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Passive Inter-Modulation; Causes, Avoidance and Mitigation Techniques

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Abstract:- A form of distortion known as passive intermodulation (PIM), which is becoming more and more of an issue in the telecommunications industry, affects the delicate receiving signals in cellular networks. The system' s signal-to-noise ratio (SNR) may be significantly limited by passive intermodulation (PIM) interference when the performance of other radio frequency (RF) components is correctly designed. To reduce interference and improve network capacity in multicarrier networks, there are strict PIM level requirements for base stations, satellite systems, and indoor distributed antenna systems. PIM results from signals running through nonlinear systems at different frequencies which results in false distortion signals. Even though it can exist in active circuits of radio systems, PIM is most frequently found in passive wireless systems, especially with quite high transmit power. This article reviews sources of PIM and classifies the PIM into as rusty bolt, assembly, and design PIM. Two categories of mechanisms have been shown to be the primary cause of PIM, nonlinearities of contact and material. Passive nonlinearities mainly cause from electro-thermal processes, the junction of metal, insulator, and metal-insulator-metal (MIM) junctions, surface roughness and contact mechanical deformations. These mechanisms in charge of producing PIM are presented and also, analog and digital cancellation methods for PIM are reviewed.

I. INTRODUCTİON

One of the biggest worries in communication systems is the interference that is caused by passive components at the system' s front end. Passive intermodulation (PIM) is the term for the nonlinear interference issue of passive systems, components, and devices [1, 2]. Non-linearity in a communication system is the main cause of PIM. These nonlinear sources produce higher order harmonics of the fundamental frequency in multichannel, high-power [3]. As a result, the receiving end of the communication system can no longer use some portions of the frequency range.

PIM is a very important issue in the telecommunications industry and troubleshooting is quite difficult. PIM can interfere with cell communications and reduce receiver sensitivity or block communication altogether. This negative effect can affect the cell that creates it, as well as the receptors next to it. For instance; the downlink and uplink frequency bandwidths in an LTE frequency band are 1930 MHz to 1990 MHz and 1850 MHz to 1910 MHz, respectively. If two carriers are transmitted with frequencies of 1940 and 1980 Mhz from a base station including PIM, it will result in an item at 1900 MHz that will go into the receive frequency band. This affects the buyer. Moreover, at 2020 Mhz the intermodulation element can also affect other systems. In severe circumstances, the channel might even become inoperative. Another example system which is very susceptible to interference from PIM is satellite systems as extremely low power levels can be observed in received transmissions, whereas very high power levels are observed in transmitted signals. Also, because satellites are so tiny, their transmitters and receivers are often only a few meters apart. Thus, to successfully prevent or reduce PIM effects, creative solutions that take advantage of PIM detection, avoidance, and cancelation strategies are needed. Generally speaking, a passive device is one that runs off no exernal power. Examples of passive components that can cause PIM include coaxial cables, connectors, and waveguide flanges. Two examples of passive non-linearities include the rectification of current flow at corroded or loose metal junctions and the hysteresis phenomenon, which is observed in ferrites and ferromagnetic materials.

A power series can be used to describe the response for a large number of non-linear systems. As an illustration, the transfer function of a non-linear unit can be expressed as follows using an n^th^ order power series [2]:

$$Y_0 = b_1 Y_i + b_2 Y_i^{\,2} + b_3 Y_i^{\,3} + \ldots + b_n Y_i^{\,n} \tag{1}$$

Where the n^{th} coefficient is represented by b_n. This design produces not only the single frequency itself, but also multiple times of it and it is referred to as harmonic distortion. If the input signal is represented by:

$$Y_i = V[\cos(w_1 t) + \cos(w_2 t)] \tag{2}$$

Then, the output signal will be like,

$$Y_o = b_1 V(\cos w_1 t + \cos w_2 t) + b_2 V^2(1 + 1/2\cos 2w_1 t + 1/2\cos 2w_2 t + \cos(w_1+w_2)t + \cos(w_1-w_2)t) + b_3 V^3(1/4\cos 3w_1 t + 1/4\cos 3w_2 t + 3/4\cos(2w_1-w_2)t + 3/4\cos(2w_2-w_1)t + \ldots) + \ldots b_n V^n \tag{3}$$

Thus, distortion components at $lw_1 \pm kw_2$ generally emerge at the output. A system' s harmonics are created as multiples of its fundamental frequencies; for example, second order harmonics are produced as (2f1, 2f2), third harmonics as (3f1, 3f2), and so forth. When fundamental signals and harmonic signals mix, third-order IMD products like 2f1-f2 and 2f2-f1 are generated. Additionally, the fundamental signal combination is examined as second-order IMD products too.

The element at $lw_1 \pm kw_2$ is referred to as the (l+k)th order intermodulation (IM) product. As a result, the entire frequency spectrum of Y_o is represented in Figure 1 and is made up of the two stimulation signals at w_1 and w_2 (f_1 and f_2), in addition to numerous newly created harmonic and intermodulation products. Such supplementary signals are not produced by a linear system though. Also, in case of modulation of original signals, bandwidth of IM products will increase and if input signal power is not so high, IM product amplitudes will not be high, however, when the input power levels are high as in radio systems, IM products will have much higher amplitudes as well.

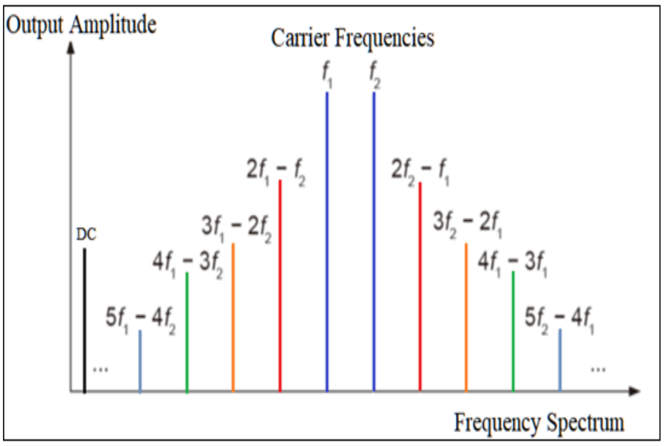

Fig 1 Spectrum of PIM Signal Centered on the Carrier Frequencies f_1 and f_2

Generally, only the minus term is expected to fall within the working bandwidth; however, often, the plus items of each pair of intermodulation products go oustide of the working bandwidth. The minus term $(f_2 - f_1, 2f_2 - f_1)$ that is close to the DC item in even order intermodulation products will also be outside the working bandwidth. Consequently, only the odd-order intermodulation minus elements are focused on.

II. CAUSES OF INTERMODULATİON DİSTORTİON

Generally speaking, a passive device is one that works with no external power. Three passive well known elements are inductors, capacitors, and resistors. Passive components in a radio unit will be things like filters, couplers, isolators, and antennas. Conversely, external bias is necessary for the activation of active devices. The fundamental components of active devices are transistors and diodes. An active device is any circuit that has a transistor or a diode in it. A digital memory unit with a million of transistors or an analog amplifier with only one transistor could both be considered as active devices. Every effort is done during the design process to guarantee that every active device can function within the linear zone. For simulations, transistors working in the active area are modeled using the little signal model. Conversely, active devices function in the nonlinear area with high level signal input [4, 5]. It is not anticipated that passive devices will produce noticeable harmonics, in contrast to active devices. However, passive components can also behave nonlinearly in specific situations. So, passive nonlinearity is now a major design problem due to the many radio coexistence systems' increasing development.

➢ *Intermodulation Distortion can Happen in Three Primary Contexts [1]:*

- Output phase of transmitter, because the power amplifier circuits are nonlinear,
- İnput phase of receiver input stages, as radio frequency (RF) and components and mixing components are nonlinear
- Nonlinear behaviour of loose contacts, corroded contacts in coaxial cables, connectors, wire barriers and similar mountings.

The passive IMI issue is frequently referred to as the "rusty bolt" effect, despite the fact that experience has shown that loose metallic joints, not rusty ones, are the primary source of most IMI issues. Understanding the types and causes of passive nonlinearities is essential to solving the passive IMI problem. Primary causes of passive nonlinearities is electro-thermal processes, the junction of metal, insulator, and metal-insulator-metal (MIM) junctions, surface roughness and contact mechanical deformations [6].

➢ *Two Categories of Mechanisms have been shown to be the Primary cause of PIM [1, 4].*

- Nonlinearity of Material
- Nonlinearity of Contact

➢ *Nonlinearity of Material*

The term "material nonlinearity" invokes massive materials with nonlinear electrical properties, such as carbon fibers and ferromagnetic materials. Non-linear I-V characteristics are shown by bulky materials, as ferromagnetic materials [7]. One essential characteristic of ferromagnetic materials is magnetic hysteresis. These materials represent nonlinear response, where transparency depends on magnetic field strength [1].

➢ *Nonlinearity of Contact*

The three main categories of contact nonlinearities that are seen in conductor joints and connections are electrical, thermal, and mechanical which is given in Figure 2 [6]:

- Mechanical effects include contact area extension and asperity distortions of conductors with shaggy planes and their contacts subjected to mechanical stresses,
- Electrical effects include tunneling and constriction current at asperities of shaggy contacts planes,

- Thermal effects include thermal extension, self-heating and electro termal effect because of ohmic losses in contacts

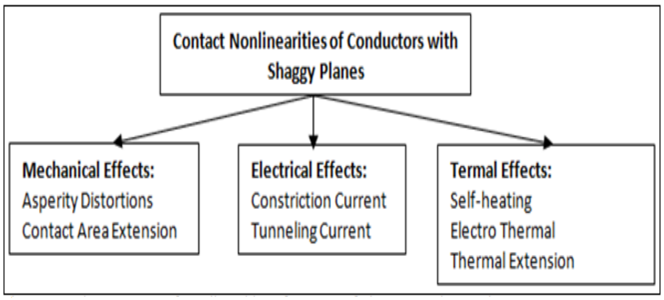

Fig 2 Primary Types of Nonlinearities of Contact of Shaggy Conductor Planes

Loose, oxidized, and polluted metallic joints are common examples of contacts that exhibit nonlinear current/voltage behavior. One of the metal-to-metal contact junction's nonlinear I-V relationships has been recognized as one of the principal PIM sources. Any contact with non-linear current and voltage behavior, such as unevenly bending coaxial cable, a non-flat waveguide flange, loosening rivets and tuning screws, contact with oxidation and corrosion, etc., is referred to as non-linearity of contact [5].

➢ *It has been Determined that the Following Mechanisms are in Charge of Producing PIM [1, 8]:*

- Semiconductor activity and electron tunneling via thin oxide layers dividing conductors at metallic contacts
- Microdischarge in metals across voids and in between microcracks
- Nonlinearities connected to metal particles and grime on metal surfaces
- High contact current densities
- Carbon fibers' nonlinear resistivity
- Hysteresis effects that are not linear in ferromagnetic materials.

Between these, electron tunneling has a different mechanism and Einstein' s wave-particle duality theorem may be utilized to explain this which can also be used to define the wave-like nature of light [4, 9]. There is a certain probability that an electron trapped behind a wall will occasionally emerge on the other side of the wall because electrons behave like waves, according to quantum physics [8]. This phenomena is referred to as electron tunneling. The likelihood of tunneling will decrease with increasing distance between the two contacts. Every metal-to-metal contact has the capacity to produce PIM. There is not a flawless metal-to-metal contact in actuality; instead, a thin dielectric layer and tiny microscopic imperfections divide each contact zone. Therefore, there is always a chance that a nonlinear current will occur [10].

Apart from these mechanisms, substandard craftsmanship can result in loose connections, metal fissures, and oxidation at joints, all of which can lead to PIM. In actuality, it is possible that a combination of these elements results in PIM. This is one of the main reasons which makes it so difficult to pinpoint the precise role played by any of these variables.

PIM is known to be a significant issue for service providers and hardware suppliers. Discovering the problem and resolving it, whenever possible, results in increased system trustworthiness and lower operating costs. In this paper, we will examine the sources and kinds of PIM, as well as proposed technologies to discover and resolve it.

III. CATEGORİZATİON OF PIM

There are three different kinds of PIM, each with unique properties and needs different kinds of solutions. They can be categorized as rusty bolt, assembly, and design PIMs.

➢ *Design PIM*

When utilized with their appropriate transmission lines, certain passive components are known to induce passive intermodulation. Development teams will therefore choose, when constructing a system, passive components with low or adequate PIM levels —as specified by the component vendor. Particularly susceptible to the influence are circulators, duplexers, and switches. To allow for greater levels of passive intermodulation, designers can choose to sacrifice performance, size, or cost [11].

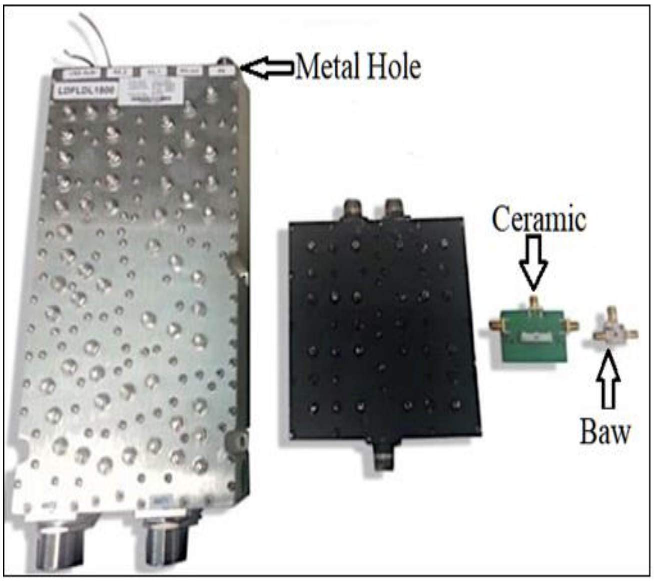

Fig 3 Size, Power, Rejection, Trade-Offs in Component Layout, and PIM Performance

In the event that designers decide to employ the lower-performing components, the receiver may become less sensitive as a result of the increased levels of intermodulation that follow. It is crucial to remember that in these situations, the desensitization of the receiver caused by PIM may be more problematic than any undesirable spectrum emissions or reduction in power efficiency. This issue is especially important for small cell radio designs. Figure 3 shows trade-offs in component layout design size, power, and rejection [11].

➢ *Assembly PIM*

Assembly PIM is the second classification of PIM. Even though the system might function well when it is first installed, bad installation or weather-related factors can cause performance to deteriorate over time. When this happens, the signal path' s passive components like the cables, connectors, cable and waveguide mountings, and other parts usually begin to behave nonlinearly. Indeed, a number of the most significant cases of PIM can be attributed to connections, connectors, and even the antenna feeder itself. As was previously said, the resulting impression may resemble that of the design PIM. Therefore, the same PIM measurement theory that looks particularly for the presence of goods that provide passive intermodulation can be applied [11].

➢ *The Following Components Often Contribute to Assembly PIM [11]:*

- Connector joining interface (usually Type N or DIN7/DIN16),
- The mechanical firmness of the cable/connector connection at the attachment point,
- Materials (Brass and copper are recommended, ferromagnetic materials show non-linear properties),
- Cleaning (Contamination caused by dirt or moisture),
- The importance of the cable (Cable quality and durability),
- Mechanical durability (Bending because of wind and vibration),
- Electrothermally caused PIM (Change of RF signals due to temperature variable)

Temperature changes, polluted air or environments exposed to excessive vibrations may increase the likelihood of PIM formation. However, although similar measurement methods as with design PIM can be utilized, the existence of assembly PIM can be considered an indicator of system performance decrease in terms of both performance and trustworthiness. If the problem is not resolved, the weaknesses that caused PIM to occur may cause more serious problems in the transmission path. In such cases, users do not want to cancel the PIM, but they want to be informed about the errors in order to fix the main problem. To solve the errors received, it must first be determined where the PIM occurs. The specified element is then repaired or completely replaced.

The approach of using PIM cancellation for assembly PIM might be considered as masking an issue, rather than resolving it. Design PIM can be thought of as measurable and stable. However, assembly PIM, on the contrary, is unstable. It might only exist in a very limited range of circumstances, and its amplitude fluctuation can exceed 100 dB. Such cases might escape detection in a single offline scan; ideally, the transmission line diagnostic should be recorded concurrently with the PIM occurrence. [11].

➢ *PIM Exceeding Antenna Coverage (Rusty Bolt PIM)*

PIM can happen anywhere outside of the antenna and is not just restricted to the wired transmission line. Among these, the rusty bolt PIM is the most well-known case. In this scenario, intermodulation is reflected back to the receiver through passive intermodulation, which takes place after the signals exit the transmitting antenna. The fact that a rusty metallic object may be the intermodulation source in many circumstances is the origins of the phrase "rusty bolt" [1, 11].

It is normal for metal things to reflect light. In these cases, however, the metal objects generate and emit intermodulation artifacts in addition to reflecting the received signals. At the intersection of two distinct metals or incompatible material combinations, intermodulation happens exactly as it did in the wired signal channel. Surface currents are generated by the electromagnetic waves, which combine and radiate again (Figure 4). Usually, the reradiated pulses have extremely little amplitude. Receiver will deaden, nevertheless, if the emtting element — a rusty barrier, shelter, or downpipe — is near a base station' s receiver and its intermodulation output goes out of the receiving band.

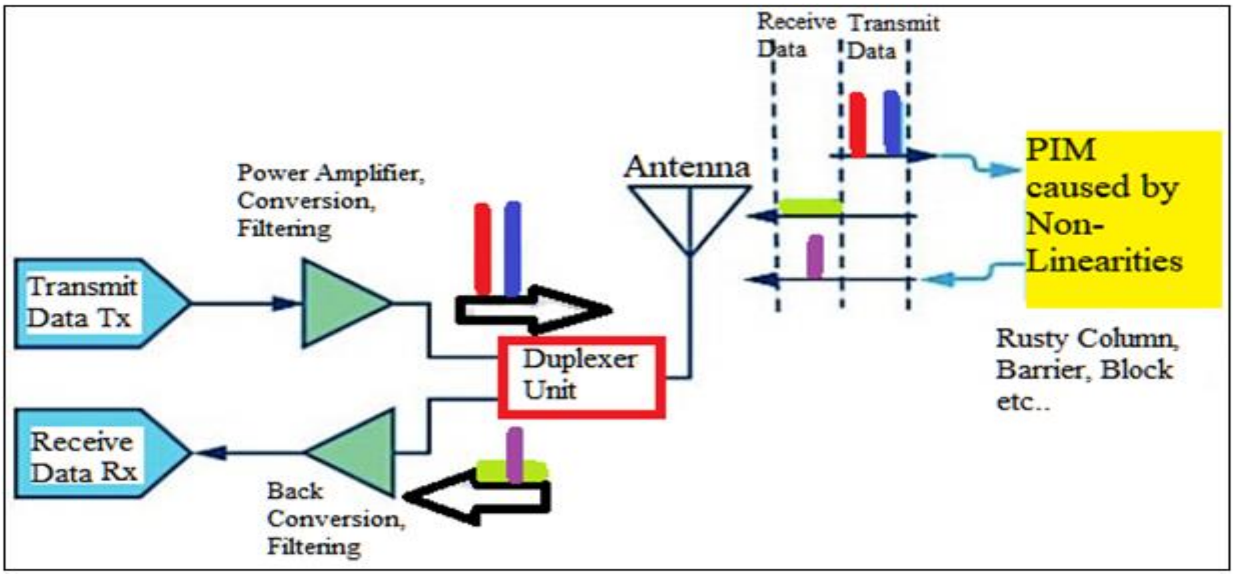

Fig 4 PIM of Rusty Bolt Effect

Antenna positioning may be used in certain situations to detect the PIM source; PIM level is tracked while antenna position is adjusted. Guessing delay of time can also be utilized to identify the source in other situations. Standard algorithmic cancellation approaches can be applied to correct for the PIM if PIM levels remain constant. But in many cases, mechanical movement, wind, and vibration can alter the PIM contribution and increase the difficulty of the cancelation issue [1, 11].

IV. GUİDELİNES FOR PIM AVOİDANCE AND ELİMİNATİON

➢ *Steps for Minimising of PIM Generation:*

Following the identification of passive nonlinearity types and causes, several actions can be implemented to reduce PIM formation in communication systems [1, 11].

- Nonlinear materials in or close to the existing routes should not be utilized. Should their presence be necessary, they ought to be covered with linear materials.
- Size of the metal contact regions should be increased or larger conductors should be used to retain the existing quantities in the conduction channels low.
- Number of metallic contacts, particularly spinning joints and loose connectors should be reduced. Insulators or alternate current pathways at the connections or joints should be provided if avoiding them is not an option.
- Amount of time that sharp edges, rough surfaces, and loose connections are exposed to radiation should be reduced.
- Temperature fluctuations should be reduced as much as possible because metals and other materials' expansion and contraction can result in nonlinear connections.
- If at all possible, bonded joints should be employed; nevertheless, it should be ensured that these points are sound and free of nonlinear materials, fractures, contaminants, or corrosion.
- Moving parts and tuning screws should be kept out of the current routes. All of the joints and contacts should be tight and clean, and any vibrations should be avoided.
- Generally speaking, cable length should be kept to a minimum, and using high-quality, low PIM cables is crucial.
- Amount of nonlinear components used, such as circulators, isolators, lumped dummy loads, and some semiconductor devices should be reduced.
- By filtering and physically separating the high-level transmit signals from the low-power receive signals, good isolation should be established.
- Higher-order products should be considered when planning frequencies since they may cause interference in some communication systems.

Apart from the aforementioned broad requirements, meticulous planning, excellent craftsmanship, strict control of quality, and a good care level are equitably crucial. But remember that none of the communication systems is 100% impervious to PIM, even though paying close observation to details during the design and construction phases can significantly decrease its level.

➢ *Elimination of PIM:*

There is a temporal delay to consider because PIM sources might occur at different locations and the Tx signals' traveled path varies in length. Time delay estimation techniques are used to estimate this delay.

Low PIM components are necessary in the high-risk PIM zone near antennas due to the ongoing deployment of new frequency bands, competing carrier signals, and the resulting PIM interference. Brackets and mounts are just two of the thousands of crucial parts that make up the framework of a typical cell site. These accessories are by nature vulnerable to PIM generation due to corrosion, improper connection designs, and improper installation techniques, all of which lower network performance and produce RF interference [1, 12].

In order to address the prevention of intermodulation products, it is useful to present a more detailed picture of a representative transceiver which is given in Figure 5. Because it also focuses on the base station side, this example transceiver may have many nonlinear connectors connecting its various modules. It employs the Frequency Division Duplex (FDD) carrier aggregation (CA) technology. Connectors between modules would not exist in User Equipment (UE), particularly if the UE is a mobile device. Moreover, PIM can also originate from metal connections found in a base station' s antenna structure [12].

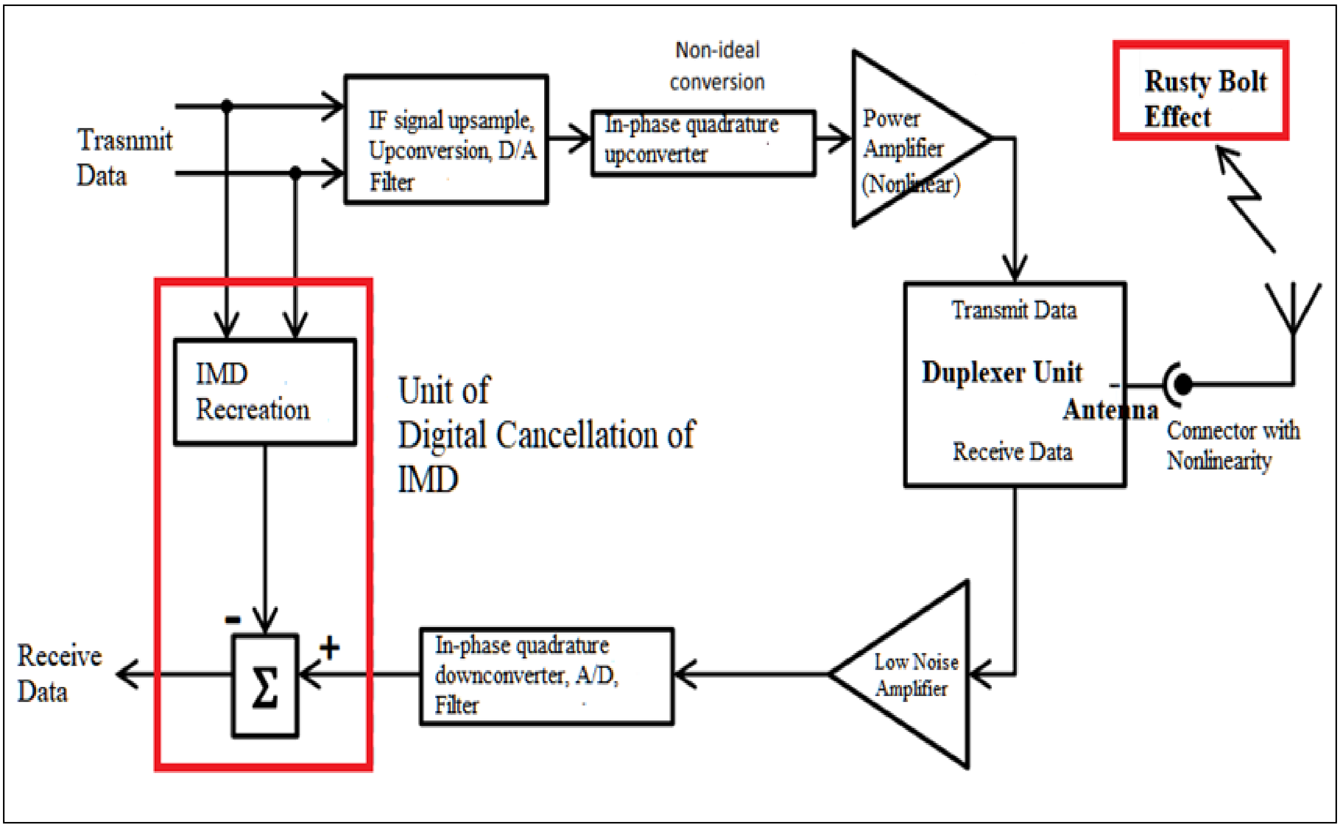

Fig 5 An Example Picture of a CA Transceiver that shows a few IM Origins Both İnside the Transceiver System and Exterior to it in the Neighboring Corroded object

As the transceiver in Figure 5 stands for for LTE CA technology, there are two TX data signals. There exist other implementation options for a CA transceiver, and this example merely represents one of them. Upsampling, digital to analog (D/A) conversion, and intermediate frequency (IF) conversion are carried out independently for each of the two TX signals in this system. Subsequently, the data signals are mixed and an I/Q modulator is used to perform in-phase quadrature (I/Q) up-conversion.

Lastly, the amplified modulated signals are fed into the TX port of the duplexer. Additional ways to modulate TX signals include combining the signals at the start of the TX sequence or in the end of the TX sequence before the duplexer [12, 13]. It would be sensible to employ an application where both component carriers (CCs) have completely different TX sequencies if they are at different E-UTRA bands, or inter-band LTE CA [14]. The easist solution —one TX sequence— might be a fine option for contiguous intra-band LTE CA because it uses the least amount of power and has the smallest chip size [14]. On the other hand, as it is less expensive and complex to implement than using distinct PAs, the example in Figure 5 may be the most suitable option for non-adjacent intra-band LTE CA [14]. Despite this, the wider bandwidth in the above method requires the power amplifier (PA) to be as linear as feasible in order to prevent high-power instant messaging products.

An analog to digital (A/D) converter, an I/Q down-conversion device, and an Low-Noise Amplifier (LNA) make up the transceiver's recevie (RX) chain. The received RX signal is amplified by the LNA before being demodulated and converted back to digital form. Figure 5 also shows a duplexer and a digital canceling device.

There are two categories of PIM cancellation approaches: analog and digital cancellation techniques [15]. Because obtaining an ideal prevention in the analog domain is difficult and expensive, PIM cancellation in the digital domain is interesting. When PIM is applied in the digital domain, the induced PIM interference in the receive band is approximated and subtracted from the Rx signal. Instead of operating in the domain of frequency, PIM is usually executed in the in the domain of time [15].

➢ *Traditional Methods for PIM Elimination*

Memoryless polynomials are used to simulate the introduced PIM in the Rx signals in one line of current PIM cancellation techniques [15]. This strategy will be referred to as the traditional way. This traditional method could be divided into three phases [15]:

- Creation of a foundation vector $Y(t) = [Y_0(t)\ Y_1(t)\ ...\ Y_n(t)]^T$
  Here, each $Y_i(t)$ at instant t is a collection of T_x signals.

- Fitting of each foundation $Y_i(t)$ vector with a weight w_i using an appropriate argument learning scheme, such as least mean square. Now, the PIM in a receive channel at instant t might be represented by the equation

$$z(t) = w^H Y(t).$$

- In certain situations, switching the reference frame from the transmit band to the receive band is necessary. This is accomplished using a frequency shift function f_c. An exponential term, $z(t) = w^H Y(t) e^{2\pi fct+\theta}{}_0$, could be used to simulate this frequency shift in the time domain. Here, θ_0 represents the phase at t = 0. As every PIM source will result in distinct intermodulations, every model must be tailored to each unique environment using PIM origins.

- *PIM Elimination using Neural Networks (NN):*

Neural networks have proven to be effective in solving the closely related self-interference cancellation problem [15, 16, 17]. Considering that simulation and PIM chamber measurement data is available, PIM cancellation using NN could be conceptualized as a problem of supervised time series fitting. Promising results have been observed in the first trials conducted by Ericsson to simulate the resulting PIM in the Rx channels. Comparing the traditional strategy to utilizing NNs for PIM cancellation, the NN approach outperforms the traditional approach in the scenarios handled by Ericsson. Figure 6 shows a frequency domain comparison of the NN approach applied to a signal including PIM and the old method [15]. In this case, the blue curve represents the PIM prediction generated by the NN technique, the cyan arc represents the PIM forecast obtained by the old approach, and the red arc represents the Rx signal with PIM interference. In this instance, just the outcome ranging from frequency -25 MHz to 25 MHz is significant. The old method is far more unstable compared to the NN technique, which estimates the PIM extremely well (the blue arc nearly perfectly includes the red arc). The receive signal Rx after noise mitigation based on the NN technique is represented by the green curve, and the receive signal Rx after noise mitigation based on the traditional strategy is represented by the pink arc.

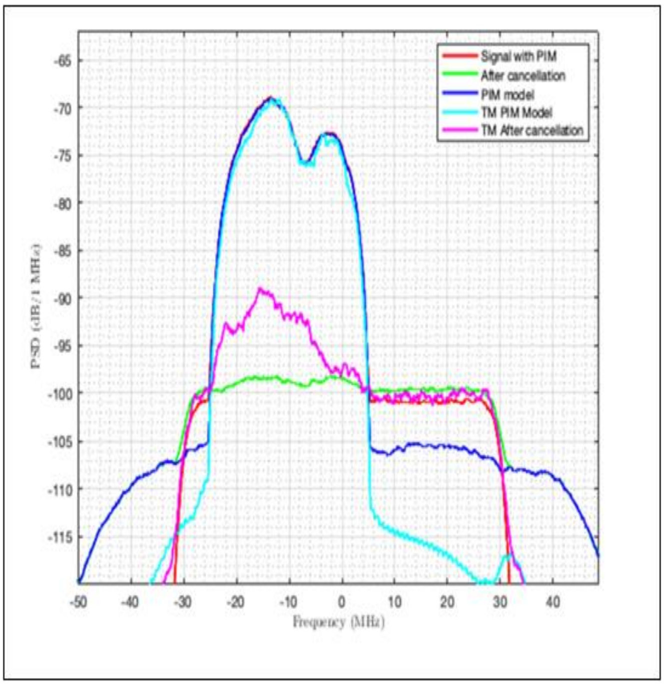

Fig 6 An Example of a Basic PIM case using the Conventional and NN Technique for PIM Cancellation, Represented in the Frequency Domain

- *Digital Elimination of PIM:*

The fundamental principle of digital elimination is to generate replicas of IM products in order to foresee them and remove them from the Rx chain [2]. PIM products formed after the Tx filter can also be cancelled because the cancellation occurs in the Rx chain after the duplexer. The primary problem with digital elimination is that the magnitudes, phases, and delays of IM products depend on the duplexer, PA, and other components that are being used. Moreover, the phases and amplitudes of these IM products change with time and are not constants. To renew IM components, the digital canceller must model various transceiver components. This can be accomplished by knowing the sent data and its frequency, but estimating the remaining regeneration coefficients [12, 15]. Different modeling approaches are used, and the regeneration coefficients required vary depending on the cancellation unit that is used. Understanding how the supplied TX signal is viewed in the RX chain is necessary for the estimation. To do this, samples from the received signal can be taken, processed, and utilized as feedback for the estimation. Ultimately, to shrink the real IM components in the receive band Rx, the inverse of the recreated IM signal might be added to the receive signal [12].

Higher order IM product estimation is also included in the simulation of interference at a specific IM product frequency band [12]. Since a particular IM band also includes higher odd order IM components, higher order IM product estimate enhances digital cancellation. Digital elimination for the third order IM band, for instance, must therefore estimate the fifth, seventh, and perhaps even higher odd order products. Theoretically, greater estimation of odd order IM products leads to greater interference reduction. However, the potency of an IM product reduces with increasing order quantity; as a result, the product's influence diminishes as the order number rises [12, 14].

When the transceiver is not in operation or does not receive any signals, the necessary parameter calculation for the digital cancelation can be completed [12]. The estimated coefficients from this kind of estimation, known as offline estimation, can be applied while the transceiver is in operation [12]. To obtain better interference cancellation, the IM products may fluctuate in time, hence estimate must be performed frequently when broadcasting. It is also possible that the transceiver needs to be used while the estimation is being done because the strength of the IM interference may increase. The HITE PAPER – Passive Inter-modulation; Causes, Avoidance and Mitigation Techniques® real Rx signal from another transmitter must be regarded as interference in this type of online estimation [12]. It is probable that both the targeted receive signal Rx and the IM product components have large powers, even though the IM products might not interfere with data transmission if the Rx signal is very strong.

In conclusion, IM products that are located at the transceiver' s own receive band can be reduced by using digital cancellation. Different transceiver components may produce different instant messaging products. Because of their high power, which the duplexer' s Tx filter is unable to fully attenuate, or because they are formed after the Tx filter in potential PIM origins, the IM products may find their way into the Rx sequence. Benefits of digital cancellation include the ability to reduce IM products produced after the TX filter and the elimination of the need for as much attenuation in the duplexer filters. High stop-band attenuation filters have greater placement loss and more complicated application, which results in lower power efficiency and higher duplexer costs [12].

V. CONCLUSİONS

When two or more high-power tones are sent over passive devices (cables, antenna, and the like), PIM occurs. When two or more high-power tones combine at nonlinearities in the device, like dissimilar metal junctions or metal-oxide junctions, like loose, corroded connectors, the PIM product is produced. Even if the system initially seems to be linear and incapable of producing intermodulation, the effect of the nonlinearities becomes more noticeable at higher signal amplitudes, and the intermodulation is more prominent.

PIM is a significant issue in today' s communication systems when a single antenna is utilized for both high power transmission and low power reception signals. While the transmit signal power is often many orders of magnitude larger, the passive intermodulation signal power is often on the same order of magnitude, if not higher, than the receive signal power. Consequently, passive intermodulation that enters the receive path is unfilterable and unisolable from the receive signal.

Two categories of mechanisms have been shown to be the primary cause of PIM, nonlinearity of material and nonlinearity of contact. Apart from these, substandard craftsmanship can result in loose connections, metal fissures, and oxidation at joints, all of which can lead to PIM. In actuality, it is possible that a combination of these elements results in PIM. This is one of the main reasons that makes it difficult to show the precise role played by any of these variables.

PIM can be categorized into three types as rusty bolt, assembly, and design PIMs, each with unique properties and needs different kinds of solutions. PIM may be a serious problem, particularly at base stations, hence it is critical to construct the transceiver system such that to prevent it. First and foremost, nonlinear substances such as carbon fiber or ferromagnetic materials should not be used in or close to transmission lines in any components. Connectors should be built for minimal PIM since they are a major source of PIM. However, it is not sufficient to design and use low PIM connectors and components in order to avoid PIM products. Base stations are subject to environmental factors, pollution, and corrosion. For this reason, it is critical that the base station be constructed and maintained correctly.

On the other hand, as PIM avoidance mechanisms are generally not enough, methods for PIM cancellation are necessary and important. Modern algorithms now offer clever methods for locating and detecting PIM and, when necessary, making adjustments for it.

Thanks to PIM cancellation algorithms, radio designers have more options now that they are not limited to selecting components that have to meet certain PIM performance standards. There are basically two categories of PIM cancellation approaches: analog and digital cancellation techniques [15]. Because obtaining a perfect cancellation in the analog domain is difficult and expensive, PIM cancellation in the digital domain is interesting. Especially, neural networks have proven to be effective in solving the closely related self-interference cancellation problem [15, 16, 17]. Considering that simulation and PIM chamber measurement data is available, PIM elimination using NN could be conceptualized as a supervised time series fitting problem.

In conclusion, PIM detection and cancelation algorithms should provide radio designers with significant short-term benefits and advantages as base station installation issues continue to rise, but further development is needed to stay up with these challenges.

- *About Yupana*

Yupana is a highly dynamic and fast growing company founded in 2011 in the San Francisco Bay Area. Working closely with the wireless carriers tailored engineering services are developed and products are customized allowing customers to build the networks of tomorrow.

Yupana team of highly skilled technicians and engineering bring an unprecedented level of quality and expertise to all field activities, combined with passionate and ambitious team of UTRAN engineers and project managers, and software developers.

Yupana leverages many years of international experience managing projects and programs in Tier 1 MNOs, along with world class Engineering expertise.

REFERENCES

[1]. P. L. Lui, "Passive intermodulation interference in communication systems", Electron. Commun. Eng. J., vol. 2, no. 3, 1990.
[2]. J. Sanford, "Passive intermodulation considerations in antenna design", In: Proceedings of IEEE Antennas and Propagation Society International Symposium, Ann Arbor, MI, USA, Jun 28–Jul 2, 1993.
[3]. S. D. Mitchell, "An investigation into the passive intermodulation properties of space qualified materials. Doctor of Philosophy (PhD) thesis", University of Kent, doi: 10.22024/UniKent/01.02.85975, 1997.

[4]. S. A. Safavi-Naeini, and S. Boumaiza, "An Investigation on Passive Intermodulation Generated by Antenna Contact", https://api.semanticscholar.org/CorpusID:65084581, 2017.
[5]. A. Sedra, and K. Smith, "Microelectronic Circuits", 7th ed. Oxford: Oxford University Press.
[6]. A. Dayan ,Yi Huang, and A. Schuchinsky, "Passive Intermodulation at Contacts of Rough Conductors”, Electron. Mater., vol. 3, no. 1, https://doi.org/10.3390/electronicmat3010007, 2022.
[7]. P. Zhao, and T. Liang, "Carrier power dependence and avoidance methods of passive intermodulation product", Proceedings of the 2015 International Conference on Mechatronics, Electronic, Industrial and Control Engineering, doi: 10.2991/meic-15.2015.236 , 2015.
[8]. "Electromagnetic Radiation (a.k.a. Light). " [Online]. Available: http://abyss.uoregon.edu/~js/ast123/lectures/lec06.html.
[9]. S. Yan, C. F. Wang, J. Kotulski, and J. M. Jin, "Time-domain finite element analysis of ferromagnetic hysteresis in three dimensions, " in IEEE Antennas and Propagation Society, AP-S International Symposium (Digest), 2014.
[10]. N. Zhang, W. Cui, and T. Hu, "Passive Intermodulation Analysis for Mesh Antennas," in IEEE Antennas and Propagation Magazine, 4th Asia-Pacific Conference, 2015.
[11]. F. Kearney, and S. Chen, "Passive Intermodulation (PIM) Effects in Base Stations: Understanding the Challenges and Solutions", vol. 51, Mar. 2017.
[12]. J. Juhani, "Passive Intermodulation in High-Power Radio Transceivers", Apr. 2016.
[13]. 3GPP, "ETSI TR 136 912 V12.0.0 Technical Report, LTE; Feasibility study for Further Advancements for E-UTRA (LTE-Advanced), 3GPP TR 36.912 V12.0.0 Relese12," [Online]. Available:http://www.etsi.org/deliver/etsi_tr%5C136900_136999%5C136912%5C12.00.00 _60%5Ctr_136912v120000p.pdf, Sep. 2014.
[14]. C. S. Park, L. Sundsröm, A.Wallén and A. Khayrallah, "Carrier aggregation for LTE-advanced: design challenges of terminals", IEEE Communications Magazine, vol. 51, no. 12, pp. 76-84, December 2013.
[15]. F. Diffner, "Explaining Neural Networks used for PIM Cancellation", 2022.
[16]. A. Balatsoukas-Stimming, "Non-Linear Digital Self-Interference Cancellation for In-Band Full-Duplex Radios Using Neural Networks, " in IEEE 19th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC), doi: 10.1109/SPAWC.2018.8445987i, 2018.
[17]. A. T. Kristensen, A. Burg, and A. Balatsoukas-Stimming, "Advanced Machine Learning Techniques for Self-Interference Cancellation in FullDuplex Radios," in 53rd Asilomar Conference on Signals, Systems, and Computers, doi: 10.1109/IEEECONF44664.2019.9048900, 2019.