

Intermodulation Distortion Problems at UMTS Cell Sites

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Abstract

With the introduction of 3G, the co-existence of 3G and 2G radio networks has become a major issue both from a network planning perspective and for realisable network performance. This paper presents the problems that may be encountered in co-location of 2G and 3G cells caused by Passive Intermodulation Distortion (PIM) and blocking. The mechanisms and effects of PIM on cell coverage are presented with the aid of a case study. A novel technique for measuring PIM at a UMTS cell site based on uplink sensitivity measurements employing state-of-the-art UMTS test equipment is presented. The paper concludes with a brief presentation of a laboratory simulation of Passive IM measurement demonstrating the new technique.

Introduction

One of the major challenges facing 3G network planners is how to deploy the network in a way that can co-exist with the existing 2G networks. Frequently, sites are acquired at great expense often with some with difficulty in managing the prevailing environmental and planning regulations. Therefore there is usually great pressure placed upon network planners to install 3G infrastructure equipment at the same or in close proximity to 2G sites. However, such co-location presents a set of challenges to network planning and performance, and hence potential revenues. In many cases, co-site problems must be accepted and the network co-planning aimed to minimise the degradation. A site which at installation time was deemed suitable may deteriorate due to environmental effects and remedial action may be required to restore the site's coverage.

Band planning has a major impact on the likelihood of co-site problems. In Europe, 2G/3G interaction has been minimised because the Band I used for UMTS has been chosen such that the risk of adjacent channel rejection and Intermodulation Distortion (IMD) problems caused by the GSM900 and GSM1800 networks is minimised. However, another effect, blocking can still occur. In the USA and other parts of the world, UMTS network planners are not so fortunate. Due to fragmented spectrum and the co-existence of a number of different radio network technologies, UMTS bands must be slotted in wherever there is available spectrum [1, 2].

This paper focuses on one of the potential causes of network performance degradation caused by co-siting: Passive Intermodulation Distortion (PIM). First the mechanisms of co-site problems including PIM and blocking are explained. Then a case study based on the PCS and AWS (Advanced Wireless System,

Band-IV UMTS) bands in the USA is presented that demonstrates the reduction in cell radius that can occur due to a PIM problem. Next a novel measurement procedure based on uplink sensitivity measurements using a state-of-the-art UMTS basestation test set is presented. The paper concludes with a description of a laboratory simulation of PIM that was carried out using the new measurement procedure that shows how observed behaviour in terms of sensitivity degradation concurs with the theoretical predictions.

The Mechanisms of Co-Site Radio Problems

IMD and blocking are generic problems that theoretically can occur between any types of radio system. In the following analysis, 2G systems such as GSM will be referred to as Narrow Band (NB) and UMTS systems as Wide Band (WB). WB systems are especially prone to blocking and IMD from NB interference because of their wide channel bandwidth.

The following table summarises possible interference mechanisms between NB and WB networks both at the user terminal end and the basestation (BTS) end.

Table 1: Summary of interference possibilities between NB and WB networks.

	NB user	NB BTS	WB user	WB BTS
NB user			Yes	Yes
NB BTS			Yes	Yes
WB user		Possibly		
WB BTS	Possibly	Possibly		

The mechanisms that can cause problems are:

- Adjacent Channel Rejection (ACR)
- Blocking
- Intermodulation Distortion (IMD)
- Cross Modulation Distortion (XMD).

Interference can be characterised as either being wide-band noise (WBN) or intermodulation related. ACR and blocking problems are generally related to wide-band noise. IMD and XMD are related to intermodulation effects. ACR tends to affect user terminals more than base stations due to component (size, and power consumption) and cost constraints. ACR is not covered in detail in this paper. More information on ACR may be found in [1] and [3].

Wide-Band Noise

Radio transmitters not only generate desired signals but also wide-band noise – phase noise, thermal noise and noise generated as a result of internally generated distortion in mixers and amplifiers etc. Since there is no such thing as a perfect “brick wall” filter, some of the wide-band noise will appear outside the transmission channel and may be propagated to cause interference to another radio system.

Generally, wide-band noise related problems may be reduced by allowing sufficient frequency separation (guard bands) between adjacent bands. The greater the separation in frequency between transmitter and receiver, the less the wide-band noise problem since the noise generally drops in power with increasing frequency offset. Similarly, the attenuation of filters increases as the frequency offset is increased.

A receiver generally employs a selective Intermediate Frequency (IF) filter that provides the bulk of rejection. Providing the front-end (RF) circuits of the receiver are not overloaded, the IF filter rejects most of the wideband noise. If the interference frequency is far removed from the receive frequency the interference is sufficiently rejected.

However, if the transmitter is too close to the receiver, its wide-band noise power can be so great that it “blocks” the front-end of the receiver even if the channel separation is relatively large. The desired signals are blocked out rendering the receiver partially “deaf”. Blocking is therefore an effect greatly influenced by the proximity of interfering transmitter to receiver.

Intermodulation Distortion

Intermodulation (IMD) is a non-linear effect in which two signals “mix” to produce additional signals which though often relatively low in power exist at discrete frequencies some of which may fall in the receive channel so will not be rejected by the receiver’s filters. For this reason, IMD can be a more serious problem for 2G/3G networks compared to wide-band noise.

Consider two signals, a narrow band (e.g. GSM) signal, $s_{NB}(t)$ and a wide-band (e.g. UMTS) signal $s_{WB}(t)$ with powers P_{NB} and P_{WB} in *dBm* respectively and frequencies f_{NB} and f_{WB} respectively.

The result of the non-linearity is that a number of distortion products are produced at a number of different frequencies. Most of these products appear at frequencies far removed from the bands of interest. However, a third-order non-linearity generates products at:

$$f_{IM3+} = 2f_{WB} - f_{NB}, \quad (1)$$

$$f_{IM3-} = 2f_{NB} - f_{WB} \quad (2)$$

That can be close to the bands of interest as shown below in Figure 1.

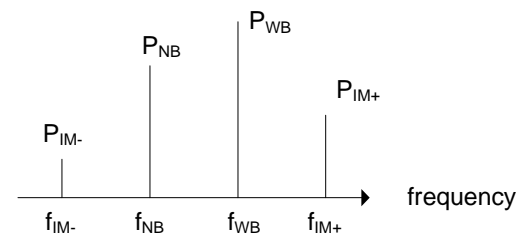


Figure 1: The spectrum of signals that have suffered intermodulation distortion.

The degree of 3rd order non-linearity of a component (either passive or active) is usually expressed in terms of its 3rd order intercept point (IP3) which may be referred to either the input (IIP3) or output (OIP3).

It must be emphasised that both active devices such as tower mounted amplifiers (TMA) and passive devices such as antennas, filters, and corroded metal such as connectors and tower fixtures and fittings can generate IMD products. Corroded metal behaves like a semiconductor diode and therefore exhibits non-linearity. A frequent cause of Passive IMD (PIM) is the so-called “rusty bolt” effect in which a corroded joint or fixture exposed to RF radiation re-radiates the IM products to be picked up as interference by nearby radio receivers as illustrated below.

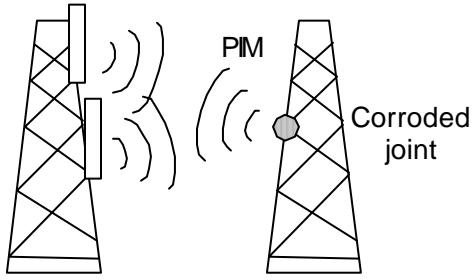


Figure 2: The mechanism of passive intermodulation distortion (PIM). The corroded joint radiates distortion products.

It can be shown that the power of the $IM3$ products is:

$$P_{IM3-} = 2P_{NB} + P_{WB} - 2IIP3 \quad (3)$$

$$P_{IM3+} = P_{NB} + 2P_{WB} - 2IIP3 \quad (4)$$

Where $IM3-$ is the product below the channels, $IM3+$ is the product above the channels and the narrow-band signal's frequency is below the wide-band signal's frequency as shown above in Figure 1. Of course, if the frequencies are the other way round, the above equations are swapped with respect to the narrow-band and wide-band signals.

It is observed from (3) and (4) that P_{IM3-} increases by 2dB for every 1dB increase in P_{NB} but only by 1dB for every 1dB increase in P_{WB} . Similarly, P_{IM3+} increases by 2dB for every 1dB increase in P_{WB} but only by 1dB for every 1dB increase in P_{NB} .

Effect of PIM on Network Coverage

Just a 1dB loss in uplink sensitivity results in an 11% decrease in coverage [1]. If a UMTS BTS receiver is subjected to strong narrow-band interference such as from a nearby GSM cell, the cell's coverage will be reduced because the uplink sensitivity of the BTS is degraded for all users. The PIM interference in the receive channel adds directly to the thermal noise thus degrading the signal to noise ratio of a user's signal (E_b/N_0). The Bit Error Rate (BER) is dependant upon E_b/N_0 . As E_b/N_0 drops, the BER increases, or the range at which a specified BER can be achieved is reduced. As a result the BTS cannot receive signals from user terminals distant from it and can only guarantee a Quality of Service (QoS) over a reduced range. User terminals closer to the BTS may be instructed to transmit at a higher power causing more interference to neighbouring cells reducing overall network coverage still further.

An Example of a PCS/AWS PIM Problem

In order to illustrate the problem of PIM in a real network scenario consider the following situation that may be found in the USA. The following figure illustrates the band allocations for PCS and AWS.

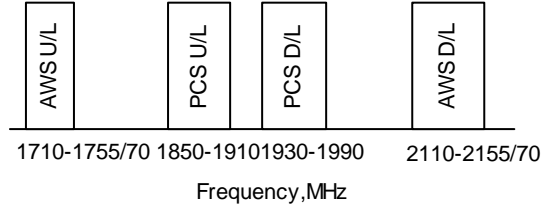


Figure 3: PCS/AWS band allocations in the USA.

Let,

$$\begin{aligned} f_{NB} &= 1955\text{MHz (PCS Downlink)}, \\ f_{WB\ DL} &= 2155\text{MHz (AWS Downlink)}, \\ f_{WB\ UL} &= 1755\text{MHz (AWS Uplink)}. \end{aligned}$$

From (2), we find that

$$f_{IM3-} = 1755\text{MHz} = f_{WB\ UL}.$$

The power of the intermodulation distortion product, P_{IM3-} given by (3) increases by 2dB/dB for the PCS downlink (P_{NB}) and 1dB/dB for the AWS downlink (P_{WB}).

The link budget shown in Table 2 illustrates the effect on cell range of PIM interference caused by a source such as a corroded fixture on a tower. Both BTS' are transmitting at 43dBm and the user's terminal is transmitting a 12.2kbps telephony circuit at its maximum power of 21dBm (corresponding to an EIRP of about 18dBm including body loss etc). It is assumed that there is 70dB path loss between the PCS antenna and the PIM source and 30dB path loss between the AWS antenna and the PIM source. The link budget calculates the uplink receiver's sensitivity and from that and the required E_b/N_0 , the approximate cell range can be estimated using the Okumura-Hata model [3]. The path loss does not include margins for log-normal fading or in-car or in-building losses so is arguably an optimistic case.

Without PIM interference present, the BTS uplink sensitivity is -120.0dBm and the approximate cell range is 3.0km. With PIM interference present as shown, the sensitivity drops to -117.9dBm and the cell range is then 2.6km; a 13% reduction. The following figure illustrates this example.

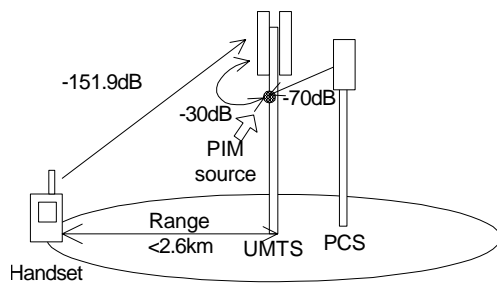


Figure 4: The PIM mechanism of the 12.2kbps uplink example.

The 3rd order intercept point (IP3) of the PIM source has a significant effect on the interference level and is difficult to measure. In this example a value of 40dBm has been used. (The interference level drops at a rate of 2dB/dBm increase of the IP3.) The levels of signals reaching the PIM source also have a major effect, especially the PCS signal which in this case where the PCS band is below the AWS downlink band the PIM level increases at 2dB/dB increase in PCS power level. The AWS antenna's gain has a two-fold effect. It both "amplifies" the radiated downlink power and the received uplink power. The higher the antenna's gain (with respect to an isotropic radiator) the worse the PIM generation and the greater its pickup. However, a high gain antenna is also highly directional so this effect may be offset to some extent if the PIM source falls in a null of the antenna's radiation pattern.

In summary, this example shows that there is a real possibility of PIM problems occurring in a network by virtue of the band allocations and that even a relatively low level of radiated PIM (e.g. -91dBm) in the wide-band system's

uplink band can cause a significant and usually unacceptable loss in cell range.

Detecting PIM Problems at a UMTS Cell Site

Given that PIM is a potential problem for a wide-band network such as UMTS, how can a network operator detect the problem and what can be done to minimise it?

Systems are available to *measure* the PIM levels of various assemblies such as duplexer filters, cables and other structures (e.g. [4]). Whilst such a PIM test set is useful in ensuring components meet a specification or even for measuring a deployed system, such test sets do not measure the problem in terms of network performance parameters. In a digital communication system such as UMTS, it is the Bit Error Rate (BER) that determines the Quality of Service (QoS) perceived by the user. Given an acceptable level of QoS and hence BER, the dimensions of the problem may be traded off against each other. Therefore it makes sense to characterise interference problems such as PIM in terms of their effect on the received uplink sensitivity which is the power of uplink signal required to attain a specified BER and hence QoS.

The Measurement of Uplink Sensitivity and PIM

A state-of-the-art UMTS basestation test set such as the Aeroflex 6413A equipped with both a built-in user terminal simulator (uplink generator) and an I_{UB} backhaul interface can be used to perform a PIM measurement characterised by uplink sensitivity. Figure 5 below illustrates the configurations used for testing PIM. In configuration (a) the combiner is placed between the BTS and the antenna system. It must provide a DC path for the TMA control signals and power.

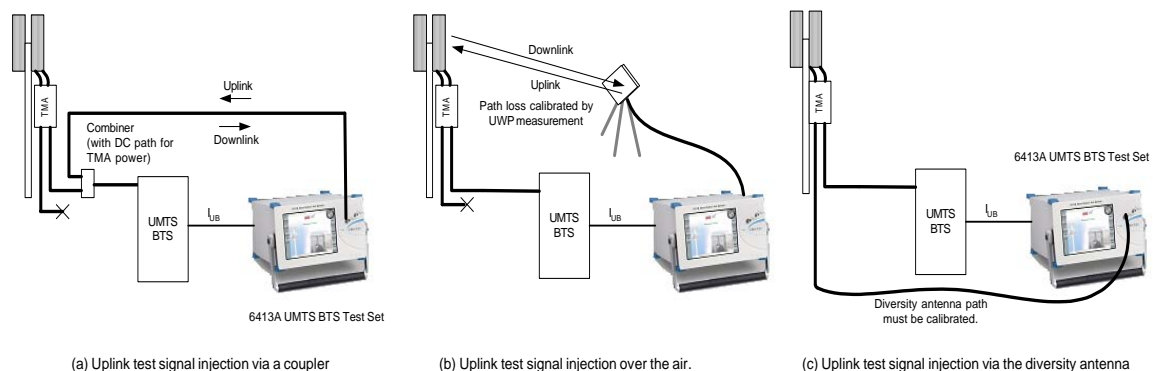


Figure 5: Configurations for PIM measurement using the 6413A Basestation test set.

This configuration gives the best results providing the uplink cable loss parameter on the test set is set correctly to take account of the TMA not being in the uplink test signal's path. Note, the diversity antenna should normally be disconnected to avoid confusion. However the diversity antenna system could be the prime source of the PIM problem so if suspected, the diversity antenna should be investigated separately by swapping over the combiner to it and using the RF out (simplex) port of the test set.

If it is not possible to connect the test set via a combiner, the configuration shown in Figure 5 (b) may be used. The test set is connected to a portable antenna. The path loss must be measured as described below.

Figure 5 (c) shows a third configuration in which the diversity branch of the antenna system is used to inject the uplink test signal. In this case, the diversity branch's low noise amplifier (LNA) must be switched to bypass mode and an uplink wideband power measurement (described below) is used to calibrate the path loss between the main and diversity antenna connections.

In order to measure the uplink sensitivity of a cell, it is necessary to disconnect the I_{UB} interface of the BTS from its controlling RNC (thus temporarily taking the cell out of service) and re-connect the I_{UB} to the test set. The test set's RF port is coupled into the antenna system of the cell via a coupler, or over-the-air via an antenna as previously described. It can then take full control of the BTS.

First the Uplink Wideband Power (UWP) which is reported by the BTS via the I_{UB} is measured. This indicates the background interference on the uplink not due to PIM (but possibly due to blocking from a PCS BTS.) If the uplink test signal is to be coupled over-the-air via an antenna or through the diversity antenna (as shown in Figure 5 (b) and (c) respectively), the initial UWP measurement is used to measure path loss using a relatively high uplink level. It may be necessary to hand off nearby users to a different cell or RAN (e.g. GSM) or drop calls to quieten down the uplink channel. The test set then brings up a cell, synchronises to the air interface of the cell and starts a dedicated traffic channel (e.g. a 12.2kbps Reference Measurement Channel, [2]).

The test set generates a reference uplink channel at a low power level carrying traffic

with a known pseudo-random binary sequence (e.g. PN9). The BTS demodulates the uplink test signal and the test set recovers the framed data from the I_{UB} . The test set accurately estimates the BER by comparing the received data sequence with the known transmitted sequence in real-time.

The test set steps the uplink power level up and down until a target BER is achieved (e.g. 0.001) thus measuring the absolute sensitivity of the uplink receiver. If PIM or wide-band noise is present, a degraded sensitivity will be observed.

In order to detect a PIM problem, it is necessary to change the BTS's downlink (transmit) power. Since the test set has control of the cell via the I_{UB} interface, this is easily achieved. If the sensitivity has been degraded by PIM, then reducing the Tx power will improve the sensitivity by about 1dB for every dB reduction in Tx power by virtue of equation (3) (assuming the NB interference frequency is below the downlink frequency). Since the wide-band noise from the cell's own downlink will be heavily attenuated by the BTS duplex filter, this test enables the PIM (rather than blocking) mechanism to be clearly identified. The AS measurement is repeated for a range of downlink Tx power levels to produce a plot of AS versus Tx power.

A UWP measurement is also made for each Tx power level to enable the PIM interference level to be measured. The total UWP P_{UWP} (dBm) measured by the BTS is given by:

$$P_{UWP} = 10 \log_{10} \left(10^{P_{UL}/10} + 10^{P_{PIM}/10} + 10^{N/10} \right) \quad (5)$$

Where P_{UL} is the uplink test power level, P_{PIM} is the power of the PIM interference, and N is the power of thermal noise, uplink interference (from other users) measured at the start of the test (All powers in are dBm.) Assuming N is negligible,

$$P_{PIM} = 10 \log_{10} \left(10^{P_{UWP}/10} - 10^{P_{UL}/10} \right) \quad (6)$$

Of course, P_{PIM} can only be measured if P_{UWP} is sufficient to be measured by the BTS (normally $P_{UWP} > -104$ dBm.) Using this technique, relatively low levels of PIM can be detected without the need for special signal generators, amplifiers and the transmission of high power CW test signals as required by a traditional IMD test.

Locating and neutralising the source of PIM

If the PIM test described above shows up a serious degradation in uplink sensitivity and thus coverage, the operator may decide to correct the problem or at least reduce its impact. There are several options:

- a) Find the source and repair or replace the faulty component or fixture.
- b) Adjust the tilt or azimuth of the antennas to reduce the effect.
- c) Reduce the cell's power – which may actually improve capacity and coverage.
- d) Reduce the power of the interfering cell.

Option (a) may require a rigging team to be deployed so could be costly. Options (b) and (c) will of course have to be carried out with care to take account of the wider effects on the network performance so would involve a degree of network re-optimisation. Option (d) may not be feasible if the interfering cell is not under the control of the operator or co-sited.

In order to control the PIM problem using one of the above options, some form of quality metric against which adjustments may be made is required. The test set's absolute sensitivity measurement operating in continuous mode is ideally suited as a metric because it enables the uplink sensitivity to be continuously measured whilst adjustments to the cell are made.

Alternatively, the Reference Sensitivity Level (RSL) test can be used to transmit a known uplink power and measure the BER at that level. RSL is particularly useful for live fault finding. For example, by providing an audible indication of the BER in real-time, the test set can assist a rigger equipped with two-way radio. As the rigger attempts to affect the problem by tapping or moving various components, he or she receives instant feedback from the test set thus making the job a lot quicker, reducing the down-time of the cell and the overall cost of the repair.

A Laboratory Simulation of the PIM Mechanism

In order to demonstrate the use of the 6413A UMTS basestation test set for PIM interference investigations under controlled laboratory conditions, the configuration shown below in Figure 6 was used.

The BTS used for the experiment was configured for Band I (1920-1980MHz uplink, 2110-2170MHz downlink). The test channel

selected was UARFCN 10700, corresponding to 2140.0MHz downlink, 1950.0MHz uplink. In order to generate an IM product on the uplink frequency of 1950.0MHz, the GSM signal generator was set to 2045.0MHz.

The "rusty bolt" was simulated by using a diode (actually a reverse power protection unit). The diode was subjected to RF signals from the GSM signal generator and the BTS combined in a 3dB combiner. (The 15dB attenuator on the output of the signal generator is to stop IM occurring in the output stage of the signal generator.) The uplink power reference point is A in Figure 6. An RF power meter was used to measure the power at point A from which the losses between the signal generator and BTS were derived. A 1920-1980MHz filter was used to extract the PIM product. This filter is required to avoid blocking of the BTS by the signal generator's wide band noise. A 3dB combiner was used to combine the uplink test signal from the test set with the IM from the diode.

Effect of GSM Interference Power

The BTS was configured by the 6413A to bring up a cell with a power of +37dBm at 2140.0MHz. This resulted in a power of 13.2dBm at the diode. The signal generator was adjusted for GSM powers at 2045MHz of Nil, -40, -30, -28 and -26dBm. For each of these power levels, Absolute Sensitivity (AS) and -100dBm Uplink Wideband Power (UWP) measurements were performed. Figure 7 shows how the AS changed with respect to the GSM interference level at the point of PIM generation (i.e. the diode).

With no GSM interference, the full sensitivity of the cell is realised at -125.2dBm. As the interference is increased to -40dBm, the sensitivity is initially only degraded by about 0.4dB; at this level, the sensitivity is still dominated by thermal noise rather than PIM. A further increase of 10dB produces only 1dB degradation in sensitivity. However, above this, the PIM started to dominate. As the interference level was increased in steps of 2dB, the sensitivity is degraded by 4dB per 2dB step clearly showing the IM mechanism at work (equation (3)).

Figure 8 shows the effect of the GSM interference on the UWP and IM3 level (equation (5)). UWP measurements were made with an uplink level of -100dBm. For interference levels below -30dBm, the reported UWP was -100dBm as expected. But as the interference level was increased, the

PIM dominated. Figure 8 also shows the PIM power. It can clearly be seen that the PIM level increased at the rate of 2dB/dB.

Effect of BTS Downlink Power

The GSM interference power was fixed at -24dBm. The AS and UWP measurements were run with the cell power as the independent variable. The Cell power was stepped over the range 19, 21, 23, 25, 27, 29, 30, 32, 33, 34, 35, 36 and 37dBm. The AS and UWP results are shown in Figure 9. The results show that sensitivity degraded by 1dB for every 1dB increase in cell power. The UWP increased by 1dB for every 1dB increase in cell power indicating that with -24dBm of GSM interference, the PIM dominated the UWP and that the prediction of equation (3) is born out in practice.

Conclusion

This paper has introduced the problem of Passive Intermodulation Distortion (PIM) and its potentially devastating effect on the coverage of a wide-band cellular radio network such as UMTS. The paper also touched upon other related effects such as wide-band noise blocking and the effects this can have on a UMTS cell and explained the mechanisms of PIM and blocking.

A case study of a potential PIM problem in the USA using PCS and AWS (Band IV UMTS) was used to demonstrate the reduction in cell radius and thus coverage caused by PIM.

The paper presented a novel way to detect PIM problems at a cell site using the Aeroflex 6413A UMTS basestation test set based on the measurement of the Absolute Sensitivity of the cell rather than the traditional "brute force" technique of using high power CW signals to detect PIM problems. It was explained that making a measurement of PIM by measuring sensitivity and uplink wideband power is a more relevant (and less invasive) approach since the parameter being measured relates directly to cell coverage and hence quality of service. The paper also suggested a variety of ways in which the source of the PIM interference could be tracked down in real time using Bit Error Rate as a metric.

The paper concluded with a demonstration of the PIM mechanism in the laboratory using a UMTS BTS and a diode to simulate a "rusty bolt". The laboratory results concurred exactly with the theoretical behaviour of PIM with respect to power levels and demonstrated how

the 6413A test set can be used to differentiate between blocking and PIM by taking control of the cell and programming its downlink power.

The 6413A UMTS basestation test set can both simulate an uplink signal *and* control the cell via the I_{UB} backhaul simultaneously in real-time. This enables a true sensitivity measurement to be made. Such a measurement makes the use of traditional IM test systems with their associated problems of CW radiation and large equipment cost and bulk unnecessary in many cases.

References

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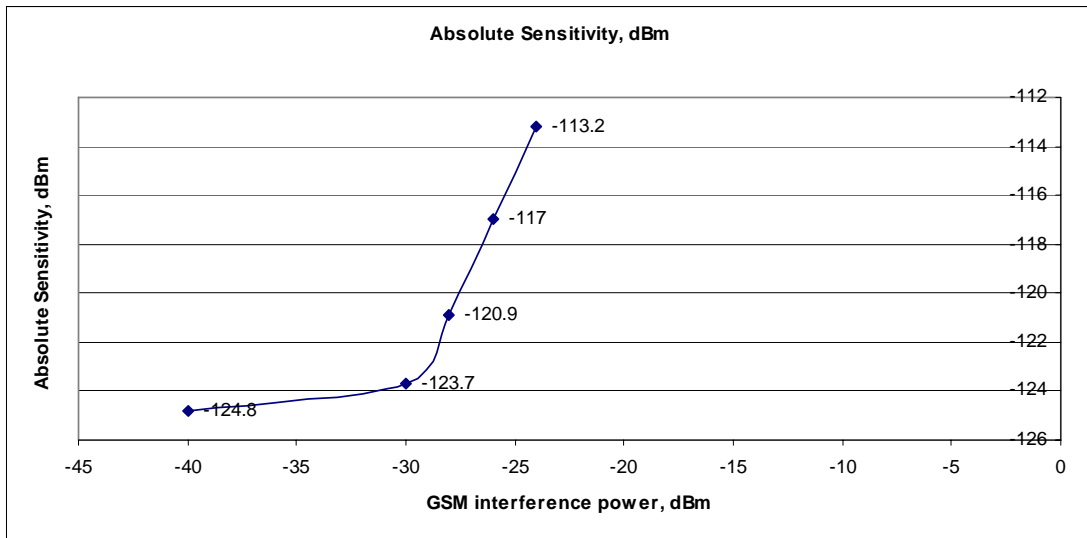


Figure 7: Absolute sensitivity with respect to GSM interference power. UMTS BTS power = 13.2dBm at the PIM source (+37dBm cell power).

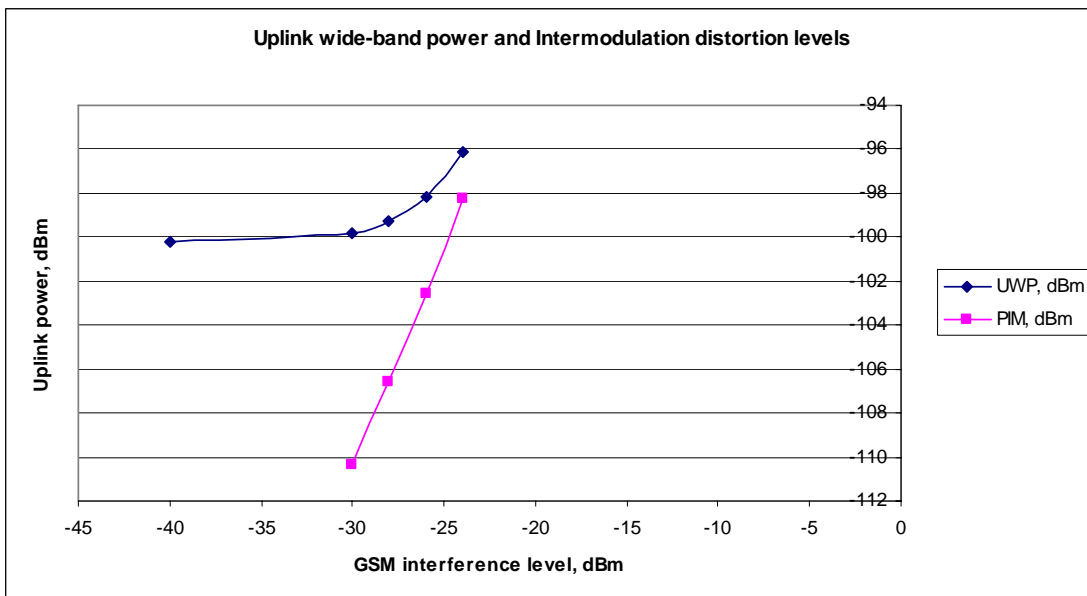


Figure 8: Uplink Wideband Power and Passive IM levels with respect to GSM interference level at the PIM source. UMTS BTS power = 13.2dBm (+37dBm cell power).

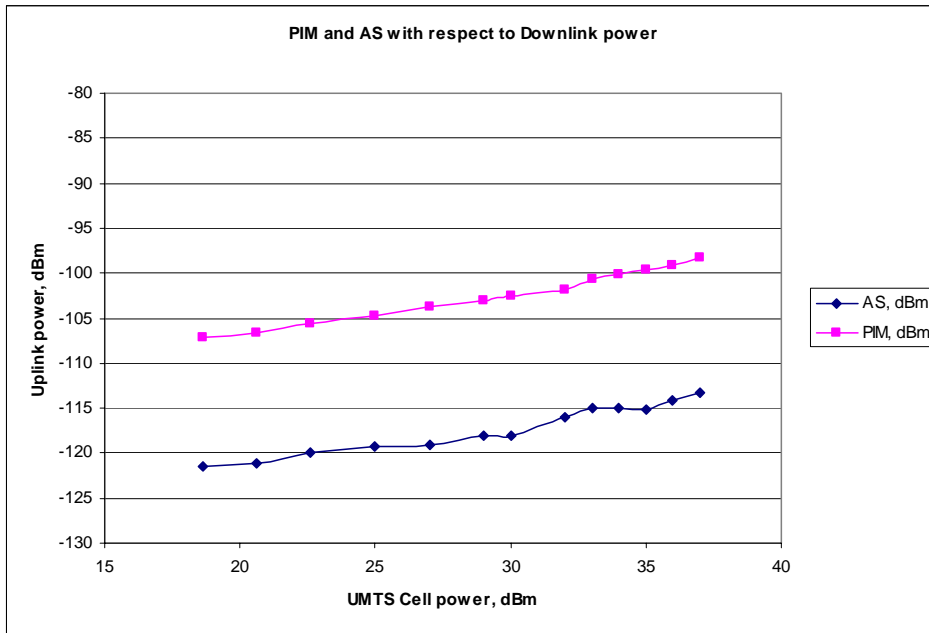


Figure 9: Absolute Sensitivity and Uplink Wideband Power with respect to BTS level. GSM interference level at the PIM source = -24dBm.