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Passive Intermodulation (PIM) in In-building Distributed Antenna Systems (DAS)

Introduction

As mobile operators upgrade existing in-building distributed antenna systems (DAS) to include LTE frequency bands, the probability of harmful passive intermodulation (PIM) increases. With low PIM components and careful construction techniques, operators are able to reduce interference caused by PIM and maximize site performance. Unlike impedance mismatches, which reduce signal level regardless of location, the non-linearities that produce PIM have varying impact depending on where they are located in the network. This application note begins with a review of decibel math and insertion loss calculations, followed by a discussion of the impact of insertion loss on PIM performance in distributed antenna systems (DAS).

Decibels

Wireless communication systems typically use dBm (decibels relative to 1 mW) to describe absolute power levels and use dB (decibels) to describe changes in power levels. The equation to convert an absolute power level in Watts to an absolute power level in dBm is:

$$Power_{(dBm)} = 10*LOG_{10} (P_{watt}/0.001_{watt})$$

Using this equation, the following absolute power levels can be calculated:

.001 W	$= 10*LOG_{10}$ (.001/.001)	$= 10*LOG_{10}$ (1)	= 10*0.0	= 0 dBm
.01 W	$= 10*LOG_{10}$ (.01/.001)	$= 10*LOG_{10}$ (10)	= 10*1.0	= 10 dBm
.1 W	$= 10*LOG_{10}$ (.1/.001)	$= 10*LOG_{10}$ (100)	= 10*2.0	= 20 dBm
1 W	$= 10*LOG_{10}$ (1/.001)	$= 10*LOG_{10}$ (1000)	= 10*3.0	= 30 dBm
10 W	$= 10*LOG_{10}$ (10/.001)	$= 10*LOG_{10}$ (10,000)	= 10*4.0	= 40 dBm
20 W	$= 10*LOG_{10}$ (20/.001)	$= 10*LOG_{10}$ (20,000)	= 10*4.3	= 43 dBm
40 W	$= 10*LOG_{10}$ (40/.001)	$= 10*LOG_{10}$ (40,000)	= 10*4.6	= 46 dBm
100 W	$= 10*LOG_{10}$ (100/.001)	$= 10*LOG_{10}$ (100,000)	= 10*5.0	= 50 dBm

Important relationships noted here are:

- A change +10 dB means that the power increased by a factor of 10
- A change –10 dB means that the power decreased by a factor of 10
- A change of +3 dB means that the power increased by a factor of 2
- A change of –3 dB means that the power decreased by a factor of 2

Insertion loss

Insertion loss is a measure of RF power "lost" as the signal passes through a device. Insertion loss is expressed in decibels, and is the ratio of the absolute power entering a device to the absolute power exiting a device. Insertion loss in decibels is calculated using the following formula:

$IL_{(dB)} = -10*LOG_{10} (P_{out}/P_{in})$

Using this equation, we can calculate the insertion loss of the following two devices:

IL device #1	= –10*LOG10 (50/100)	= –10*LOG10 (0.5)	= –10*–0.3	= 3.0 dB
IL device #2	= –10*LOG10 (10/100)	= –10*LOG10 (0.1)	= –10*–1.0	= 10.0 dB

The benefit of working in decibels is that we can use simple arithmetic to calculate changes in power as a signal passes through a device:

Pout (dBm) = Pin (dBm) – IL (dB)

When the signal passes through a series of connected devices, with individual insertion losses IL1, IL2 and IL3, the equation becomes:

Pout (dBm) = Pin (dBm) – IL1(dB) – IL2(dB) – IL3(dB)

Note that the convention is to treat insertion loss as a positive quantity that is subtracted from the input power to indicate a reduction in power.

Losses found in typical DAS components

Coaxial cables:

Coaxial cables are used in wireless communications systems to transfer power from the radio to the antenna. These cables are far from perfect conductors. Some energy will always be lost as the RF signals travel from one end of the cable to the other end. The insertion loss of a length of coaxial cable at a given frequency can be calculated using the attenuation data provided in the manufacturer's datasheet.

Coaxial Cable	Attenuation @ 700 MHz (dB/100m)
1/2 inch dia.	6.24
7/8 inch dia.	3.37

To calculate the insertion loss of a 50m length of ½ diameter cable at 700 MHz, we would begin by converting 6.24 dB/100m, from the table above, to .0624 dB/m. Then, multiply this attenuation per meter by our cable length (50m) to calculate an expected loss of 3.12 dB. Ignoring impedance mismatch losses, this means that if we transmit 20W (43 dBm) of RF power @ 700 MHz into this cable, we should expect to have 43 dBm –3.12 dB = 39.88 dBm (9.7W) exiting the other end of the cable.

Loss in coaxial cables varies with frequency. As the frequency increases, so does the loss per meter. Be sure to consult the manufacturer's datasheet to select the correct attenuation values for the frequencies you are evaluating.

Power dividers:

Another type of loss found in DAS is caused by dividing the power entering a device between multiple output ports. This is commonly referred to as "splitter" loss. If we take the input power and divide it equally into "n" outputs, splitter loss can be calculated using a simplified version of our original insertion loss equation.

Splitter Loss $_{(dB)}$ = $-10*LOG_{10}(1/n)$.

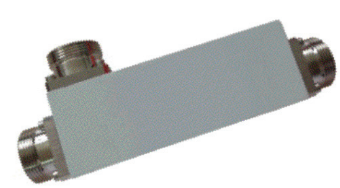
The table below gives some examples of calculated splitter loss for different power divider configurations. Since the device will also have conductor losses, the total loss from the input to any output will be slightly higher than the splitter losses shown here.

Number of output ports	Splitter loss
2	3.0 dB
3	4.8 dB
4	6.0 dB

Directional couplers/tappers:

Directional couplers and "tappers" are special types of power dividers that divide input power un-equally between two output ports. The "through" path has one insertion loss and the "coupled" path has a different insertion loss. The table below shows path losses you might find on a manufacturer's datasheet for different tapper configurations.

Coupled path loss	Through path loss
6.0 dB	1.7 dB
10 dB	0.7 dB
13 dB	0.4 dB

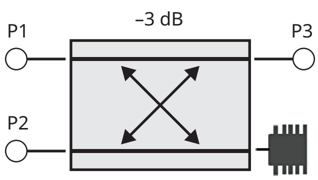


In order for the system to work correctly, it is very important to install the correct model coupler in the correct orientation at each design location. Visually, a 10:1 coupler looks the same as a 3:1 coupler, so it is important to check the device label to make sure you are installing the correct part. In addition, make sure that the correct cable is attached to each port of the coupler. Incorrect assembly will cause the actual coverage inside the building to be very different than the design coverage.

Hybrid combiners:

A hybrid combiner is a different type of power divider found in DAS networks. The signals entering each input are divided equally between the two outputs, resulting in a “splitter” loss of 3 dB. Unused ports must be terminated into a 50 Ω load capable of dissipating the power arriving at that port, which can often be high. Hybrid combiners are particularly useful for distributing the signals from multiple radios onto one or more branches of a DAS. In the reverse path, the signals from each branch are equally distributed to each connected radio.

Below are sample configurations that might be encountered in the field. Note that the loss from P1 to P3 in the first two examples is 3 dB and the loss from P1 to P5 in the second two examples is 6 dB. The loss is higher in the P1 to P5 path because the signal travels through two hybrids, causing the splitting loss to double.



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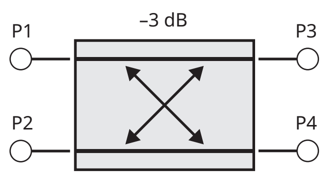

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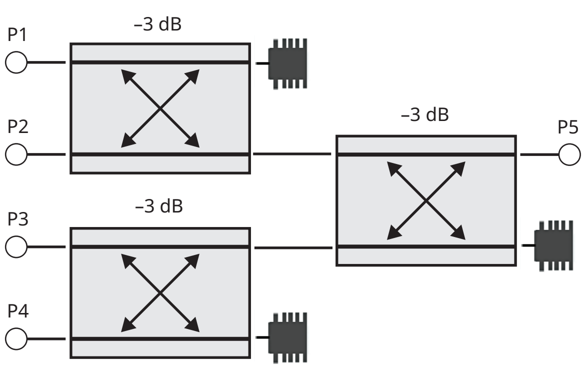

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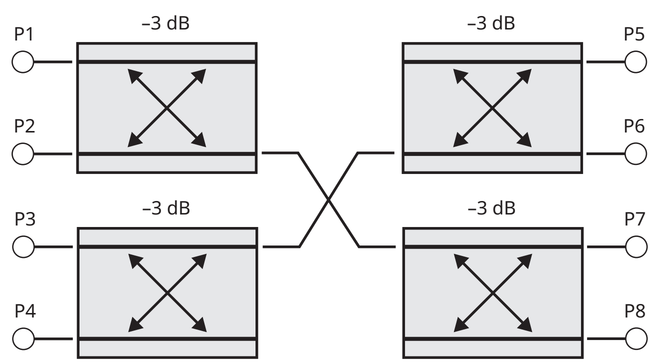

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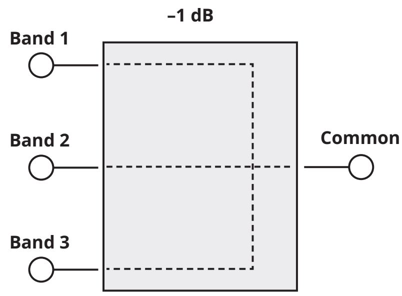
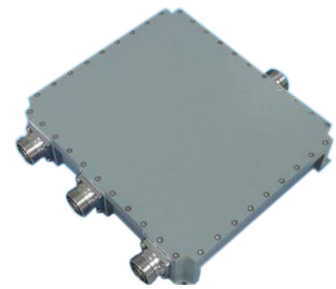
The high power terminations used with hybrid combiners often produce high third order intermodulation (IM3) levels. Whether or not the IM3 signal impacts system performance depends on the combiner’s location in the system. In many cases, 2x1 hybrids are used to combine the main and diversity ports of an individual BTS before combining with other base stations. At this location in the DAS, it is often IM7 or IM9 that actually falls in the individual operator’s receive band, allowing a “poor IM3” termination to be used without impacting system performance. If the high power termination is used at a location in the DAS where signals from multiple operators or multiple bands are present, the termination may need to be replaced with a low PIM “cable load.”

Filter combiner:

In cases where the high insertion loss of a hybrid combiner cannot be tolerated, a filter combiner can be deployed. These devices are low loss, cavity filters that divide the input spectrum by frequency band rather than dividing the total band between multiple outputs. For this reason, filter combiners will typically have less than 1 dB loss in any given frequency band compared to 3 or 6 dB loss from a hybrid combiner network.

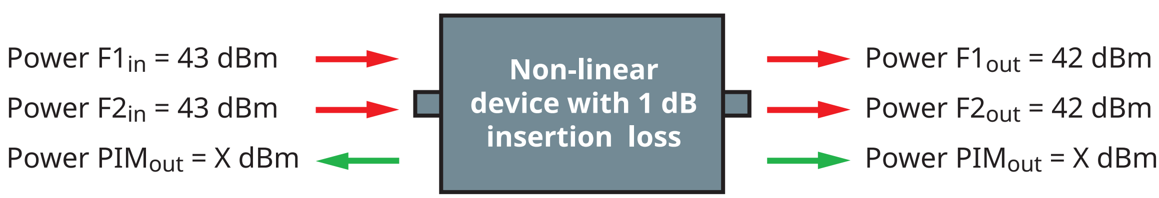




RF cables, power dividers, directional couplers, tappers and hybrid combiners are typically broadband devices supporting frequencies from 700 MHz to 2700 MHz. Filter combiners are different in that each port has a different operating bandwidth. Make sure the correct port of the filter is connected to the correct base transceiver station (BTS). In addition, when performing PIM tests through a filter combiner, make sure that the F1, F2 and IM product frequencies from the PIM tester are able to pass through the combiner. If not, that device will need to be by-passed while making system PIM measurements.

Passive Intermodulation (PIM):

Passive intermodulation (PIM) is not a type of loss. Rather, PIM is new signals created when multiple high power signals pass through a non-linear device. PIM acts like a point source radiator, with the new signals traveling in all directions from the point of origin. The power contained in the PIM signals is extremely small, but may be strong enough to interfere with mobile devices trying to communicate with the BTS. The following diagram provides a visual representation of how a non-linear device behaves:



The value of “X” in the above diagram is different for every device and is different for each IM order (IM2, IM3, IM5, etc.) produced by that device. A device is generally considered “Low PIM” when X is below –100 dBm for the 3rd order intermodulation product (IM3) when tested with two 43 dBm (20 W) test tones.

In each case discussed so far, the loss of the device has been a fixed number of dBs independent of the power of the signal entering the device. Passive intermodulation (PIM) behaves differently. The magnitude of the PIM produced by a non-linear device is highly dependent on the power level of the signals passing through that device. As the power of F1 & F2 increases, the power in the PIM signals increases. In theory, the IM3 signals produced by a non-linear device will change 3 dB for every 1 dB change in the F1 & F2 power levels.

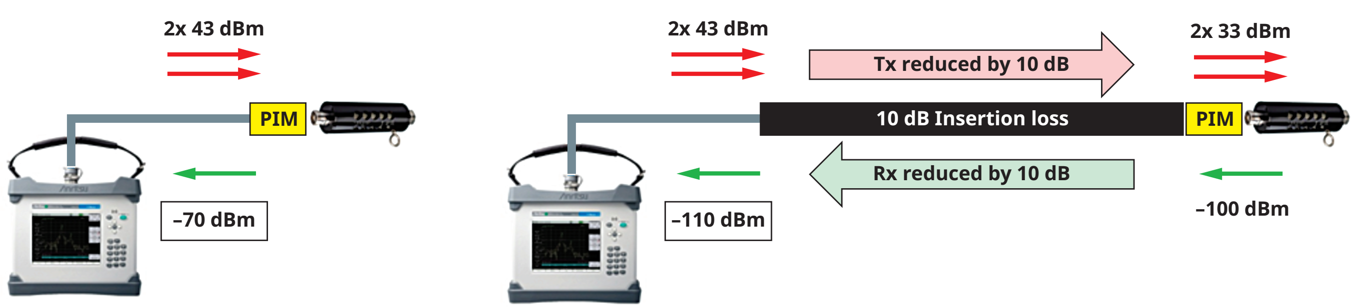
As an example, if we have a non-linear device that produces IM3 at –70 dBm when F1 & F2 = 43 dBm, the same device would produce an IM3 at – 100 dBm if we reduced the F1 & F2 signal levels 33 dBm. The math behind this is:

(–10 dB change in power) x (3 dB/dB PIM slope) = –30 dB change in PIM

The effect of insertion loss on measured PIM levels:

In mobile communications systems, the BTS acts as both a transmitter and a receiver. Downlink signals emitting from the BTS behave like our F1 & F2 signals in the previous example. As the downlink signals pass though non-linear devices in the feed system, PIM is generated that can travel back toward the BTS receiver and cause interference.

The magnitude of PIM signals arriving at the BTS receiver changes as the insertion loss between the non-linear device and the BTS changes. To demonstrate this, we could insert a non-liner device very near the BTS which might generate an IM3 signal of –70 dBm. PIM entering the BTS receiver would in this case be approximately –70 dBm. If we disconnected the system and added 10 dB of cable loss between the non-linear device and the BTS, the power arriving at the non-linear device would now be reduced by 10 dB. As a result, the PIM produced by the non-liner device would be reduced by 30 dB to –100 dBm (10 dB power loss x 3 dB/dB = –30 dB). But, it doesn't stop there! The PIM signal would now have to travel back through the 10 dB of cable loss to reach the BTS receiver, further attenuating the PIM signal by an additional 10 dB. By adding 10 dB of cable loss between the non-linear device and the BTS receiver, the PIM level entering the BTS receiver is reduced by 40 dB. This can be demonstrated by replacing the BTS with a PIM analyzer. The change in PIM level measured by adding 10 dB insertion loss is shown pictorially in the following figure.



The new PIM value (NPV) measured at the BTS when insertion loss is added can be expressed as:

NPV = PV – (PS * IL) – (1 * IL)

Where:

PV = PIM value (measured with no insertion loss)

PS = PIM slope (change in PIM level for every 1 dB change in signal power) in dB/dB

IL = Insertion loss added between the PIM source and the BTS in dB

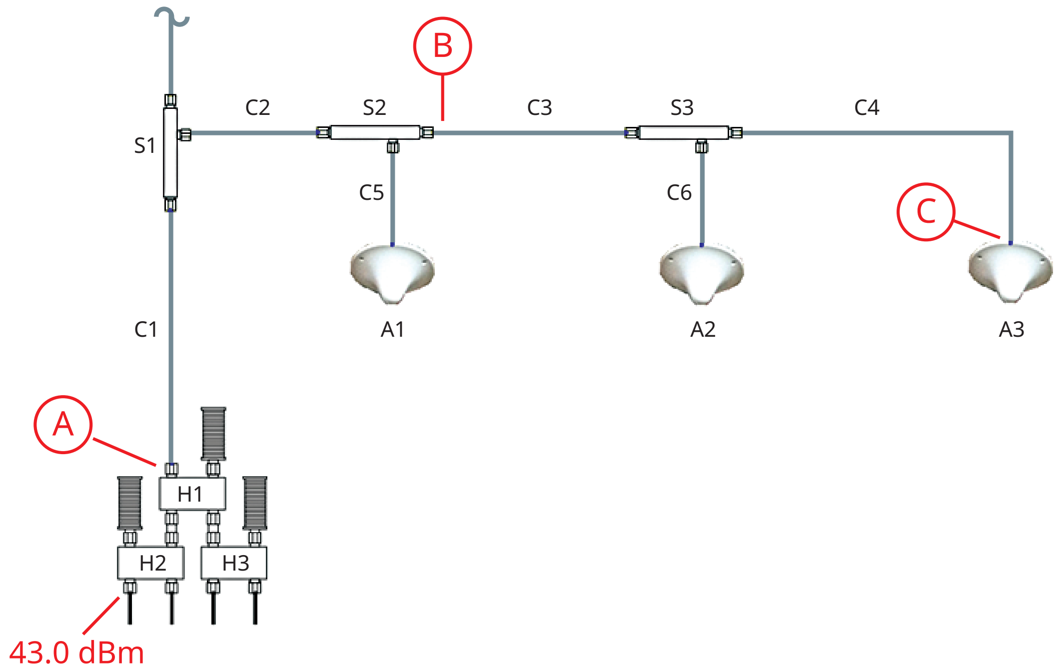
In the field, we find that PIM sources typically do not follow the theoretical 3.0 dB/dB PIM slope for IM3. Rather, the IM3 level of a PIM source typically varies 2.2 to 2.8 dB/dB with changing power. Substituting an average PIM slope value of 2.5 dB/dB, the above equation becomes:

NPV = PV – (3.5 * IL)

Note that this simplified equation is an approximation that is only appropriate for evaluating changes in IM3. A different PIM slope is required to evaluate IM orders IM2, IM5, IM7, etc.

Distributed Antenna System (DAS) branch example

In an in-building system, the power from the BTS is split and distributed to multiple antennas using coaxial cables. In the example below, the outputs from four different frequency band BTS are combined together using hybrid combiners and fed into a passive distribution network. Tapper "S1" couples energy from the riser to feed the first floor of the building, which is served by three antennas (A1, A2 and A3).



To evaluate the magnitude of PIM seen by a BTS receiver when a non-liner device is placed at points A, B and C, we need to first calculate the insertion loss between the DAS input and these three points of interest. We can do this by summing the cable and splitter losses between the input and each point of interest.

Loss to point A = H2 + H1 = 3.1 + 3.1 = **6.2 dB**

Loss to point B = H2 + H1 + C1+ $S1_{coupled}$ + C2 + $S2_{through}$
= 3.1 + 3.1 + 2.8 + 6.1 + 1.4 + 1.3 = **17.8 dB**

Loss to point C = H2 + H1 + C1+ $S1_{coupled}$ + C2 + $S2_{through}$ + C3 + $S3_{through}$ + C4
= 3.1 + 3.1 + 2.8 + 6.1 + 1.4 + 1.3 + 2.1 + 1.8 + 2.8 = **24.5 dB**

Let's assume the non-liner device generates IM3 at –50 dBm (–93 dBc) when subjected to 2x 43 dBm CW test signals. For reference, this is very "bad" PIM source! A typical system pass/fail level for IM3 is –97 dBm (–140 dBc.) The PIM signal produced by this non-linear device would need to be reduced by 47 dB before being considered acceptable! Or, saying this a different way, the PIM magnitude would need to be reduced by a factor of 50,000 before it would be acceptable.

Let’s further assume that we are able to insert this “bad” PIM source at the locations A, B and C in our DAS design. Keeping the test power constant, the new PIM value (NPV) measured at the DAS input can be estimated for each location.

Location of the PIM Source	IM3 level measured by PIM Analyzer	Result
At the DAS input	**–50 dBm**	**FAIL**
Location A	–50 – (3.5 x 6.2) = **–71.7 dBm**	**FAIL**
Location B	–50 – (3.5 x 17.8) = **–112.3 dBm**	**PASS**
Location C	–50 – (3.5 x 24.5) = **–135.8 dBm**	**PASS**

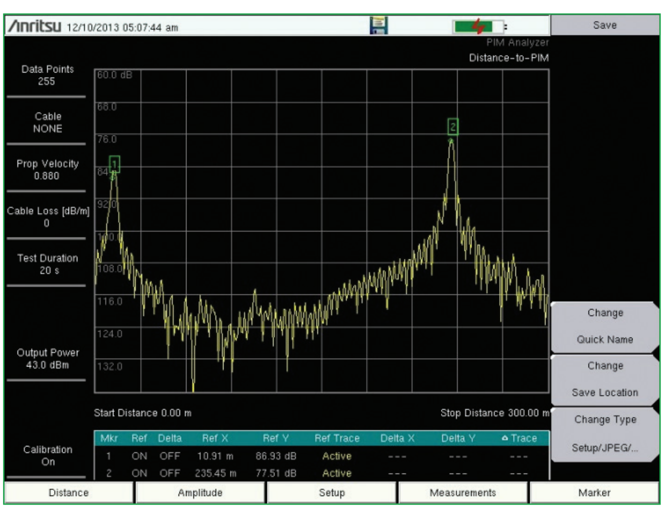
If the operator’s IM3 pass/fail level had been –97 dBm (–140 dBc) when tested at the DAS input using 2x 43 dBm test tones, the site would only have failed when this “bad” PIM source was located close to the DAS input. When the “bad” PIM source was placed far away from the DAS input, the insertion loss of the DAS reduced the PIM signal to a level that would no longer impact site performance.

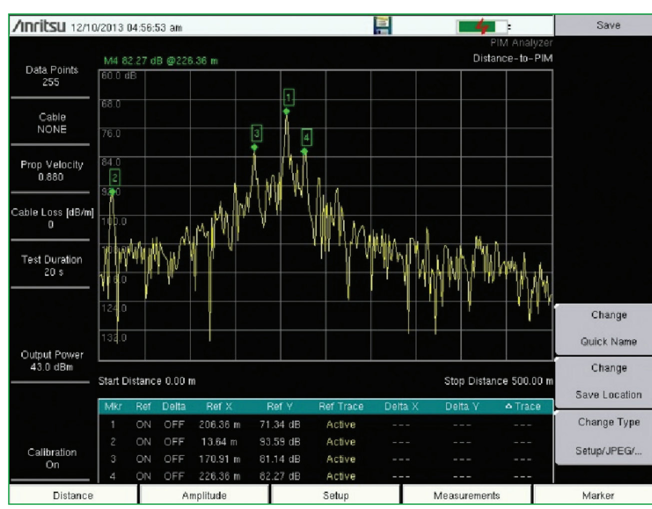
Distributed Antenna System (DAS) field results:

The previous example does not mean that PIM is only a problem at locations close to the DAS input. Poor cable construction techniques and loose metal connections near indoor antennas can create surprisingly high PIM levels. Even with high insertion loss, PIM sources are possible that create harmful interference levels even when located 100’s meters from the DAS input.

The following two examples show Distance-to-PIM (DTP) measurements recorded in the field at a DAS installation. Measurements were recorded using an Anritsu MW82119A PIM Master™ in the UMTS 2100 MHz band with test power set to 43 dBm. The long cable runs in this system were 1-¼ inch coaxial cable, which according to the manufacturer’s datasheet has a loss of 4.333 dB/100m @ 2100 MHz.

In the first example, one non-linearity is identified 11 m from the DAS input and a second non-linearity is identified 226 m from the DAS input. In the second example, non-linearities are identified at 14 m, 170 m, 206 m and 226 m from the DAS input. Each of these PIM problems is able to generate noise at a level high enough to impact site performance.





Distance-to-PIM (DTP) measurements from a DAS installation

Conclusion:

Passive Intermodulation (PIM) is highly power dependent. Adding insertion loss between a non-liner device and a BTS receiver typically reduces the power of the PIM generated by a factor of 3.5 dB for every 1 dB of added loss. This means that non-linear devices located far away from the BTS receiver are less likely to impact site performance than those located close to the BTS receiver. This is good news for Distributed Antenna Systems (DAS) which can include thousands of RF connections and passive devices in the feed network. While the probability of harmful PIM is reduced at locations far away from the DAS input, care must still be taken during construction to prevent PIM. Even with high loss, it is possible to produce extremely non-linear junctions capable of impacting site performance deep within the DAS network.

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