International Journal of Informatics, Information Systems and Computer Engineering

INJIISCOM

Testing and Analysis of PIM performance in a Passive DAS network - Experimental Approach

Muhammed Abudu Aniru and Emagbetere Joy Omoavowere

Department of Electrical/Electronic Engineering, University of Benin, Benin City, Nigeria
*Corresponding Email: abudu.muhammed@uniben.edu

A B S T R A C T S

Passive intermodulation (PIM) poses a significant challenge in telecommunication networks, with potentially severe impacts on network performance and signal integrity if not addressed during the initial deployment phase. This study investigates PIM levels within a passive distributed antenna system (DAS) network for cellular mobile radio communication across multiple floors of a building. The network comprises coaxial cables, connectors, splitters, combiners, and antennas structured in a systematic plan. This work used the experimental method to test for PIM in the network used for this investigation. Designed as a multicarrier system, it handles RF signals across frequencies of 700/850MHz, 1900MHz, 2100MHz, and 2600MHz. On-site PIM testing was conducted during the network deployment phase to analyze the behavior of high-power RF signals. Utilizing Kaelus iQA-1921C and iQA 850C series PIM analyzers, tests were conducted following known industry codes and standards. High RF power was preset to 43dBm for full band, 35dBm for high bands, and 25dBm for low band. The test equipment was calibrated on high PIM load and low PIM load. Test points were selected at both vertical and horizontal subsystem cabling structures, focusing on riser cables. The standard baseline performance PIM levels was set to -150dBc. The analysis focused on examining the characteristics of PIM signals captured via time-domain PIM traces, investigating the impact of altering the frequency of the two-tone signal

A R T I C L E I N F O

Article History:
Received 16 May 2024
Revised 10 Jun 2024
Accepted 24 Jun 2024
Available online 04 Aug 2024
Publication date 01 Jun 2025

Keywords:
Distributed Antenna,
Multicarrier;
Modulation,
Passive Intermodulation,
RF path System,
Telecommunication network

on the IM3 frequency component, and highlighting the importance of selecting an appropriate frequency for the two-tone signal that is not positioned near the edges. Results were based on pass or fail test, and resolution measures were taken to mitigate interference.

1. INTRODUCTION

Passive Intermodulation (PIM) has emerged as a significant challenge in modern communication networks, posing threats to signal integrity, network performance, and overall user experience. With the proliferation of wireless communication technologies and the increasing demand for seamless connectivity, the need to effectively mitigate PIM-induced issues has become paramount. In this context, Passive Distributed Antenna Systems (DAS) play a crucial role in enhancing coverage, capacity, and reliability in various indoor and outdoor environments (Yan et al., 2017).

The deployment of passive DAS networks presents unique challenges in managing and mitigating PIM, particularly due to the presence of numerous passive components such as cables, connectors, splitters, and antennas. These components, while essential for signal distribution and coverage extension, can inadvertently introduce non-linearities that give rise to PIM. Consequently, understanding the performance characteristics of PIM within passive DAS networks is essential for ensuring optimal network operation and mitigating potential interference issues.

This paper presents an in-depth exploration into the testing and analysis of PIM performance within a passive DAS network through an experimental approach. By leveraging advanced measurement techniques and methodologies, this study aims to elucidate the underlying factors influencing PIM generation, propagation, and mitigation strategies in passive DAS environments.

The primary objectives of this research are;

1. To investigate the impact of PIM on signal integrity and network performance within a passive DAS network.
2. To evaluate the efficacy of various PIM testing methodologies and analysis techniques in assessing PIM performance in passive DAS environments.
3. To identify potential sources of PIM generation and propagation within passive DAS networks and explore mitigation strategies to address these issues.

By addressing these objectives, this study seeks to advance the understanding of PIM phenomena in passive DAS networks and provide valuable insights into effective PIM mitigation strategies for network operators, equipment manufacturers, and telecommunications professionals.

The remainder of this paper is organized to provides a comprehensive review of relevant literature on PIM phenomena, passive DAS networks, and PIM testing methodologies, details of the experimental setup and methodology employed in this study, presents the results and analysis of PIM testing within the passive DAS network, discusses the implications of the findings and finally concluding remarks of this study.

2. LITERATURE REVIEW

Passive intermodulation (PIM) is a significant concern in communication systems, particularly in high-power RF environments such as cellular networks. It occurs when nonlinearities in passive components, such as connectors, cables, and antennas, generate unwanted intermodulation products at frequencies that interfere with the desired signals. This phenomenon can degrade signal quality, reduce network performance, and cause interference in wireless communication systems.

In a typical communication network, Passive Intermodulation (PIM) may also arise due to various factors such as equipment wear and tear over time, addition of new carriers in proximity, the integration of new carriers onto existing antenna infrastructure, occasional deterioration of insulation films between connector mating surfaces, and the presence of loose, dirty, or incorrectly compressed connectors and cables (Bent, 2018). These PIM sources can collectively or individually create impedance mismatches or voltage barriers along the path of RF transmission thereby causing PIM in cellular networks built on a DAS network (Anristu.com).

Passive Intermodulation (PIM) poses a significant threat to communication networks, necessitating early attention during the network deployment phase to mitigate its adverse effects. PIM often manifests as poor performance statistics in terms of throughput and signal to noise ratio within affected sectors, leading to interference that compromises cell receive sensitivity and has the potential to block calls as PIM bandwidth increases (Fargard, 2019). This interference adversely affects both originating and receiving networks nearby and can even result in sector shutdowns. Additional indications of PIM include shortened average call duration, elevated dropped call rates, reduced data rates, and diminished call volume (Meyer, 2020). If there are complaints of these sorts and the system is checked but no resolve, the common thing that should be investigated is if PIM exist in the system. An early indication of PIM can be observed in cells with dual receive paths, where an unequal noise floor between the paths suggests PIM generated within the noisy receive path, referred to as Receive Diversity Noise Floor Imbalance (Parr, 2017). Typically, the path shared with the transmitter is prone to noise due to sufficient power, often necessitating the addition of nonlinear devices or junctions. In this case, elevated noise floors on both receive paths may result from external factors such as rusty bolts or interference from external sources, necessitating thorough site analysis (IEEE, 2021).

According to Morris, 2015, the impact of PIM on cellular network performance is often worse during dry seasons with certain cell sites experiencing poor performance that significantly improves during rainy seasons, likely due to rusty mounts in the vicinity. Additionally, sites with recurrent performance issues during peak traffic periods may indicate PIM, even without visible physical faults in the network. In such cases, the fault may not become apparent until the sector handles a specific volume of traffic, even after resetting or calibrating the sector (Fargard, 2019).

Studies have investigated the root causes of PIM, including material properties, manufacturing processes, and environmental factors. Research conducted by (Liu et al., 2019) explored the impact of surface roughness and contact pressure on PIM generation in coaxial connectors. They found that high-contact pressure and smooth contact surfaces can reduce PIM levels significantly. (Lin et al., 2020) investigated the relationship between PIM levels and network performance metrics such as signal-to-noise ratio (SNR) and bit error rate (BER). Their findings demonstrated that higher PIM levels correlate with degraded system performance, highlighting the importance of PIM mitigation strategies.

Passive DAS networks play a crucial role in extending wireless coverage and capacity in large indoor and outdoor environments. These systems distribute RF signals from a centralized base station to remote antennas via passive components such as cables, splitters, and combiners. While passive DAS architectures offer cost-effective solutions for enhancing wireless coverage, they are susceptible to PIM issues. Research on passive DAS networks has focused on optimizing system design, minimizing signal loss, and mitigating PIM interference. Studies by (Sharma et al., 2018; Wang et al., 2021) proposed novel DAS architectures and antenna configurations to improve signal distribution efficiency and reduce PIM susceptibility. Additionally, advancements in passive DAS technologies, such as the integration of fiber-optic systems and digital signal processing, have been explored to enhance performance and flexibility. Research conducted by (Zhang et al., 2019) investigated the use of distributed fiber-optic DAS for high-capacity and low-latency wireless communication applications.

Accurate and reliable PIM testing methodologies are essential for identifying and mitigating PIM issues in communication systems. Various testing techniques and instruments have been developed to assess PIM performance in passive components and networks. Two-tone testing is the most common method used to measure PIM levels, where two high-power tones are simultaneously transmitted through the system, and the resulting intermodulation products are analyzed. Advanced testing equipment, such as vector network analyzers (VNAs) and PIM analyzers, provide precise measurements and diagnostic capabilities for PIM characterization. Moreover, time-domain analysis and sweep testing techniques offer insights into the temporal and spectral behavior of PIM signals, enabling thorough assessment of system performance and identification of PIM sources. Real-time monitoring solutions have also been developed to continuously monitor PIM levels in operational networks and facilitate proactive maintenance and troubleshooting. Recent research has focused on enhancing PIM testing methodologies through automation, integration with network management systems, and advancements in signal processing algorithms. For instance, studies by (Lee et al., 2020; Smith et al., 2021) proposed automated PIM testing frameworks using machine learning algorithms for predictive analysis and anomaly detection in communication networks. While automation and ML methods have their merits in certain applications, the complexity and variability of real-world environments make on-site field measurements indispensable for comprehensive PIM testing and analysis (Rappaport et al., 2017; Wang et al., 2019; Kroh, 2019; Singh et al., 2020; Lin et al., 2018; Kuo et al., 2019).

In a communication network, RF signal is carried along a given transmission medium. This signal could be in form of voltage and current, electromagnetic propagating wave etc. The relationship between current and voltage or between electric and magnetic component of a wave are usually linear. However, when a non-linear relationship exists between these signal components of a propagating wave, harmonic frequencies, and linear integral combinations of these frequencies are generated (3GPP, 2012; Kuale & Emagbetere, 2017). PIM is caused by the nonlinear behavior of passive components when subjected to high-power RF signals, typically from multiple carriers present in a communication system or an RF path (Sharma et al., 2019). The inter-modulated products result in multiple frequencies of higher product orders, 3rd, 5th, 7th, are as shown in Fig 1. In PIM testing, odd order harmonics are particularly considered for signal analysis since nonlinearities in system components, such as connectors, cables, and amplifiers, often exhibit symmetrical behavior and produce odd-order harmonics in the output signal (Baxter et al., 2012). This is so because even-order harmonics, such as second-order harmonics, can sometimes cancel out due to phase cancellation effects in a system but this is not the case with odd-order harmonics which can more likely lead to more significant intermodulation distortion and higher PIM levels (Baxter et al., 2012).

As a result of broader spectrum of newly generated frequencies, higher-order products may include the operating frequency band of the received signal, leading to interference and consequent degradation of the system's overall performance, as shown in Fig 2. The third-order product poses a greater problem to the system compared to the higher-order products because of its amplitude and high potential to spread within the receive band. Conversely, while the higher-order products elevate the adjacent noise floor, their impact is comparatively less severe (Baxter et al., 2012; Anristu.com).

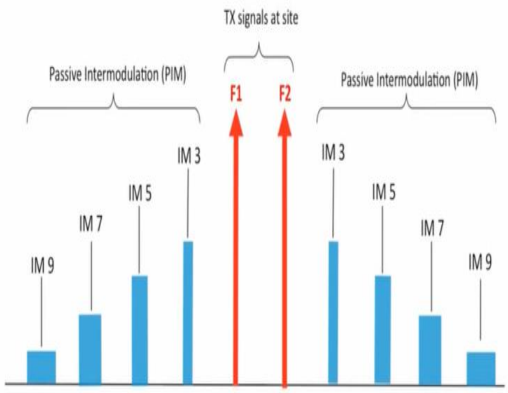

Fig. 1. Carriers F1 and F2 with 3rd through 7th order products (3GP, 2012).

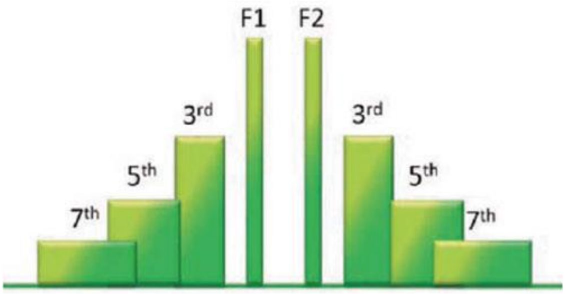

Fig. 2. PIM bandwidth increases with the order of the product (Anristu.com).

Where F1 and F2 are carrier frequencies.

In high-rise buildings deploying Distributed Antenna Systems (DAS) such as the environment considered for this investigation, Passive Intermodulation (PIM) presents a critical challenge. The investigation outlined here focuses on a network architecture tailored for a multicarrier system carrying bands 2, 4, 5, and 7. These carriers operate within frequency bands known to be susceptible to PIM generation (Zhang et al., 2018). Given the prevalence of PIM-induced performance degradation in such environments, a thorough investigation into PIM within the network becomes imperative to ensure a stable, optimal network performance and reliability.

3. METHOD

This work was conducted in a 25-floor high-rise building, where Radio Access units and antennas were strategically installed on each floor to optimize coverage and mitigate signal attenuation according to design specifications. The specific details of the network design are not discussed in this paper. Fronthaul connections utilized coaxial cables, with antennas distributed across each floor and network couplers, such as splitters and combiners, employed as needed. The cabling infrastructure followed a vertical structure for risers and a horizontal layout for cabling within each floor of the building. PIM testing was performed at various points, including each riser cable point and selected locations on each floor, to assess the performance and stability of the DAS network against predefined criteria. At points where a test failed, subsequent adjustments, maintenance, or component replacements were executed based on the outcomes of each test and retested until acceptable PIM power level is achieved. PIM testing indeed offers a more targeted approach to identifying and mitigating interference issues caused by nonlinearities within the system components.

This paper describes an on-site Passive Intermodulation (PIM) test conducted during the installation phase of a multicarrier picocell site to assess linearity, signal integrity and construction quality. Tests were performed across various carrier bands using Kaelus PIM analyzers, the iQA-850C and iQA 1921C series, to evaluate the network response to high-power RF signals. A two-tone test signal, with power levels of 2 x 43dBm for bands 4 and 7, 2 x 35 dBm for band 2, and 2 x 25dBm for band 5, was utilized as the input signal. The frequency for each tone, designated as F1 and F2, were selected and preset for each test based on the respective frequency bands. Calibration of the iQA tool was performed on both high and low PIM loads to ensure accuracy, establish baseline reference points, maintain quality control, and optimize performance for PIM testing. The selection of F1 and F2 values considered factors such as maximum RF bandwidth, duplex gap size, and band size as specified by the 3GPP TS37.808 standard, to ensure precise and meaningful PIM measurements.

This approach ensured that the chosen test frequencies fell within the maximum RF bandwidth of the system to prevent interference with adjacent channels or bands. Furthermore, the selected frequencies were within the operator's licensed spectrum and designed to generate the designated IM3 product without interfering with the receive band of the system. The DAS network utilized in this project is a multicarrier system designed to transmit and receive on bands 2, 4, 5, and 7, with paired bands selected according to the 3GPP TS 37.808 standard (see Table 1).

Table 1. Paired bands in E-UTRA, UTRA and GSM/EDGE [21]

E-UTRA Band number	Band designation (MHz)	Uplink (UL) BS receive - UE transmit			Downlink (DL) BS transmit - UE receive			Maximum RFBW without IM3 in own Rx (MHz)	Duplex gap size in relation to band size
2	1900	1850 MHz	–	1910 MHz	1930 MHz	–	1990 MHz	40	small
4	2100	1710 MHz	–	1755 MHz	2110 MHz	–	2155 MHz		large
5	850	824 MHz	–	849 MHz	869 MHz	–	894MHz	22.5	small
7	2600	2500 MHz	–	2570 MHz	2620 MHz	–	2690 MHz	60	small

After calibrating the iQA and ensuring the correct configuration of signal parameters, the test cable was connected to one end of the link under examination, while the other end was terminated with a low PIM load. A total of 50 test points were selected, with two points identified on each floor for PIM analysis.

The research methodology employed time-trace PIM analysis on the test equipment to gain valuable insights into signal behavior, offering a comprehensive characterization of the PIM signal. Adopting a dynamic approach to PIM testing, a stress test methodology was applied during each test cycle. A stable signal characteristic of ≥ -150dBc PIM power level observed throughout each test period indicated a successful test outcome, while any deviation led to test failure. This procedure was repeated at each designated test point, with measurements of both reflected power level and PIM signals recorded to assess system performance. Additionally, IM3 and higher product orders were obtained for each set frequencies, as shown in Table 2, to ascertain the signal bandwidth resulting from the emergence of new frequencies and their alignment with the receive band. The influence of band size on F1 and F2 two-tone signals selection was also considered, with appropriate values selected to avoid PIM near the spectral band edges, and observations were documented as presented in Table 3. Throughout the report, PIM signals were measured in decibels relative to the carrier (dBc).

4. RESULTS AND DISCUSSION

This paper presents selected results for clarity. The time-domain and frequency-domain PIM analysis obtained in this study are depicted in Figs 3-5 and Fig 6-7 respectively. The time-domain trace illustrates the relationship between PIM level and time. A baseline of -150dBc is recommended as the acceptable threshold for PIM levels (International Telecommunication Union, 2019; European Telecommunicataions Standards Institute, 2018), applicable to LTE, PCS, and AWS systems. In Figs 3-5, seen on the analyzer, PIM levels below -150dBc are deemed acceptable, constituting a passing result. Conversely, any PIM levels surpassing -150dBc are classified as failures. For instance, PIM level of -174dBc is lower or weaker compared to -150dBc. The Fig 3 illustrates a test link with an acceptable PIM level with a PIM signal level of -174.4 dBc. In this test, there was stability in the system over time despite the high RF input signal applied. Figs 4 and 5 depict PIM levels of -126dBc, higher than the acceptable threshold hence a failed test. Although the trace Figs 6 and 7 remained stable for a brief period below -150dBc, applying a stress test revealed instability in the PIM signal after a period, resulting in a failed PIM test at -129dBc and -121dBc respectively.

Fig. 3. Time domain trace PIM signal level versus time Pass scenario @43dBm RF power for band 4

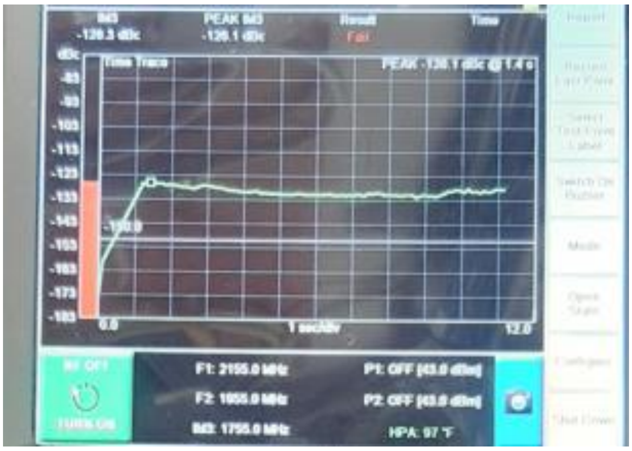

Fig. 4. Time- domain trace PIM signal level versus time – Fail scenario @43dBm RF power for band 4

Fig. 5. Time- domain trace PIM signal level versus time – Fail scenario @43dBm RF power for band 4

Fig. 6. Time- domain trace PIM signal level versus time – Stress test scenario @43dBm RF power for band 4

Fig. 7. Time- domain trace PIM signal level versus time – Fail scenario @43dBm RF power for band 4

Fig. 8. Frequency-domain trace PIM level for 1900MHz band - Pass scenario @35dBm RF power

Fig. 9. Frequency-domain trace PIM level for 850MHz band - Pass scenario @25dBm RF power

In addition to measuring the PIM power levels arising from the interaction of the two-tone signal, the frequency components of higher product orders were also documented and summarized in Table 2. This step was crucial for diagnosing potential PIM issues and evaluating signal integrity under high RF input power utilized. This helped to avoid frequency components spreading to other usable bands on the spectrum outside the originating source. By scrutinizing the performance of the link at these frequencies, it became possible to optimize the values of F1 and F2 in accordance with the standards set by the network operator and referencing the 3GPP, thereby mitigating the impact of the IM3 component and minimizing noise levels. Reference to Table 1 was instrumental in ensuring that the frequencies of the higher product-orders did not overlap on the receive band, thereby reducing interference and noise floor effects that could compromise service quality if left unaddressed. In

Table 2, frequency components marked with a '*' could cause a spreading effect that can degrade system performance quality particularly when this frequency component falls within the receive band. Analysing Table 2 suggests a higher likelihood of encountering PIM issues on bands 2, 5, and 7 compared to on band 4. Consequently, prioritizing PIM testing before deployment is advisable for networks utilizing these bands. Interestingly, no significant correlation was observed between bandwidth of F1 and F2 and the measured PIM levels during the assessment period, but this may not be the case in an actual network passing real-time traffic especially at peak hour Observing the harmonic components of the transmitted signal to minimize interference on the receive band was important. However, the choice of F1 and F2 is crucial to minimize the probability of IM3 component spreading to the band gap or possibly spreading on the received band which could have caused sensitivity degradation from IM3 products. Our findings shows that selecting F1 and F2 not too close the spectral edges of a band size, prevent PIM products from falling within the band gap. The results obtained from this approach are shown in Table 3. Analysis using data on Table 3, revealed that IM3 and higher-order product IM had minimal effects on the receive band as their frequency components predominantly fell outside the receive bandwidth. Thus, opting for an appropriate band size that avoids proximity to the spectral edges when choosing F1 and F2 frequencies in PIM testing serves to minimize edge effects, mitigate spurious signals, circumvent bandwidth limitations, and ensure compliance with standards. This meticulous approach leads to more precise and dependable PIM measurements, facilitating the effective evaluation and remediation of PIM issues in communication systems.

Table 2. Product order for F1 and F2

F1	F2	IM3-	IM3+	IM5-	IM5+	IM7-	IM7+
2155	1955	2355	1755*	2555	1555	2755	1355
1930	1990	1870	2050	1810	2110	1750	2170
869	891.5	846.5*	914	824	936.5	801.5	959
2110	2170	2050	2230	1990	2290	1930	2350
1930	1990	1870*	2050	1810	2110	1750	2170
1930	1970	1890*	2010	1850	2050	1810	2090
1930	1960	1900*	1990	1870	2020	1840	2050
1930	1950	1910*	1970	1890	1990	1870	2010
1930	1940	1920	1950	1910	1960	1900	1970
2110	2155	2065	2200	2020	2245	1975	2290
2110	2140	2080	2170	2050	2200	2020	2230
869	894	844*	919	819	944	794	969

869	889	849*	909	829	929	809	949
2620	2690	2550*	2760	2480	2830	2410	2900
2620	2660	2580*	2700	2540	2740	2500	2780

Table 3. Effect of choosing the appropriate band size

F1	F2	IM3-	IM3+	IM5-	IM5+	IM7-	IM7+
2640	2660	2620	2680	2600	2700	2580	2720
840	860	820	880	800	900	780	920
2115	2145	2085	2175	2055	2205	2025	2235
1940	1970	1910	2000	1880	2030	1850	2060

5. CONCLUSION

This study delved into testing and analyzing Passive Intermodulation (PIM) performance within a Passive Distributed Antenna System (DAS) network, employing an experimental approach. Our investigation underscored the critical importance of addressing PIM issues early in the deployment phase of communication networks. PIM can cause significant performance degradation and signal integrity compromises, ultimately impacting user experience and network reliability. In this work, the effectiveness of using time-domain PIM traces analysis in assessing the performance and stability of the DAS network was shown. By measuring PIM levels and observing harmonic components, we were able to identify potential sources of interference and evaluate signal integrity under varying conditions. This study also emphasized the significance of selecting appropriate test parameters, including frequency selection for the input signal, power levels, and band size considerations, to ensure accurate and meaningful PIM measurements. Adhering to industry standards and best practices in PIM testing was essential for mitigating interference issues and network performance.

This study provides a foundation for further research and practical implementations aimed at enhancing the reliability and performance of communication networks in real-world environments. By analyzing the time-trace PIM plots, engineers can identify specific PIM events, such as spikes or fluctuations in PIM levels, and correlate them with system conditions, or equipment changes. The higher-order products observed at specified input frequencies can also be detected to ascertain any indication of an expansion in PIM bandwidth. This helps pinpoint the root causes of PIM interference and facilitates troubleshooting and mitigation efforts.

REFERENCES

3GPP TR 37.808 V0.2.0 (2012-05), Technical report, release 11

Anristu, Kaelus Summitek document, Passive Intermodulation (PIM) Testing Guidelines, https://www.anritsu.com/en-us/test-measurement/technologies/pim.

Baxter, P., et al. (2012). Passive intermodulation: causes and effects in cellular networks. *IEEE Communications Magazine, 50*(5), 64-71.

Bent, J. (2018). "Understanding Passive Intermodulation." Artech House.

European Telecommunications Standards Institute. (2018). Electromagnetic compatibility and Radio spectrum Matters (ERM); Compatibility between Radio Frequency Fields and Electromagnetic Interference (EMI) in the range of 0 Hz to 300 GHz. ETSI EN 300 019.

Fargard, K. (2019). "Passive Intermodulation (PIM) in Communication Systems." Wiley.

IEEE. (2021). "IEEE Standard for Performance Test Methods for Installed Multichannel Wireless Transmitter and Receiver Antenna Systems." IEEE Std 1379-2021.

International Telecommunication Union. (2019). Passive Intermodulation in Base Stations. ITU-T Recommendation P.IM310-1.

Kroh, M. (2019). Passive Intermodulation (PIM) Testing. In *Wireless Connectivity* (pp.159-182). Springer, Cham.

Kuale P.A and Emagbetere J.O, (2007), Investigation of Harmonics in Power Generating Systems, *Advanced Materials Research 18-19*, 99-106.

Kuo, C. C. J., Naghshvar, M., Soltanalian, M., & Sayed, A. H. (2019). Learning to optimize: Training deep neural networks for interference management. *IEEE Signal Processing Magazine, 36*(6), 49-61.

Lee, S., et al. (2020). Automated Passive Intermodulation Testing Framework for Communication Networks. *IEEE Communications Magazine, 58*(9), 40-46.

Lin, X., Liu, L., & Yan, Z. (2018). Machine learning-based active interference mitigation in D2D communication. *IEEE Transactions on Vehicular Technology, 67*(1), 349-362.

Lin, Y., et al. (2020). Passive Intermodulation-Induced Degradation in MIMO Systems: Analysis and Mitigation. *IEEE Transactions on Wireless Communications, 19*(4), 2683-2697.

Liu, X., et al. (2019). Investigation of Contact Surface Roughness on Passive Intermodulation Generation in Coaxial Connectors. *IEEE Transactions on Microwave Theory and Techniques, 67*(7), 2867-2876.

Meyer, C. (2020). "Troubleshooting Passive Intermodulation (PIM) in Cellular Networks." Artech House.

Parr, R. (2017). "Advanced Cellular Network Planning and Optimization." Wiley.

Rappaport, T. S., Sun, S., Mayzus, R., Zhao, H., Azar, Y., Wang, K., ... & Thomas, R. (2017). Millimeter wave mobile communications for 5G cellular: *IEEE Access, 1*, 335-349.

Sharma, A., et al. (2018). Design and Optimization of Passive DAS for In-Building Wireless Communication. *IEEE Transactions on Antennas and Propagation, 66*(12), 7293-7304.

Sharma, S., Kumar, V., & Khanna, M. (2019). "Performance Analysis of Distributed Antenna Systems in High-Rise Buildings." *International Journal of Computer Applications, 975*(8887), 1-5.

Singh, R., Akhtar, F., Kumar, P., & Alazab, M. (2020). Machine learning in 5G networks: A comprehensive survey. *Computer Networks, 180*, 107395.

Smith, T., et al. (2021). Machine Learning-Based Anomaly Detection for Passive Intermodulation Testing in Cellular Networks. *IEEE Transactions on Vehicular Technology, 70*(4), 3907-3918.

Wang, C. X., Haider, F., Gao, X., You, X. H., Yang, Y., Yuan, D., ... & Hepsaydir, E. (2019). Cellular architecture and key technologies for 5G wireless communication networks. *IEEE Communications Magazine, 52*(2), 122-130.

Wang, J., et al. (2021). A Novel Passive Distributed Antenna System for Indoor Wireless Communications. *IEEE Access, 9*, 34189-34197.

Yan, M., Wu, Q., & He, Z. (2017). "A Review of Distributed Antenna Systems in High-Rise Buildings." *IEEE Access, 5*, 19351-19362.

Zhang, H., et al. (2019). High-Capacity and Low-Latency Wireless Communications Using Distributed Fiber-Optic DAS. *Journal of Lightwave Technology, 37*(5), 1191-1198.

Zhang, Z., et al (2018). "Analysis and suppression of passive intermodulation (PIM) in distributed antenna system." *Journal of Microwaves, Optoelectronics and Electromagnetic Applications, 17*(1), 150-163.