Understanding PIM
Content

Introduction ........................................................................... 1
How is PIM Generated? .......................................................... 2
PIM from Modulated Carriers ................................................. 3
Typical Sources of PIM .......................................................... 4
The General Power Dependence of PIM ......................... 5
In Summary ........................................................................... 7
Abbreviations ........................................................................ 8
Appendix
  PIM from a Mathematical View........................................ 1
  PIM Levels ...................................................................... 3
Introduction

Passive Intermodulation (PIM) is not in any way a new phenomenon. When duplexing Rx/ Tx to a common antenna system, PIM disturbances become directly visible in the receive band (Rx).

Why should we put more focus on PIM and why do PIM affect the mobile communication systems? There are several good reasons:

1. Compared to earlier generations of digital mobile networks, 4G and 5G mobile communication systems suffers a lot more from PIM noise. Both in capacity and data rate.
2. The Tx power have increased significantly over the years, however the typical requirement specifications on the system components remain unchanged.
3. When MIMO is implemented each system will transmit on more ports. This often leads to several systems sharing the same antenna port and feeder system.
4. Network operators add more and more frequency bands, making it virtually impossible to plan away the PIM problem, at least without sacrificing spectrum.
5. The cost of spectrum has risen to a point where sacrificing any spectrum to create a guard band is not financially viable.

Figure 1

PIM Survey in EMEA by PIM Testing Company
- > 430 feeder lines surveyed
- 25 Operators and OEMs, 17 countries

<table>
<thead>
<tr>
<th>Sites or Sectors With PIM &gt; -97 dBm</th>
<th>Sites or Sectors With VSWR Problems</th>
<th>Sites or Sectors with PIM &lt; -97 dBm</th>
</tr>
</thead>
<tbody>
<tr>
<td>72.26%</td>
<td>2.80%</td>
<td>27.74%</td>
</tr>
</tbody>
</table>

Bad performance Moderate performance
How is PIM Generated?

When two or more RF-signals pass through a nonlinear element in the RF path, new signals are generated, through a “trigonometric multiplication”. This multiplicative effect can be analyzed by trigonometric polynomial mathematics. The math is not too complicated and can be found in the appendix in the back of this document.

The new signals generated consist of so called odd and even PIM products. It is the odd order PIM products that are of special interest, the reason is that they pop up nearby the Tx signals that created them and therefore also often appear inside the receive (Rx) band (figure 2).

The position of the PIM product is related to the separation between the Tx signals that generate them. The positions are easily calculated. If two Tx signals are separated by 10 MHz, the third order PIM products will pop up another 10 MHz outside the two Tx signals, the fifth order will appear 20 MHz outside and so on.

Note that this is how it works in theory, assuming CW (continuous wave) signals and constant coefficients in the polynomial description. In a real situation the coefficients are constant, they have a slight power dependence and the 3:1 rule is a slight exaggeration. But it is still close enough to be an excellent rule of thumb for delta calculations with reasonable deviations from a measured value.

Figure 2

PIM products explained. Adding 3dB more Tx power increases the 3rd order PIM by 9dB.
PIM from Modulated Carriers

Most literature describe and analyze PIM based on two unmodulated CW signals. In this case the resulting PIM products are also narrow CW spurs. But in all live radio systems there must be modulation to carry information. This modulation will always widen the Tx signal and in modern spread spectrum systems it will widen the signal a lot. As an example, a UMTS signal has over 4 MHz of occupied band width.

The widening of the PIM product is quite easy to understand if we do the experiment of looking at the edge frequencies of two modulated carriers, in a static way. In this example the third order PIM product would be three times the band width of the carrier and the fifth order PIM would be five times wider. However, depending on the modulation index of the TX signal (depends on system and modulation) there will be slopes on this widened band width of the PIM products (figure 3). From those wider PIM products, the real impact on the system is that the PIM products get so wide that it becomes very difficult to plan away from PIM disturbances. Especially if not large bandwidths can be blocked out, which would deem them useless.

Real PIM will never be seen as spurs in a live network. PIM will always appear as a wide band noise rise. The noise is so wide that the different PIM products often overlap each other and create a noise rise that slopes away from the Tx band (figure 4). This is probably why PIM is often mistaken for general interference from the cell instead of PIM.

Source: Anritsu, PIM Measurements - the fundamentals
Typical Sources of PIM

A common source of PIM is a metallic joint with high current density, often a connector. Especially if the joint is contaminated or contains any Ferro magnetic materials. The contamination is often oxide or other “normal” material found on a metal surface. In RF filters a single fingerprint in the wrong place will cause a fail in the PIM test.

To improve the linearity of a metallic joint the metal is often given a surface treatment, like a thin layer of for example silver. Silver is both a good conductor and have a very soft oxide that “squashes” away when the joints are pressed together. A clean, even metallic contact is achieved. At high frequencies the so-called skin effect makes the RF power flow in a very thin layer on the surface and therefore also the silver layer can be rather thin.

The opposite of silver is aluminum. Even though aluminum is a reasonably good conductor, the oxide is crystal-like and extremely hard. So even if the surfaces are pressed together with very high pressure it is still very likely that only parts of the surface reach direct metallic contact and in those small spots a very high current density appears.

Other common sources of PIM are burs and tiny fragments of metal residing in critical areas. Typical examples are chafing’s from rough assembly and tightening of connectors, burs from sloppy manufacturing (bad “deburring”), fragments grinded off during tuning or assembly. Of course, all those fragments will move around if the unit is vibrated and handled. Refer to figure 5 to see where the PIM is.

Figure 5

Source: Anritsu, PIM Measurements - the fundamentals
The power dependence of PIM

The 3:1 rule of PIM is that, one dB more Tx power give 3 dB stronger PIM. But few think further about what this means for their system. There are at least two things that should be considered.

First, the actual Tx power of the BTS/RRU needs to be considered. The Tx power level has increased a lot over the years, from the typical 40 dBm for a first generation RRU, to 46 or even 49 dBm in RRU’s of today. This justify 12 to 18 dB stricter PIM requirements in the specifications of product requirements. But how many network operators have changed their purchase requirements or site approval specifications? Most operators still use the 150 or 153 dBc as their standard requirement, a level tested at 2 x 43 dBm, even though they use much higher Tx power in most parts of their systems today.

The second aspect that should be considered is the different power levels within the system. A 3 dB loss in the feeder system means that a device located at the top end will be affected by 3 dB lower power level compared to if the same device would be located at the lower end.

There should be different PIM specifications on the devices located at the lower end compared to devices located at the top (figure 6).

A very important task for all system designers is to avoid costly over specifications. If the best available antenna is specified at -153 dBc PIM, why would I ask for 160 dBc from my diplexer, SBT (Smart Bias Tee) and other devices at the lower end?

The antenna is affected by a 3 dB lower Tx level, this will correspond to a 9 dB lower PIM level. This PIM noise, generated in the antenna, must then travel down the feeder to reach the receiver and that will lower the PIM another 3 dB. So, all in all, the PIM from a device sitting in the top end of a 3 dB loss will generate 12 dB lower PIM compared to the same unit in the lower end of the same feeder.
This means that the PIM from the -153 dBc antenna corresponds to -165 dBc at the lower end. So, in this example, the -160 dBc diplexer in the lower end will completely dominate and define the PIM performance of the site even though the antenna is -153 dBc.

Comparing RTWP in this example between a normal 150 dBc device and a Microdata Telecom product with 160 dBc would give a 9.3 dB better RTWP with the Microdata Telecom product, even if the product is only a tiny SBT.

This example shows how important it is to understand the impact of loss within the system. It is easy to forget the tiny components like SBT’s and jumpers in the lower end, when in fact, that is the spot to focus on.

The rule of thumb that we arrive at is a modification of the 3:1 rule where we add the loss going back to the receiver and get a 4:1 rule. This means that the requirement is 4 dB’s higher for every dB we approach the BTS with.
In Summary

PIM is generated whenever two or more high power signals flow through a non-linear element in the RF path. PIM can be detected in e.g. feeder line, base station antenna, filter, SBT, connector or other passive components.

Nearly every time when signals from the low band (700 to 900 MHz) are mixed in a common RF path we will see contamination from PIM products in the receive (Rx) bands. There are also combinations of higher frequencies (1710-2690 MHz) causing PIM interference in the Rx bands.

The main effect of having PIM contamination in the Rx band is that the PIM noise will add to the noise floor and block desired traffic. PIM will thereby reduce receiver sensitivity which results in increased amount of dropped calls, reduced system performance and reduced spectrum efficiency. i.e. Less Bits/Hz/second.

For a system to achieve its full operating potential, each RF component and each interconnection must be clean, well tightened and of highest quality to perform up to its designed standard. Any deviation from the above give degradations in the order of 5-10 dB and results in a performance less than half of the potential capacity.

With the evolution of Radio Access Systems, the TX power has increased, but the Product Specification Requirement for RF Path equipment has not been changed accordingly.

The PIM Product Requirement Specification for RF Path equipment should be changed to at least -160 dBC / -117 dBm.
Abbreviations

PIM - Passive Intermodulation
RF - Radio Frequency
TX - Transmitter
RX - Receiver
MIMO - Massive Input Massive Output
CW - Continuous Wave
UMTS - Universal Mobile Telephony System, (3G)
BTS - Base Transceiver Station
RRU - Remote Radio Unit
RTWP - Received Total Wideband Power
SBT - Smart Bias Tee
Appendix

PIM from a Mathematical View

First of all, it is not necessary to understand this part in order to read the rest of the document and understand the content. But for those with a mathematical interest it can explain the 3:1 rule and frequency separation between the PIM products. There is a more verbal description following the mathematical part below.

The output signal from a device can be described as:

\[ y = A \cdot x + B \cdot x^2 + C \cdot x^3 + \ldots \]

But in a perfectly linear device the constant A represent the gain (or loss) and constants B, C and so on are all zero, leaving the more familiar expression, the linear term:

\[ y = A \cdot x \]

With the input signal \( x \), composed by two signals \( E_0 \) and \( E_1 \), it can be described by:

\[ x = E_0 \cdot \cos \phi_0 + E_1 \cdot \cos \phi_1 \]

On the output of the device we will then get, the linear amplified/attenuated term [2]:

Here we can see the two individual components of the input signal amplified or attenuated with full integrity.

But in a real amplifier the constants B, C ... and so on, are not zero. So if we start with the second term (the squared term), this means that the constant \( B \) is not zero from a math handbook we can find the trigonometric formulas for “squaring” the input signal and we will get:

\[
B \cdot x^2 = B \cdot \left( E_0 \cdot \cos \phi_0 + E_1 \cdot \cos \phi_1 \right)^2 = \\
\frac{B \cdot E_0^2}{2} + \frac{B \cdot E_1^2}{2} + \\
\frac{B \cdot E_0^2}{2} \cdot \cos 2\phi_0 + \frac{B \cdot E_1^2}{2} \cdot \cos 2\phi_1 + \\
B \cdot E_0 \cdot E_1 \cdot \left[ \cos(\phi_0 + \phi_1) + \cos(\phi_0 - \phi_1) \right]
\]
If we assume that our two input signal components are closely spaced, all the second order terms are either close to DC or close to double the frequency and will be completely suppressed by our TX and RX filters, so we can normally ignore them.

\[ C \cdot x^3 = C \cdot (E_0 \cdot \cos \phi_0 + E_1 \cdot \cos \phi_1)^3 = \]
\[ = \frac{3 \cdot C}{2} \left( E_0 \cdot E_1^2 + \frac{E_0^3}{2} \right) \cdot \cos \phi_0 + \frac{3 \cdot C}{2} \left( E_0^2 \cdot E_1 + \frac{E_1^3}{2} \right) \cdot \cos \phi_1 + \]
\[ \frac{C \cdot E_0^3}{4} \cdot \cos 3\phi_0 + \frac{C \cdot E_1^3}{4} \cdot \cos 3\phi_1 + \]
\[ + \frac{3 \cdot C \cdot E_0^3 \cdot E_1}{4} \cdot \left[ \cos(2 \cdot \phi_0 + \phi_1) + \cos(2 \cdot \phi_0 - \phi_1) \right] + \]
\[ + \frac{3 \cdot C \cdot E_0^2 \cdot E_1^2}{4} \cdot \left[ \cos(2 \cdot \phi_1 + \phi_0) + \cos(2 \cdot \phi_1 - \phi_0) \right] \]

If we now do the same analyses of the third order (the cubic term) term we get:
The two last terms are the terms that we normally call third order intermodulation. Within the brackets we can see the terms \( \cos (2\Phi_1 - \Phi_2) \) and the similar term \( \cos (2\Phi_2 - \Phi_1) \) those terms will give us the frequency of our PIM. As we can notice they are placed very close to our original input signals and therefore they cannot be filtered away easily. We can also see that the amplitude has \( E_0 \) multiplied by \( E_1^2 \) squared, so if \( E_0 \) and \( E_1 \) are equal the PIM level have a three to one dependence, to the input power, \( E_1 \cdot E_1^2 = E_1^3 \Rightarrow 30\log(E) \), which is the mathematical explanation to the so called “3 to 1 rule” for third order intermodulation. Meaning one dB up for the input signal will give 3 dB up for the third order PIM.

Graphically this is often described as below:
Even though this picture is perfectly accurate, it is still misleading. The reason is that both input signals are unmodulated CW signals, and this means that the PIM products will also be CW signals, which leads to the impression that we can plan our frequencies so that we will not suffer from any PIM disturbance in our receive channels.

But in a real system we have modulated signals, today with very broad spread spectrum modulation. This means that third order PIM is roughly three times the bandwidth of the input signals and a fifth order PIM is five times the bandwidth. So the actual PIM disturbance is nothing like the line spectrum in the graph above, it is better described as an increase in the wide band noise floor. For example, a third order PIM product from an LTE system with 20 MHz bandwidth is almost 60 MHz in band width. Then it becomes obvious for everyone that it cannot be avoided by frequency planning. It also becomes obvious that the contributions from multiple PIM sources will be fairly uncorrelated, even if the sources are close in distance and can be added like noise. The positive effect of the band spreading is that the PIM level per RF channel goes down with the spreading as the same energy is now spread over a wider bandwidth.

**PIM Levels**

The level of the PIM products will depend on the power level of the Tx signals, the order of PIM and the coefficients within the polynomial expression resulting from the trigonometric multiplication of the two Tx signals.

A Look at the mathematics description above will show that the power of the PIM product will be raised to the power of 3 for IM 3, as the exponent will be the sum of the order of its “generators”. So, third order PIM is generated by one fundamental (1) and one first overtone (2) and thus have the sum 1+2 =3, giving Tx P3. This means that it will move with a 30-log relation to the Tx signals, the same way we will have 50 log for 5th order PIM and so on.

This will lead us to the common 3:1 rule for IM3, meaning that the IM3 changes 3 dB for every dB of change in the Tx levels. But this is also based on the assumption that the coefficients in the polynomial model are constant. This assumption of constant coefficients is fairly accurate but should not be taken for a fact, larger changes will normally show a growth curve that is not a straight line and therefore calculations of IM levels at other Tx levels than what is used during test, typically 43 dBm, must be used carefully.
About Microdata Telecom

Founded in 1981, Microdata Telecom is the market leader for RF filter technology solutions.

Mobile Network Operators and OEMs around the world trust Microdata Telecom’s products to deliver improved radio coverage, capacity and quality in mobile communication networks.

Microdata Telecom’s focus is RF-filter based solutions including MIMO Filters for MACRO and Small Cell Applications. The product range also includes multiplex, reject filters, massive MIMO and TMAs, in a super compact design for minimum tower load and visual impact.

Combining innovative product design, fast and flexible inhouse development and the best PIM performance available in the market (-165 dB), Microdata Telecom gives mobile device users the best RF performance experience.

Visit microdatatelecom.com for more information.