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## Demystifying PIM...in today's wireless networks

Passive InterModulation (PIM) has become the new benchmark in determining the health of a cell site. Today's mobile handset users expect consistent high throughput from their devices and, consequently, push current networks to their limit. The upcoming fourth generation (4G) networks feature an increased mobile data rate of 100 Mb/s and this higher transmission rate will expose PIM vulnerabilities in today's networks like never before. Fourth generation FDD networks require superior network transmission fidelity, higher than previous generations. Network operators also face the challenge of maintaining customer loyalty in an unforgiving competitive arena. As such, good network PIM performance is now imperative.

This article attempts to clarify PIM to all who have interest on this subject, but should particularly be appreciated by field technical personnel as well as anyone responsible for performance engineering, some of whom may be required to perform PIM measurements as part of their daily work routines. This article does not focus on PIM sources such as loose connectors, contaminants, dirt, etc.... Although important, such PIM sources can easily be resolved with regular cell site transmission line maintenance and work quality awareness of installers and site technicians.

### What is PIM?

Descriptively, **P**assive **I**nter-**M**odulation is an undesired, non-linear, signal energy generated as a bi-product of two or more carriers sharing the same down link path in wireless networks. Due to network hardware configurations, this multi carrier interaction can cause significant interference in the up-link receive band, which can lead to reduced receiver sensitivity. To the mobile phone user, this often translates to a loss in audio fidelity in conversations, decreased data speeds, or in extreme circumstances, dropped calls or an inability to make or receive calls or utilize data services. Since there is a mathematical correlation between the known carrier frequencies and the resultant interference signal in the receive band, accurate measurements of PIM signals can be achieved consistently. For practical PIM testing applications, we will only concern ourselves with those PIM signals which interfere directly with our network's receive band. Typically these PIM signals are:

$$3^{\text{rd}} \text{ order PIM, } = 2 \times F1 - F2$$

$$5^{\text{th}} \text{ order PIM, } = 3 \times F1 - 2 \times F2$$

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For example: CCI’s PIM-Pro 850 analyzer has a default setup with two transmit frequencies at 869 and 894 MHz, producing a 3<sup>rd</sup> order IM at 844MHz and a 5<sup>th</sup> order IM at 819 MHz. In this example, the focus would be on the 3<sup>rd</sup> order IM at 844 MHz since it falls within the receiver range of 824 to 849 MHz. The 5<sup>th</sup> order IM at 819 MHz is outside of the receiver range and, as such, can be ignored for the purposes of PIM testing. It is important to observe that the actual IM frequency is determined by the two transmit frequencies and the spacing between them. A 25 MHz frequency spacing between the transmitters also results in a 25 MHz spacing between the IM signals.

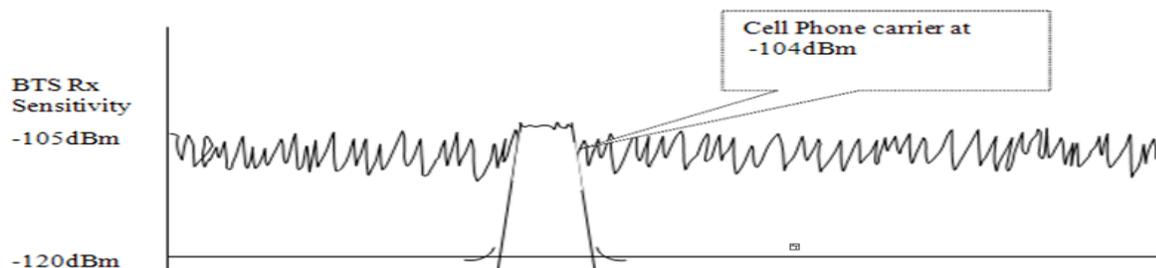
Typically, the 3<sup>rd</sup> and 5<sup>th</sup> order PIM signals are the most likely to fall within the receive band with enough PIM energy to cause disturbances, while 7<sup>th</sup> and 9<sup>th</sup> order PIM signals are usually very low in power. CCI’s PimPro Passive Intermod Analyzer allows you to select which order PIM you want to measure and highlights the ones that fall in the receive band for simplicity.

It should be noted that PIM signals exist as a result of the combined transmission of multiple carrier frequencies within a transmission line path. The objective is to ensure that these levels, by design and in practice, should occur at an amplitude which is below the Base Stations receiver sensitivity. The amplitude of these undesired signals is directly influenced by the fidelity of the transmission line path, including all components and junctions that can introduce a non-linear effect to the signals passing through them.

### PIM: dBc or dBm?

Although PIM measurements can be presented using both (dBc and dBm) engineering units, it is more meaningful and consistent to keep measurements in dBm. This is particularly true when trying to compare PIM measurements at different carrier power levels, where measurements in dBc may be misleading. Using dBc simply means that the value is relative to the transmitter power. For example, a -100 dBm PIM level generated from two 43 dBm tones (20W) equates to a PIM of -143 dBc.

Figure and table (below) show an example of an operator needing to keep PIM signals below -106 dBm since the Base Station (BTS) Rx sensitivity is at – 105 dBm.



**Figure 1 - BTS Receiver Sensitivity (dBm) Requirement**

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**Table 1 - BTS Receiver Sensitivity Input Power and Measurement Requirements (dBm vs. dBc)**

Two (2) tone carrier power Watts (dBm)	2W (33 dBm)	20W (43 dBm)	40W (46 dBm)
Desired PIM performance in dBm	-106 dBm	-106 dBm	-106 dBm
Equivalent in dBc	-139 dBc	-149 dBc	-152 dBc
Difference in dB	Reference	10 dB	13 dB

The above table demonstrates that the power of the transmitter dramatically effects the PIM dBc value, where the desired PIM dBm level is the same for all three. Testing at 40W is shown to be a more stringent network test with the combination of higher power and the need for a more sensitive receiver. As can be seen in the table above, a device tested at 40 Watts actually performs 13 dB better than a device tested at 2 Watts even though both devices meet the desired -106 dBm PIM performance level. More importantly, a device that meets the desired PIM performance at 2 Watts, may well fail if subjected to higher power levels of 20 Watts or 40 Watts. PIM tests that are performed at Low Power can mask PIM nonlinearities by not bringing them out. Although performing PIM testing at 40W is considered to be a more stringent test then what is currently required, it exposes a cell site's PIM vulnerabilities in a significantly more quantitative manner leaving little room for conjecture as to the integrity of the device(s) under test. Meeting the 20 W PIM specification today at 40 W gives operators and contractors more measurement confidence and allows room for growth. The 20 W standard was intended to simulate issues for the power of a single carrier or multiple carriers not exceeding an aggregate power of 20 W on a given transmission path. However this does not guarantee performance if the number of carriers or total aggregate power increases as is typical with network growth, thus testing at 40 W accommodates these conditions and can eliminate the need for repeated testing and PIM mitigation in the future.

### **PIM nonlinearity discussion**

PIM energy increases, in theory, at a ratio of 3:1 (PIM to TX signal ratio). A 1 dB increase in carrier power correlates to a theoretical increase of 3 dB in PIM signal power. In practice, the actual ratio is closer to 2.3 dB because of measurement error contributors such as the thermal noise constant of -174 dBm/ Hz, connector design constraints and power handling capacity. The actual receiver noise floor is closer to -138 dBm as PIMs are measured in a narrow IF filter where the noise floor increases at a theoretical rate of 10 dB/decade. This -138 dBm noise floor is considered a PIM analyzer's measurement noise floor. PIM-Pro will not display PIM measurements below -132 dBm (-175 dBc @ 20W) to maintain an acceptable measurement error due to the receiver noise floor.

## DIN 7/16 Connectors

The popular DIN 7/16 RF connector was designed to achieve good PIM performance and is regarded as the standard RF connector for engineers who design today's wireless networks. It has a large contact area enabling the handling of 20 and 40 watt signal levels with minimal contribution of non-linear PIM energy. With a PIM specification of better than -122 dBm and a return loss of higher than 22 dB (up to 3 GHz), the DIN 7/16 connector is a trusted ally to today's network designers. The traditionally popular N connector does not perform as well in the presence of 20W or 40W multi tones primarily because of ferromagnetic effects. Some connector manufacturers have improved their N connector PIM performance through silver plating techniques, but the DIN 7/16 connector remains the preferred connector for low PIM requirements.

### What causes PIM?

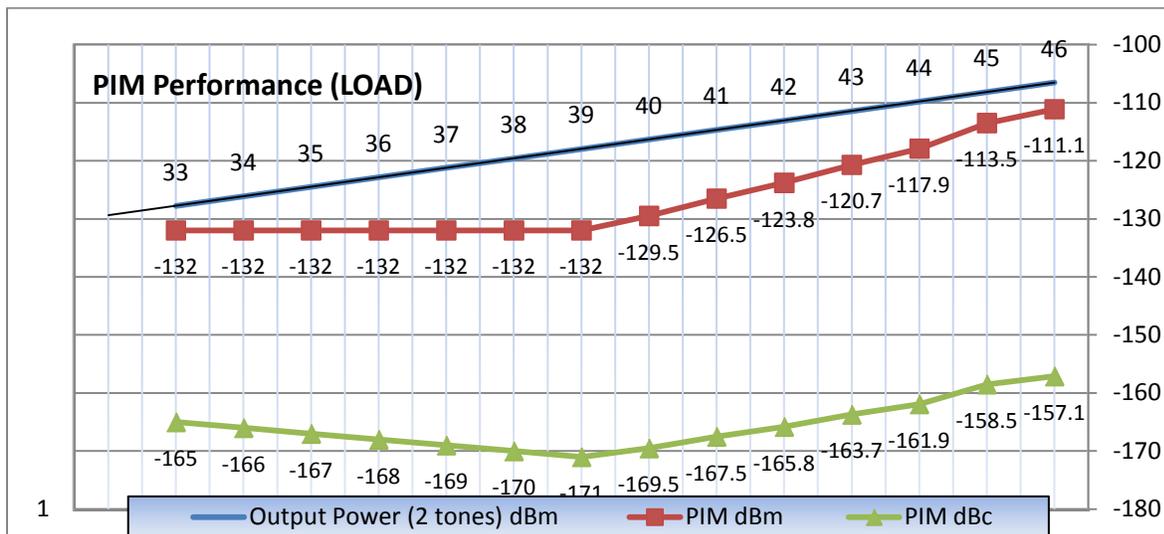
Ferromagnetic materials, when in the current path, exhibit a non-linear voltage to current ratio. This non-linear effect is accentuated at higher power levels because of increased current density. Looking at Ohm's law from the perspective of "Power" helps clarify the fact that the squaring effect of current results in a higher magnetic flux, which makes metals with high bulk resistivity, such as, iron, steel and nickel exhibit a magnet like memory effect. This effect is better known as magnetic hysteresis. Metals that exhibit this asymmetrical magnetic flux are often the main contributor of PIM energy.

Poor metal to metal contact junctions can create additional nonlinearities resulting in PIM. Such nonlinearities can come from under-torqued male to female DIN 7/16 mates, as well as irregular contact surfaces such as poorly manufactured connectors and surface metal oxidation. Oxidation (corrosion) creates tiny air gaps, which promote voltage potential barriers, which in turn result in a nonlinear voltage to current ratio, sometimes referred to as the diode effect.

### 40 Watt Vs 20 Watt test power levels

In order to better represent real traffic network conditions, PIM measurements should be performed at the BTS radio power level or slightly higher. In the last several years, a handful of 2 Watt PIM analyzers have entered the market place touting their benefits as being, smaller, more portable, and conveniently battery operated. Although these features are obvious, these units offer limited value since 2 Watt PIM testing is not representative of typical BTS power levels of 20 Watts or higher, where PIMs are likely to be generated. PIM testing when measured in dBc is a measurement of relative non-linearity. For network operators, it means establishing a confidence factor in their network while under real traffic stress. Networks engineers want a confidence buffer in their power range where PIM begins to show marginal levels. Most of second and third generation FDD radios have a 20 W power output, the new LTE technology is now at 30 or 40 Watts and in some cases even higher power levels. Network

operators need to question whether testing at 20 watts (43 dBm) is satisfactory, as it may not expose marginal network PIM conditions and is not an accurate simulation of today’s actual network power density. 40 W PIM testing, although a more stringent test, is still far less than the actual power density generated into today’s antennas from their respective radio within the uplink ranges of interest. Another important consideration in favor of higher power PIM testing is the presence of IM5 energy which covers a broader frequency range (more blocks) than IM3 energy. 20 W PIM testing does not expose this important new PIM reality. This is the main reason why CCI engineers designed the PIM-Pro PIM analyzer family with 40 Watts of output power.



**Figure 2 - PIM Performance of a Load at Varying Power Levels (dBc and dBm)**

Above graph displays actual PIM measurement results of a load. Note the slope of the red (PIM dBm) and green (PIM dBc) compared the 2 tone signal power. Also note that there is hardly any measurable nonlinearity in the 2-10 W power range, due to lack of PIM generating power.

### TMA measurement considerations

In situations where a TMA is in the PIM measurement path, a technician should be cognizant of the gain of the LNA as it will amplify all signals in the receive path, including PIM energy. The gain value of the LNA (typically 12 dB) should be taken into account if the desire is to mathematically remove the amplifier’s gain contribution to the measured PIM value. However, since the receiver’s up-link band is directly in line with the LNA in regular traffic, then the measurement should be taken at face value without gain compensation. Additionally, the LNA’s Noise Figure (1.6 dB) should be added to the measurement error budget. The affect being that a typical +/- 3.0 dB PIM measurement error is now closer to +/- 5 dB.

## Is it PIM, or Interference?

While taking PIM measurements at a given site, it is sometimes difficult to differentiate PIM energy generated as a result of internally transmitted carrier signals from external interference signals permeating from outside the antenna. PIM Testing is intended to be performed within a site's 50 ohm transmission line path, specifically from 50 ohm line path from the radio to the antenna. When Antenna manufacturers test antennas for PIM performance, measurements are taken in an anechoic chamber where the presence of external interference signals is not possible. In the field, external interference signals can often be construed as PIM signals because they occasionally fall within the uplink received band. The source of these unwanted signals is usually adjacent cell sites, old TV transmitters or the presence of metallic structures near the site. Interfering signals from adjacent cell sites or TV transmitters can be identified by using a spectrum analyzer and comparing spectrum responses between sectors to identify the direction of the interference. Varying noise floor levels between the three sectors will help determine the presence of interference energy coming from local metallic structures with the sector showing highest noise floor as having the highest level of broadband noise interference. PIM-Pro's RX interference function was specifically implemented for the measurement of interfering signals within the RX band. RX interference measurements can quickly pinpoint the direction of interfering signals and assess the relative signal energy strength at each sector. Field technicians can store results and compare all three sector signal strengths. Figure 3 below shows a PIM-Pro RX Interference screen shot.

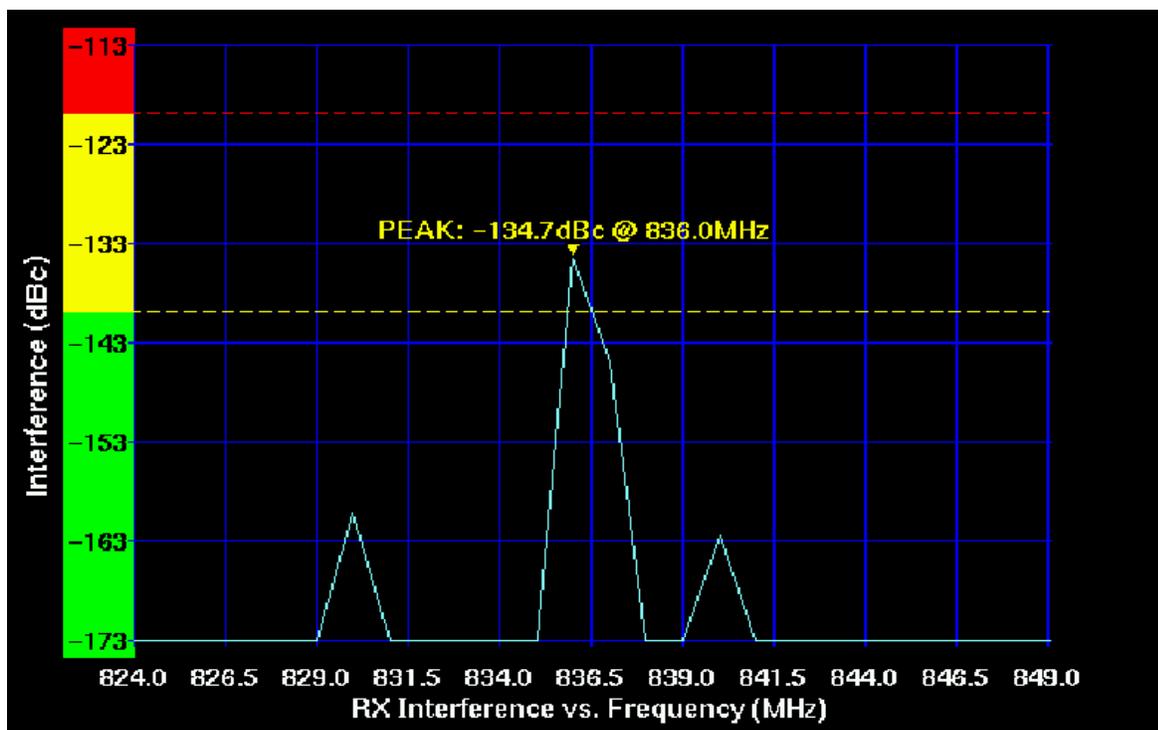


Figure 3 - PiMPro RX Interference Screen Shot

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## PIM Source Location Vs. Distance to Fault

The concept of PIM location is getting more attention lately. Proponents are comparing the feature to that of a DTF (Distance to Fault) measurement feature with the insinuation that it provides similar measurement benefits and value. Although the idea of a feature which can locate a PIM source within a network's physical structure has a lot of appeal, this section intends to show that, for PIM source identification, the technique has severe limitations and may not provide much value. For two reasons:

1. Poor distance resolution – Distance resolution is inversely proportional to swept frequency bandwidth
2. Low PIM power levels limit measurement consistency

The concept of DTF is a mathematical conversion of a frequency spectrum response to an equivalent time response using (IFT) Inverse Fourier Transform mathematical modeling. FFT is the opposite, being a conversion from Time domain signals to an equivalent frequency domain spectrum. The technique works rather well in traditional swept return loss measurements and is now a feature available on today's portable site RF sweep gear. The swept frequency return loss measurement requires the user to enter parameters such as propagation velocity (cable's dielectric material properties) as well as a cable's insertion loss characteristics. With this information the DTF (IFT) math model allows an analyzer to display the distance to a 50 ohm discontinuity, within a 50 ohm transmission line under test. This DTF model works well because of two reasons: The ability to sweep wide frequency ranges (> 500 MHz) and the existence of a good reflection reference, an open circuit (100% reflection).

In DTF, a user has access to multiple GHz of swept bandwidth which inversely translates to fine time resolution giving an equivalent fine distance resolution. Wide frequency band swept return loss measurements are technically feasible because such measurements can be performed at low output power levels, typically 1 to 10 mW (0 to 10 dBm), thus a 20 dB reflected signal being at -10 to -20 dBm levels and well within the detection range of a relatively inexpensive diode detector. In short, DTF is not a difficult technical challenge and provides meaningful measurement value.

Locating the PIM contribution of individual components in a serial RF path is a much different task and a far more challenging technical requirement. PIM levels are generally at very low levels, in the -75 to -95 dBm range and when the antenna is connected can show substantial amplitude variation. At a cell site, the process of trying to pin point the location of a specific PIM source where PIM signal levels are constantly changing, and with very coarse (5-7 meter) distance location filtering can lead to a wild "ghost" chase.

See graphs and table below. Measurements were taken to provide the reader a visual comparison of distance resolution and available swept frequency bandwidths. Graphs clearly show that the limited swept frequency bandwidths of our cellular bands make such a feature impractical.

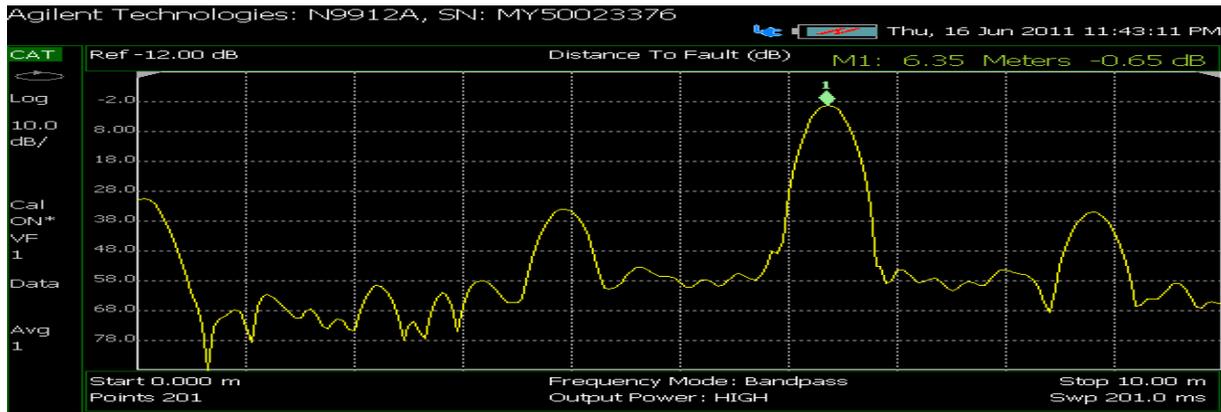


Fig 3 - (above) shows the distance resolution available with 1 GHz of swept frequency bandwidth.



Figure 4 - (above) shows the distance resolution provided with 100 MHz of swept frequency bandwidth. This is more frequency range than any cellular band but still not very practical for PIM location.



Figure 5 - (above) shows an example of distance resolution given the LTE 700 swept range of 22 MHz. Within the 10 M range shown, a user could have multiple PIM contributing components, but would be unable to distinguish the exact location of the contributing source.

**Table 2 - Comparison of Distance Resolution for Wide Bandwidths and Smaller Bandwidths Applicable to Cellular Bands**

Frequency Span (MHz)	Wireless Band	Distance Resolution (m)*	EDR (m)**	Distance resolution (ft)*	EDR (ft)**
1000	N/A	0.15	0.2	0.5	0.6
500	N/A	0.3	0.4	1.0	1.2
100	N/A	1.5	1.8	5.0	5.9
60	PCS1900	2.5	3.0	8.3	9.9
25	850	6	7.2	19.8	23.8
22	LTE 700	6.8	8.2	22.5	27.0

\* Mathematical best distance resolution available to discern PIM locations

\*\* Conservative effective estimate taking cable VOP and band roll off (20% degradation) into account

EDR : Effective Distance Resolution

## Measurement recommendations

Due to their low power levels, less than -80 dBm, PIM measurements are difficult to make with good accuracy in the best of lab conditions, let alone the harsh conditions of cell sites. A valid and repeatable PIM measurement requires an analyzer with stable linear amplifiers, exceptionally low PIM duplexer and related components and a well-designed receiver with very low receiver noise floor. The CCI PIM-Pro with a residual noise floor of <-138 dBm is well suited to perform PIM measurements.

Since Passive Intermodulation energy cannot be mathematically modeled and therefore cannot be simulated using today's engineering design tools, using a PIM analyzer is the only way to quantify it.

Recommended measurement practices:

1. Visually inspect and clean all connectors before mating them.
2. Torque all connections to a min. of 16, max. of 18 ft-lbs (23-24 Nm).
3. Allow measurements to thermally stabilize, especially in cold weather. Use PIM vs. Time mode at highest available power (40W on PIM-Pro) to establish confirmation of a stable measurement using a low PIM load on the test port.
4. In order to maintain measurement confidence, verify measurement accuracy using a quality load and a PIM standard regularly. Using a quality low PIM load will confirm faulty components.

### Measurement recommendations (Cont.)

5. Due to the nonlinearity of the PIM response it is wise to test at higher power levels than necessary to ensure an acceptable measurement error margin.
6. Use higher power to confirm marginal measurements as 2 X 20 Watt tone PIM testing is often not enough power to uncover a marginal PIM situation. Higher power 2X 40 Watt testing provides additional field diagnostic capability.
7. The 7-16 DIN connector is rated for 500 mates, although the connector can probably survive up to 1000 mates, it is important to be cognizant of the constant wear and tear on cables and the PIM tester's output connector. In the world of RF measurements, problems often start in the components used to perform the measurement at hand. Test cables are typical culprits.