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Passive Intermodulation (PIM) Effects in Base Stations: Understanding the Challenges and Solutions

By **Frank Kearney** and **Steven Chen**

Introduction

It is well known that *active* components will generate nonlinearities in systems. Various techniques have been developed to improve the performance of such devices during both the design and operational phase. It is easy to neglect that the passive devices can also introduce nonlinear effects; although sometimes relatively small, these nonlinearities can, if not corrected, have serious effects on system performance.

PIM stands for "passive intermodulation." It represents the intermodulation products generated when two or more signals transit through a passive device with nonlinear properties. The interaction of mechanical components generally causes nonlinear elements. This is particularly evident at the junction of two different metals. Examples include: loose cable connections, dirty connectors, poor performance duplexers, or aged antennas.

Passive intermodulation is a significant issue within the cellular industry and it is extremely difficult to troubleshoot. In cell communication systems, PIM can create interference and will reduce receiver sensitivity or may even inhibit communication completely. This interference can affect the cell that created it, as well as other nearby receivers. For example, in LTE Frequency Band 2, the downlink is specified from 1930 MHz to 1990 MHz, while the uplink ranges from 1850 MHz to 1910 MHz. If two transmitter carriers, located at 1940 MHz and 1980 MHz, are transmitting from the base station system with PIM, their intermodulation will lead to a component at 1900 MHz, which will fall into the receive band. This will affect the receiver. Furthermore, the intermodulation item at 2020 MHz may affect other systems.

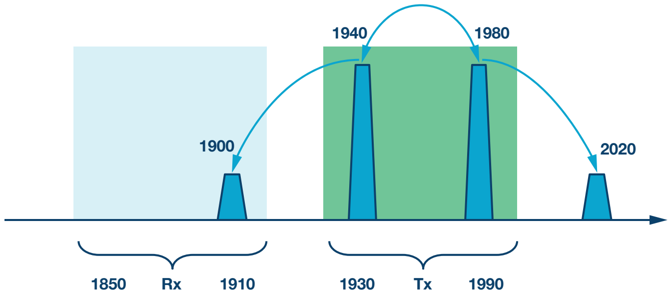

Figure 1. Passive intermodulation, falling back into the receiver band.

As the spectrum has become more crowded and antenna sharing schemes become more common, there is a corresponding increase in the possibility of PIM generation from the intermodulation of different carriers. The traditional way of using frequency planning to avoid PIM becomes almost impossible. Coupled with the challenges just mentioned, the adoption of new digital modulation schemes like CDMA/OFDM means that the peak power of the communication system also increases, adding to the severity of the PIM issue.

PIM has been highlighted as a serious problem for service providers and equipment suppliers. Detecting and, where possible, solving the problem delivers increased system reliability and reduced operation cost. In this article we attempt to review the sources and causes of the PIM, along with technologies proposed to detect and solve it.

PIM Classification

Our initial observations indicate that PIM has three distinctive types, each with differing characteristics and each requiring differing solutions. We choose to classify those type as *design PIM*, *assembly PIM*, and *rusty bolt PIM*.

Design PIM

Certain passive components in combination with their transmission lines are known to contribute to passive intermodulation. Therefore, when designing a system, development teams will choose passive elements with minimal or acceptable levels of PIM as specified by the component manufacturer. Circulators, duplexers, and switches are particularly prone to the effect. Designers may choose to accept higher levels of passive intermodulation by selecting lower cost, smaller size, or lower performance options.

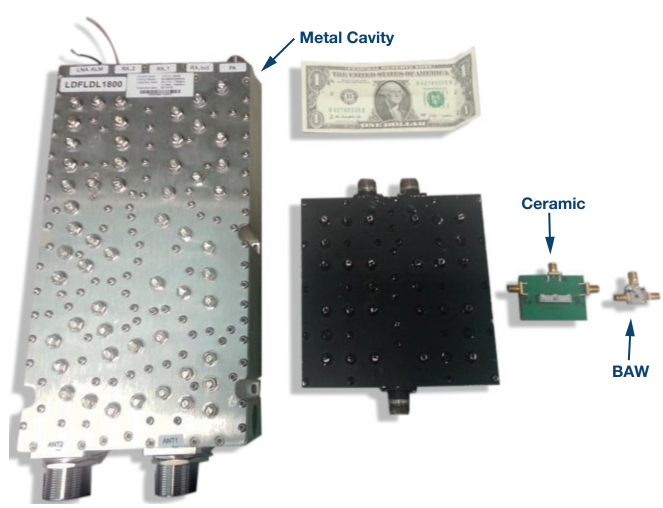

Figure 2. Component design trade-offs, size, power, rejection, and PIM performance.

If designers do choose to use the lower performance components, the resultant higher levels of intermodulation may fall back within the band of the receiver and result in desensitizing it. It is important to note that in these instances, the unwanted spectral emissions or loss of power efficiencies may not be as concerning as the desensitizing effect of PIM on the receiver. This problem is of particular significance in small cell radio designs. ADI is currently at an advanced development stage, whereby the PIM contributed by the static passive elements such as the duplexer can be detected, modeled, and subtracted (canceled) from the received signal (see Figure 3).

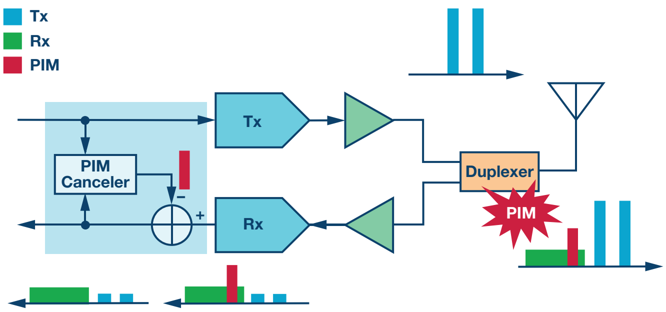

Figure 3. PIM generation and cancellation algorithm.

The algorithm works because it has knowledge of the carriers and can use correlation at the receiver to determine the intermodulation artifact before subtracting it from the received signal.

Limitations on the algorithm start to emerge when correlation can no longer be used to determine the intermodulation artifact. Figure 4 provides an example of this. In this instance, two separate transmitters share the same antenna. If we assume that the baseband processing for each path is independent from the other, then the algorithm is unlikely to have knowledge of both and, hence, is limited in the correlation/cancellation it can perform at the receiver.

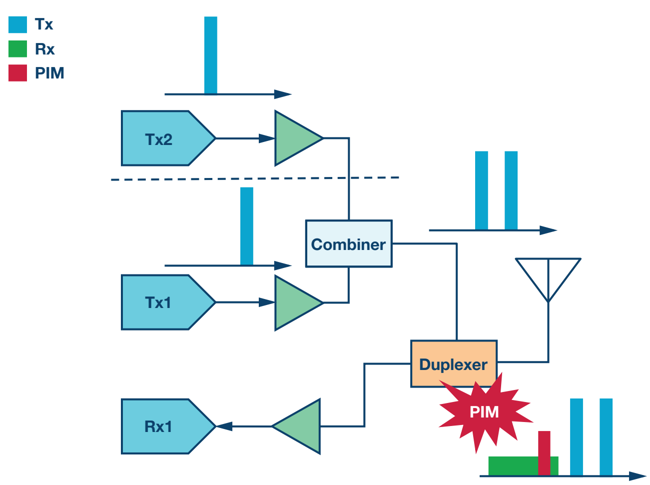

Figure 4. Multiple sources sharing the same antenna.

Complexity Adding to the PIM Challenge

As site access and costs challenge service providers, we are starting to see an increasing number of instances where separate transmitters share a single wideband antenna. The architectures can be a mix of band and formats: T_{DD} + F_{DD}; T_{DD}: F + A + D, F_{DD}: B3, etc. Figure 5 provides an overview of such a configuration. In this instance, the customer is implementing a complex but real configuration; one branch is T_{DD} dual band and the other is F_{DD} single band, employing a duplexer. The signals are combined and share a single antenna. The intermodulation between the Tx1 and Tx2 signals occurs passively in the path from combiner, in the transmission line to the antenna, and in the antenna itself. The resultant intermodulation artifact falls back within the band of the F_{DD} receiver, Rx2.

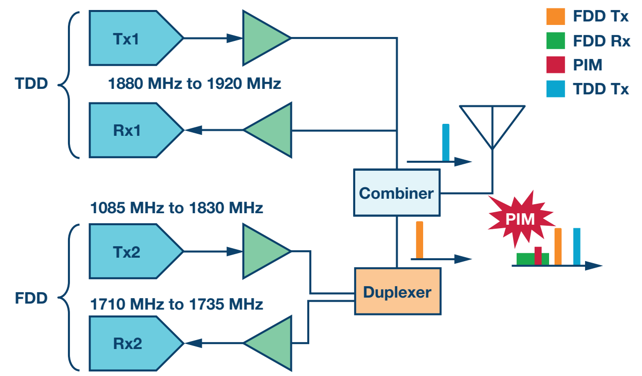

Figure 5. F_{DD}/T_{DD} single antenna implementation.

Figure 6 shows a practical analysis for a dual-band system. Note that in such instances we need to consider well beyond third-order passive modulation artifacts. In this case, the focus is on intermodulation artifacts from one band (intra) falling within the receive band of the other.

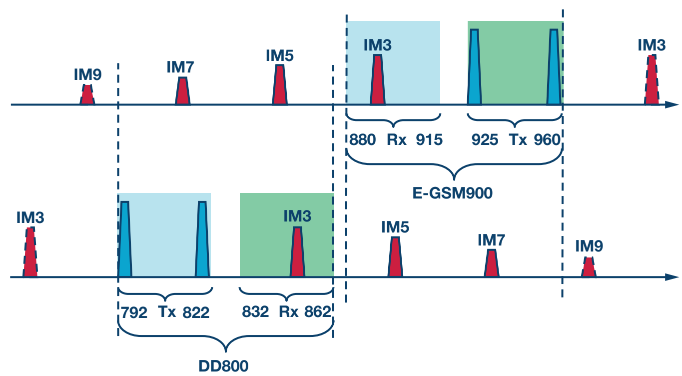

Figure 6. Multiband PIM issues.

Assembly PIM

The second categorization of PIM is what we might term *assembly PIM*. While the system may operate satisfactorily when installed, the performance will often degrade over time due to weather or poor initial installation. When this occurs, passive elements (that is, connectors, cables, cable assemblies, waveguide assemblies, and components) of the signal path will typically start to exhibit nonlinear behavior. In fact, some of the major occurrences of PIM will be caused by connectors, connections, and even the feeder for antennas themselves. The resultant effect can be similar to that of the design PIM, as discussed earlier. Hence the same PIM measurement theory can be used that is specifically looking for the presence of passive intermodulation products.

Typical contributors to assembly PIM are:

- Connector mating interface (typically Type N or DIN7/DIN16),
- Cable attachment (mechanical stability of the cable/connector junction),
- Materials (brass and copper are advised, ferromagnetic materials show nonlinear characteristics),
- Cleanliness (contamination from dirt or moisture),
- Cable considerations (quality and robustness of cable),
- Mechanical robustness (flexing due to wind and vibration),
- Electrothermally induced PIM (due to the variation of conductance as temperature varies in response to the time varying power dissipated by RF signals with nonconstant envelopes).

Environments where there are wide temperature variations, salt air/polluted air, or excessive vibrations tend to exacerbate PIM. Although the same PIM measurement techniques can be used as for design PIM, the presence of assembly PIM can be considered as an indication of system degradation both in terms of performance and reliability. If unresolved, the weaknesses that are causing PIM may continue to escalate until complete transmission path failure occurs. The approach of using PIM cancellation for assembly PIM might be considered as masking an issue, rather than resolving it.

In such circumstances it would be expected that users will not want to cancel the PIM but be notified of its existence with the aim to rectify its root cause. Elimination comes from first determining where on the system the PIM is been introduced and then repairing or replacing that specific element.

Whereas we might consider design PIM as being quantifiable and stable, assembly PIM, as previously described, is not stable. It may exist under a very narrow set of conditions and its amplitude variation can be in excess of 100 dB. One single shot offline sweep may fail to capture such instances; ideally the transmission line diagnostic needs to be captured in tandem with the PIM event.

PIM Beyond the Antenna (Rusty Bolt PIM)

PIM is not limited to the wired transmission path but can also happen beyond the antenna. The effect is also known as rusty bolt PIM. In such a circumstance, the passive intermodulation occurs after the signals have left the transmitter antenna with the resultant intermodulation reflecting back into the receiver. The term rusty bolt comes from the fact that in many instances the intermodulation source can be a rusty metallic object such as a mesh fence, a barn, or even a drain pipe.

Reflections caused by metal objects are to be expected. In these instances, however, the metal objects do not only reflect the received signals but also produce and radiate intermodulation artifacts. The intermodulation occurs just as it did within the wired signal path—that being at the junction of two different metals or junctions of dissimilar materials. The electromagnetic waves create surface currents that mix and reradiate (see Figure 7). The reradiated signals are usually very low in amplitude. However, if the radiating element (rusty fence, barn, or downpipe) is close to the receiver of a base station and if its intermodulation product falls within the receive band, the result will be receiver desensitization.

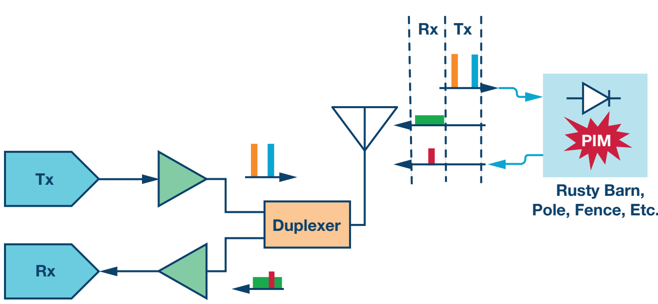

Figure 7. Beyond the antenna, or rusty bolt PIM.

In some instances, detection of the PIM source can be achieved by antenna positioning: the PIM level is monitored while the antenna position is changed. In other instances, time delay estimation can also be used to locate the source. If PIM levels are static, then standard algorithmic cancellation techniques can be used to compensate for the PIM. However, in many instances, vibration, wind, and mechanical movement can modulate the PIM contribution and make the cancellation challenge even more difficult.

PIM Detection: Locating the Source of PIM

Line Sweeping

Various *line sweeping* techniques can be implemented. Line sweeping measures the signal losses and reflections within a transmission system over the band of interest. It cannot be assumed that line sweeping will always accurately indicate the possible causes of PIM. Line sweeping can be considered more as a diagnostic tool that helps identify issues on the transmission line path. Early stage assembly issues can manifest themselves as PIM; if left unresolved, those assembly issues can escalate into more serious transmission line failures. Line sweeping usually breaks down into two basic tests: return loss and insertion loss. Both are very frequency dependent and both can vary greatly within a specified band. Return loss measures the power transfer efficiency of the antenna system. It is essential that minimal power is reflected back toward the transmitter. Any reflected power can distort the transmitted signal and, when powerful enough, cause damage to the transmitter. A return loss figure of 20 dB indicates that 1% of the transmitted signal is being reflected back to the transmitter and 99% is reaching the antenna—this is generally considered good performance. A return loss of 10 dB indicates that 10% of the signal is being reflected and should be considered poor. If the return loss measured 0 dB, 100% of the power would be reflected, and this would likely be the result of an open or short circuit.

Time Domain Reflections

Advanced TDR techniques could be used to first provide a reference map of an optimal system and second be used to determine where exactly along the transmission path impairments start to occur. Such a technique may allow operators to locate sources of PIM and make targeted and efficient repairs. Transmission line mapping could also alert operators to early signs of failure before they start to have a significant impact on performance. Time domain reflectometry (TDR) measures the reflections that result from a signal traveling through the transmission line. The TDR instrument sends a pulse through the medium and compares the reflections from the unknown transmission environment to those produced by a standard impedance. A simplified TDR measurement block setup is shown in Figure 8.

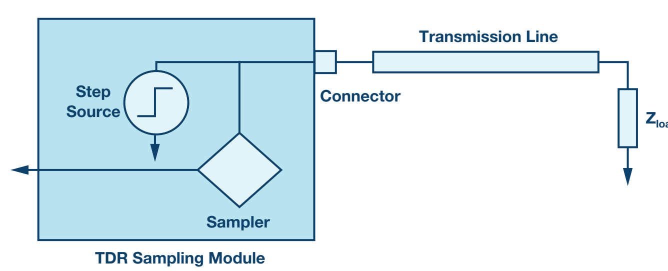

Figure 8. TDR setup block diagram.

Figure 9 provides an example of TDR transmission line mapping.

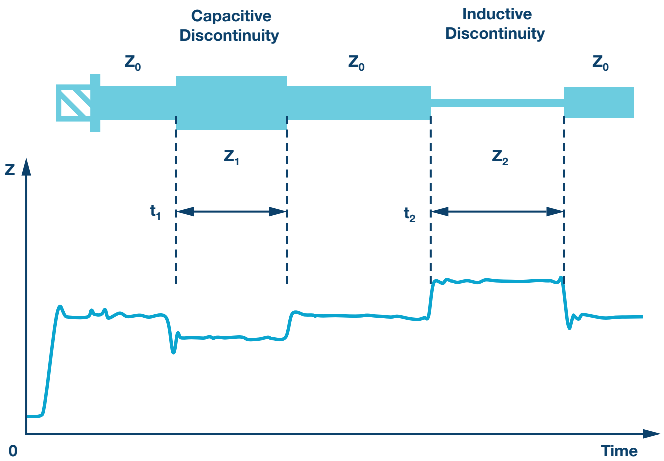

Figure 9. TDR mapping of transmission line.

Frequency Domain Reflections

While TDR and FDR both rely on the principle of sending stimuli down the transmission line and analyzing the reflections, the implementation of the two techniques is very different. The FDR technique uses an RF signal sweep instead of dc pulses as used by TDR. FDR is also far more sensitive than TDR and can locate faults or degradation in system performance with higher precision. The frequency domain reflectometry principle involves a vector addition of the source signal with reflected signals from faults and other reflective characteristics within the transmission line. While TDR uses very short dc pulses that inherently cover a very large bandwidth as stimulus, FDR swept RF signals can actually be run at the specific frequencies of interest (usually within the range where the system is expected to operate).

Figure 10. FDR principles, swept frequency return loss vs. distance.

Distance to PIM

It is important to note that while line sweeping may indicate impedance mismatches and, hence, the source of transmission line PIM, PIM and transmission line impedance mismatches can be mutually exclusive. PIM nonlinearity can occur at points where line sweeping results do not indicate any transmission line issues. Hence a more sophisticated implementation is required whenever users are to be provided with a solution that not only indicates the presence of PIM, but also allows them to identify precisely where along the transmission line path the issue occurs.

Comprehensive PIM line testing operates in a similar mode to that described for design PIM cancellation, except in the instance where the algorithm examines the time delay estimation of the intermodulation product. It should be noted that the priority in these instances is not the cancellation of the PIM artifact, but the pinpointing of where along the transmission path the intermodulation is occurring. The concept is also known as distance to PIM (DTP). For example, in a two tone test:

Tone 1:

$$e^{j(w_1(t+t_0)+\theta_1)}$$

Tone 2:

$$e^{j(w_2(t+t_0)+\theta_2)}$$

w_1 and w_2 are the frequency; 0_1 and 0_2 are initial phase; t_0 is the initial time.

The IMD (lower side, for example) will be:

$$e^{j((2w_1-w_2)(t+t_0)+(2\theta_1-\theta_2))}$$

Many existing solutions require the user to break the transmission path and insert a PIM standard (a PIM standard is a device known to generate a fixed amount of PIM, which is used to calibrate the test equipment). The use of the PIM standard provides the user with a reference IMD that has a known phase at a specific position/distance along the transmitter path. Figure 11(a) provides an overview. The IMD phase 0_{32}, as shown in Figure 11, is used as a reference to position zero.

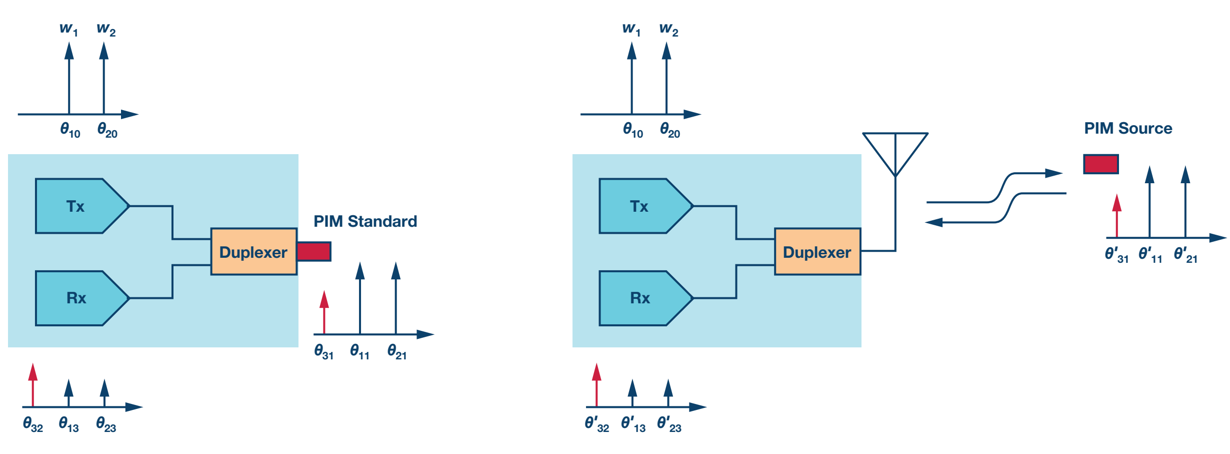

Figure 11. Distance to PIM.

Once the initial calibration is performed, the system is then reconstructed and a system PIM measurement is taken, as shown in Figure 11(b). The phase difference between Θ_{32} and Θ'_{32} can be used to calculate the distance to PIM.

$$(2w_1 - w_2) \times \frac{(2D)}{S} = \theta'_{32} - \theta_{32}$$

where D is the distance to PIM and S is the wave propagation speed (dependent on the transmission media).

Assembly and *rusty bolt* PIM can be slow and incremental processes; the base station may work efficiently after the initial installation, but over time these types of PIM phenomena may start to become more pronounced. As the level of PIM may be subject to environmental issues such as vibration or wind, the nature and characteristics of the PIM may be dynamic and fluctuating. Masking or canceling the PIM may not only be difficult, it could also be seen as masking a more serious issue that may, if unresolved, cause total system failure. In such circumstances operators will want to avoid the cost of total system tear-down but instead efficiently locate the PIM contributor and replace it.

Distance to PIM (DTP) technology also offers base station operators the possibility to track the degradation of their systems over time and highlight in advance what could emerge as problem issues. The knowledge allows the replacement of the weak points during scheduled maintenance, thus avoiding costly system downtime and dedicated repair efforts.

Conclusion

Passive intermodulation is nothing new. It's a phenomenon that has existed for many years and has been understood for some time. In recent times, two distinct changes in the industry have brought it back into the forefront of attention:

First, advanced algorithms now provide a smart way to detect the presence/location of PIM and, where appropriate, compensate for it. Whereas previously radio designers had to choose components that met particular PIM performance requirements, with the assistance of PIM cancellation algorithms they have now gained a new degree of freedom. They have the ability to push for higher performance or, if they should choose, maintain the same performance level but with lower cost and smaller hardware components. The cancellation algorithms are digitally assisting the hardware elements.

Second, with the explosive growth in the density and diversity of base station towers, we are seeing a whole new range of challenges caused by particular system setups, such as the sharing of antennas. Algorithmic cancellation depends on knowledge of the primary transmitted signals. In instances where space on towers has a premium, various transmitters may share a single antenna, making the existence of unwanted PIM effects very likely. In such instances, an algorithm may have knowledge of certain portions of the transmitter path and may work efficiently. In cases where not all sections of a transmit path are known, the performance or implementation of the first generation of advanced PIM cancellation algorithms may be limited.

As the challenges in base station installations continue to grow, PIM detection and cancellation algorithms can be expected to deliver substantial gains and advantages to radio designers in the short term, but require development work to keep up with future challenges.

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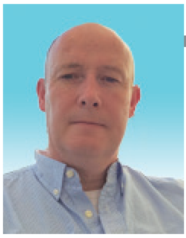

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Complex RF Mixers, Zero-IF Architecture, and Advanced Algorithms: The Black Magic in Next-Generation SDR Transceivers

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