floor crosses into the Rx band, it then has an open door (and sometimes gain via LNA) into the BTS.

IM from Modulated Signals

Intermodulation products from continuous wave (CW) signals, such as those that might be created by a PIM tester, appear as single-frequency CW products. When spotting PIM that is created from modulated carriers, the sort of fault that might be seen with live signals, it is important to know that intermodulation created from modulated signals takes more bandwidth than the fundamentals. For instance, if both fundamentals are 1 MHz wide, the 3rd-order product will have a 3 MHz bandwidth, the 5th-order product, a 5 MHz bandwidth, and so forth. PIM products can be very wideband, covering wide swaths of frequencies.

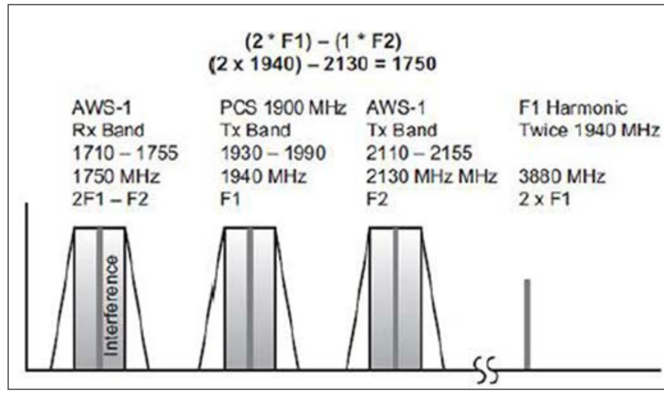


Figure 3. PIM causing receiver de-sense at 1,710 MHz

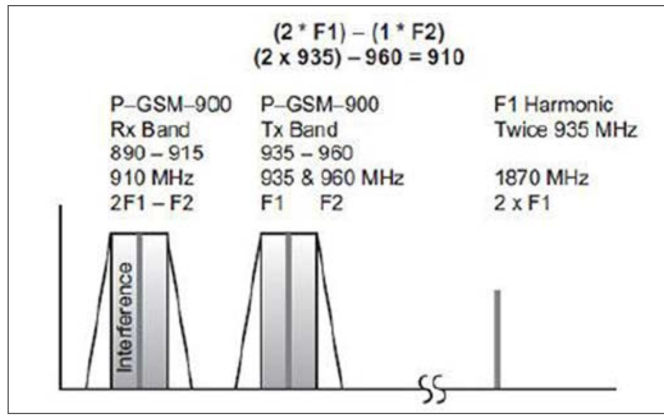


Figure 4. PIM causing receiver de-sense at 910 MHz

With the overlay of spread spectrum signals into current site infrastructure, mixing of a three-channel UMTS transmission with a 10 MHz LTE (assuming 10 MHz and not 20 MHz) due to a transmission system linearity problem would be disastrous. In theory, this could create a 3rd-order product with a bandwidth of over 30 MHz and this does not include any effect that the 5th- and 7th-order would introduce. This would be an interesting experiment to document as 100 MHz+ noise issues are certain to be present.

Three or More Carriers

The calculations so far have assumed that there are only two carriers present. That is not always the case in the real world. At the base station, one needs to account for not only carriers within an antenna system, but the stronger signals from nearby transmitters as well. The signals can backfeed into an antenna system, find nonlinear devices, mix with other carriers, and create PIM. This issue compounds quickly when highly complex modulation platforms are used; something that is already very evident in the cellular field, even when relatively narrow bandwidths are in use.

When three or more carriers are involved, the calculations quickly become complex. There are programs and spreadsheets available online to help with this task. A quick alternative, if possible, is to turn the transmitters off one at a time to find out which carriers and antenna runs contribute to the PIM. This can greatly simplify the calculations and the troubleshooting task.

PIM from Bursty Sources
A PIM-like effect can also be caused by periodic breakdown of an insulating film between connector mating surfaces. Corrosion or foreign deposits and their effects can cause this insulation to appear over time. Interference caused by this mechanism is wideband and bursty in nature, occurring at rates ranging from infrequent to as often as two or three times per second. This effect is caused by micro-arcing or fritting and can be found with PIM testing.

Preventing PIM: Best Practices
It is important to take advantage of the manufacturers' installation training courses whenever possible, as they know how their connectors fit and how they are best assembled.

There are several best practices to follow when working with precision RF cables and connectors. It is important to keep the connecters clean, avoid distorting the connector, and keep the connector center conductor undamaged.

Inspection
When the connectors are apart, inspect them for physical damage. The center connector should not be loose, and it should have no visible dents or scratches. A small magnifying lens will help with this inspection. Any damage or contamination may allow micro-arcing or the diode effect to occur, causing some level of PIM. This inspection will also help spot sources of Voltage Standing Wave Radio (VSWR) problems.

Cleaning
Keep connectors clean to minimize PIM. This procedure, borrowed from laboratory practice, is useful any time a connector is suspect. It requires a cotton swab, low pressure air, Isopropyl alcohol, and a toothpick to clean connectors before re-assembly.

The process goes like this:

- Remove loose particles by using low-pressure compressed air.
    - Small volumes of compressed air are available in spray cans for this purpose.
    - The particles may come from the shielding, when cut, or from the connector itself.
    - A toothpick is useful to remove any small particles that the air does not remove.
- Use Isopropyl alcohol on cotton swabs to clean the rest of the surface.
    - Use only enough to do the job, because the Isopropyl alcohol may melt any plastic parts.
- Use the low-pressure air again to remove any remaining small particles and dry the surface.

Be careful not to twist connectors when reassembling or mating them. If they are twisted, small scratches will form on the center pin, which can destroy its precision.

Precision connectors can be destroyed in as few as five attachment/detachment cycles if the center pin is allowed to twist freely. The small scratches can generate both excessive VSWR and PIM.

Excess flux from any soldering should be cleaned since the flux is sticky and will attract contaminates. This, in turn, may encourage PIM.

Torque
Tighten connectors to the proper value. Proper torque on the connector is both required and will help minimize PIM. Low torque will allow gaps and PIM from the center connector. High torque will damage the center connector, again causing PIM.

However, if it is required to connect and disconnect the same joints several times, mating cycles may be an issue. Manufacturers specify the number of mating cycles they can guarantee.

Some devices cannot handle any more than a few complete torque cycles and care must be exercised so the device is not technically "worn out" before it is even installed. A good example is the connector on an antenna panel. Very few designs appear to be able to handle more than a couple of cycles before the connector base loosens from the chassis. This generally causes the antenna to fail PIM testing and will most likely show a questionable line sweep.

For 7/16 DIN connectors, 20 foot-pounds is an accepted value, and for Type N connectors, 12 inch-pounds is common. Some manufacturers may specify slightly lower values. If they do, use the manufacturer's values. The recommended practice is to ensure every person tightening connectors has the proper torque wrench (*Figure 5*).

It is important to check with each manufacturer for torque specifications, as they vary slightly depending on the situation.

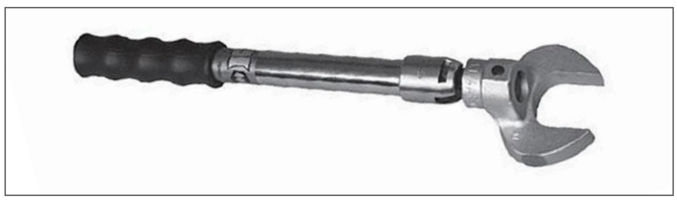


Figure 5: Breakaway torque wrench

Summary

Lack of linearity can limit the sensitivity of a cellular system. This limits the reliability, data rate, capacity, coverage, and return on investment of the system. The PIM test is an excellent indicator of linearity and construction quality.

PIM comes from two or more strong RF signals mixing in a non-linear device. These non-linear devices, or junctions, occur in improperly tightened, damaged, or corroded connectors or in damaged antennas. Rusty components, such as mounts and bolts, are also suspect when hunting for sources of PIM.

Many common frequency combinations can produce PIM in a cell's receive band. Signals in the cell's receive band will raise the noise floor, increase the bit error rate, and shrink the reception area for cellular communications. Avoiding PIM starts with frequency assignments that put potential PIM products outside of receive bands. However, increasing capacity, new services, and aging infrastructure are all working against this strategy, making PIM testing more important every day. It is apparent that most onsite PIM issues that affect service are derived from the sidebands of internally generated interference, not the calculated frequencies themselves.

Proper care and maintenance of connectors is essential to keeping PIM low. Inspection and cleaning are a central part of good performance. Proper torque is also important, as this keeps the center connector from damage.

PIM testing is becoming more critical as cellular systems age and the carrier count is increased. A test that was not as important when cellular systems were lightly loaded is becoming a critical part of modern cellular maintenance. A cell site constructed with PIM in mind will cost less to maintain over time. This same site will show cleaner performance than similar sites that were not PIM tested.

RUSTY BOLT OR PIM: EMI AND EMC DEVELOPERS FACE INCREASING CHALLENGES

John Blyler
Editor, *Interference Technology*

RUSTY BOLT OR PIM: EMI AND EMC DEVELOPERS FACE INCREASING CHALLENGES

Today's modern communication systems are being challenged by an old radio phenomena, quaintly referred to as the "rusty bolt" effect. Put simply, the "rusty bolt" or "diode" effect is a form of radio interference caused by the interactions of radio waves with dirty connections or corroded parts that lead to harmonics and other unwanted signals. Its more technically accurate name is "passive intermodulation," or "PIM."

Nonlinearities in the mechanical components of a wireless system (e.g., antennas, coax connectors, and cables) can create unwanted, interfering signals that lead to PIM. The effect occurs when two signals mix together to produce sum and difference signals and products within the same band, which leads to interference.

To learn more about PIM, Interference Technology Editor John Blyler spoke with Emilio Franchy, Sr. Product Manager at Anritsu. The following is an edited portion of that interview. — JB

Blyler: PIM has been around for a long time. Why has it now become a more important issue in today's communication systems?

Franchy: PIM is a problem in 4G telecommunication systems and even more of a challenge in 5G. There are a couple of reasons why PIM issues are getting worse in new systems. First, there is a proliferation of additional bands; i.e. there is more mixing that could happen. But, perhaps the bigger issue is the higher data throughput rates that require very low noise floors on the receivers. You can not use the faster modulation techniques if your noise floor is high, because of the loss of data bits. PIM tends to raise a system's noise floor, which effectively reduces the data throughput. A related effect with a higher noise floor is the reduction of coverage area. The receiver will only be able to reach radios that are closer to the site.

Blyler: How does PIM relate to sideband distortions or harmonics?

Franchy: PIM results from a mixing of two or more signal products. LTE and 5G have a lot of subcarriers that can be mixed, so you'll have multiple effects that are distributed. [***Editor's Note:*** A subcarrier is a sideband of an RF carrier wave.] For PIM, the most important intermodulation distortion coefficients that result from unwanted subcarriers in the uplink band tend to be IM3, IM5, IM7, etc. For example, IM3 products will be around three times wider than your original desired signals, whereas IM5 would be five times wider. These broadband signals are now three to five times wider, and really raising your noise floor.

[***Editor's Note:*** Consider the two cellular frequencies of f1 = 869 MHz and f2 = 894 MHz. Mixing two signals f1 and f2 together produces f1 – f2 and f1 + f2. The resulting signals tend not to be a problem for PIM. However, these resulting signals mix again to form a second harmonic and higher that do fall within the range of the desired uplink signals. The second harmonics can be mixed with the base frequencies to produce what we call third-order intermodulation products 2f1 – f2 and 2f2 – f1. Of course, if your PIM effects are not falling in your uplink band or none of the other systems are complaining, then it's not really a problem for you.]

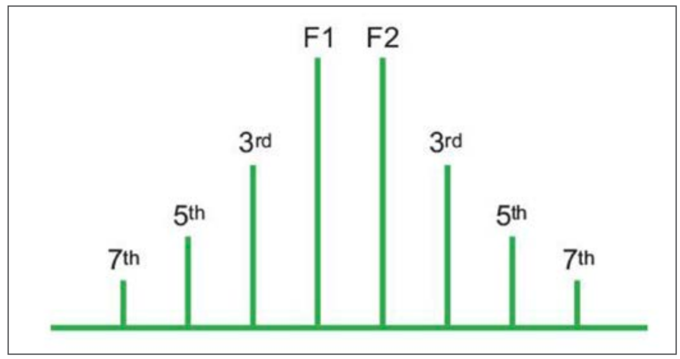


Figure 1: Carriers F1 and F2 with third through seventh order products. (Courtesy of Anritsu, https://www.anritsu.com/en-US/test-measurement/technologies/pim)

Blyler: Are certain kinds of networks on different telecommunication carriers more susceptible to PIM than others?

Franchy: At some point, all are susceptible to PIM. It really depends on the frequencies the carriers are using, and how many bands are sharing the same feedlines or antennas, because that is a great place for them to all mix. The problem occurs due to limitations on how many antennas and cables are connected together. 5G will be a more integrated solution, which will help. Still, if you have multiband radios or radios that are sharing antennas, then you have a potential mixing at the antenna level. Or if the desired signals are going through filters, then you may have PIM at the filter level. Distributed antenna systems (DAS) present a huge issue as they basically run everything through a single antenna.

Blyler: How does an indoor DAS potentially cause PIM?

Franchy: iDAS, or indoor DAS, is used to provide cellular coverage at a stadium or big shopping mall. All of the radios are located on the radio head, which is connected to a distribution system. Passive DAS is connected with coax cables. In this case, you are summing all of the different radios together and running coax out throughout the building. Splitters are used at different points for

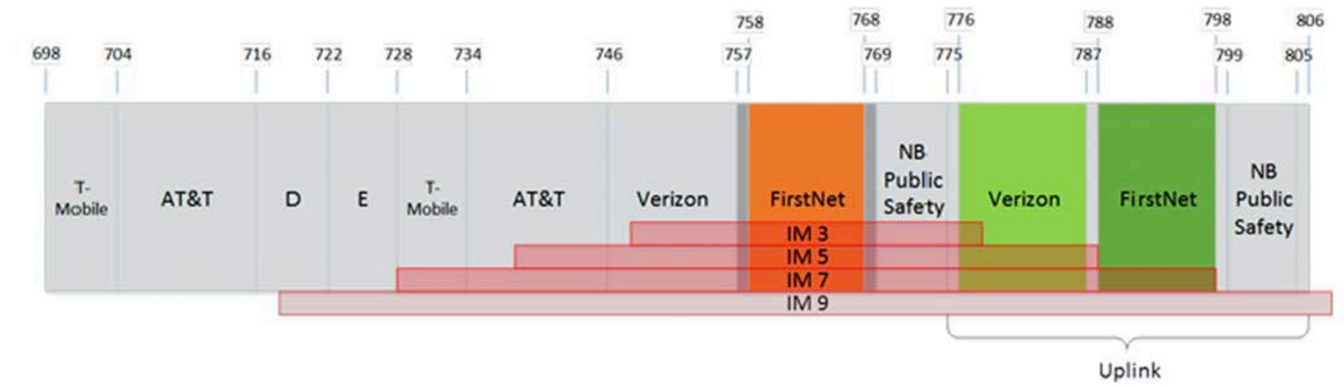


Figure 2: When looking at the effects of PIM in LTE networks, what we see are LTE subcarriers that come together to form the "wedding cake of PIM". (Courtesy of Anritsu, "Fishnet" https://www.anritsu.com/en-US/test-measurement/technologies/firstnet)

different floors, intersections, etc. Antennas are placed at different points in the building. All of these connection points may result in PIM.

Hybrid systems exist where fiber optics run out to radios and short jumper cables are used to connect to different antenna systems. Here, the antennas would be the source of PIM because at that point everything gets converted from electrical to RF.

Blyler: Let's return to next-generation communication systems. How does the move to multi-carriers increase the risk of PIM?

Franchy: In the past, 3G technologies like CDMA and W-CDMA operated on a single carrier. PIM wasn't a problem as there wasn't another carrier with which to interact. On the other hand, LTE consisted of many 15 kHz subcarriers, and that interaction within that LTE carrier caused PIM. One of our whitepapers calls it the "cake effect" due to the layering caused by IM3, IM5, IM7, and IM9. Essentially, these 15 kHz subcarriers could potentially mix and cause PIM, where before it was just a single signal. Multiple carriers are needed to cause PIM.

Today, bands are denser so you have a higher chance of mixing and creating an intermodular product that falls in some uplink band.

Blyler: The readers of *Interference Technology* do a lot of EMI and EMC testing, but not all of this activity is done in the telecommunication space. Are there other markets besides telecommunication that are affected by PIM issues?

Franchy: It's true that cellular is the biggest market for PIM. Another potential market would be satellite systems, which have a wide communication channel. In general, most systems that use frequency division duplex (FDD) systems will be susceptible to intermodulation effects. PIM occurs when you are transmitting, but it is also a problem for the receiver. PIM goes away when you shut off your communication system. So any system that remains always on will be more likely to have PIM issues.

In EMI or EMC testing for intermodulation, effects can be done at the component and system levels. In essence, you send out two calibrated tones. For testing, you must have a filter system that can handle those strong signals going out with very little PIM. Then the return signal can be easily separated without being affected by the two transmission tones. This typically requires 140 to 160 dBm between the two tones. So you are really talking about the internals of the test system that is creating and testing for the problem.

It is critical that the test system be capable of generating two strong test tones. The receiver must be capable of listening at as low as -122 dBm or even lower. Usually you want to have 10 dB below what you are measuring as the dynamic range. Remember that both the tone transmission and reception are occurring through the same filter system so you must have very good design on the filters when testing for PIM.

Blyler: Thank you.

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