Impact Analysis of Induced FM Radio Interferences on Aeronautical Radio Navigation Systems: Case Study of Kotoka International Airport, Accra-Ghana

Amevi Acakpovi
Department of Electrical/Electronic Engineering
Accra Technical University
Accra, Ghana
Email: acakpovia@gmail.com

Isaiah Tefutor
Department of Graduate Studies
Open University Malaysia
Accra, Ghana
Email: istefutor@gmail.com

Kester Quist-Aphetsi
Department of Computer Sciences
Ghana Technology University College
Accra, Ghana
Email: kquist-aphetsi@gtuc.edu.gh

Nnamdi Nwulu
Department of Electrical Engineering
University of Johannesburg
Johannesburg, South Africa
Email: nnwulu@uj.ac.za

Robert Sowah
Department of Computer Engineering
University of Ghana
Accra, Ghana
Email: bobsowah@gmail.com

Ruhiya Abubakar
Department of Telecom Engineering
Ghana Technology University College
Accra, Ghana
Email: ruhi4win@yahoo.com

Abstract - **This paper investigates the effect of interference on Aeronautical Navigation systems by Frequency Modulation (FM) broadcasting signals. Precisely, the paper evaluated the impact of 3rd order intermodulation distortion on the VHF omnidirectional range and the instrument landing system (Localizer) used at the Ghana Civil Aviation Authority (GCAA). The necessity of this study stems from the fact that, electromagnetic compatibility (EMC) between FM audio broadcast and aeronautical radio communication services operating in the range of 85.7-108MHz and 108-117.975 MHz respectively is essential for safe flight operation. An analytical method of estimating the 3rd order intermodulation distortion has first been presented followed by simulation approach with the intermodulation analysis software v.10 and subsequent simulation with the Matlab software to determine and display the power spectral density of the output signals. All FM station frequencies in the Greater Accra region have been considered and paired to form dual tone signals that were considered input signal before assessing the impact of the 3rd order intermodulation harmonic. It was found that multiple 3rd order intermodulation harmonics distort and perturbate the aeronautical communication system in the Greater Accra region and these lead to severe safety implications for the operation of the aeronautical navigation system. It was recommended that broadcasting stations should implement cavity filters to reduce the effect of 3rd order intermodulation harmonics; they should respect the specification prescribed to them by the NCA and operate within limits allocated to them in order not to breach the international regulation of ITU that deems it an offense to interfere with the aeronautical communication system and to further ensure safety to the aviation navigation system.**

Index Terms - Intermodulation, interference, filter, FM broadcasting, EMC, VHF Omni directional Range, Localiser ILS

I. Introduction

Communication, Navigation and Surveillance (CNS) are indispensable for safe operation of flight. Transportation in the air has witnessed a significant increase recently and this is partly due to the increase confidence and reliability of CNS. The international Air Transport Association (IATA) estimated the total number of air travelers in 2016 to be 3.8 billion, a figure that was predicted to increase to 7.2 billion in 2035. The estimated rise in number of passenger by 2035 is merely double that of 2016, proving the extensive increase rate of air travelers [1], [2]. Ghana in 2017 had about 26726 scheduled commercial airline departures. This was an increase of 10.2 % from 2016. Throughout the last five (5) years, departures have increased on average by 14.0 % [1].

CNS serves as means of communications and monitoring of flight activities in the air, especially at crucial points which are taking off and landing. Failure of CNS systems for the shortest possible time may lead to high probability of plane crash as the pilot will lack directions especially when landing. The reliability of CNS systems is therefore vital for safe operation of flight.

Furthermore, every flight, whether national or international, is supervised by an entity that manages the air traffic. Figure 1 presents the airspace internationally delegated to Ghana, being divided into various Flight Information Regions (FIRs). These FIRs are controlled by an Air Navigation Service Provider (ANSP), that is in charge of controlling and assisting the departure and arrival of aircrafts, and also maintaining a secure traffic throughout the airspace. Each of the ANSPs must comply with numerous quality standards, whether national or international

On a global scale, the International Civil Aviation Organization (ICAO) is responsible for assessing and supervising the required standards for the provision of air navigation services. These requirements comprise every area that is involved in this process and radio equipment and telecommunication regulations are not excluded. Ghana Civil Aviation Authority (GCAA) is the Ghana Air Navigation Service Provider (ANSP), being responsible for Accra Flight Information Region(FIR). GCAA is the mandated national body in charge of air transportation in Ghana. GCAA's

978-1-7281-0818-6/19/$31.00 ©2019 IEEE
DOI 10.1109/ICCMA.2019.00011

headquarters is located at the Kotoka International Airport in Accra. In addition to its national mandate, GCAA also takes care of air navigation services relating to the Accra Flight Information Region (FIR). The Accra FIR covers a very large airspace comprising of the Atlantic Ocean in the Gulf of Guinea, and three countries: Ghana, Benin and Togo.

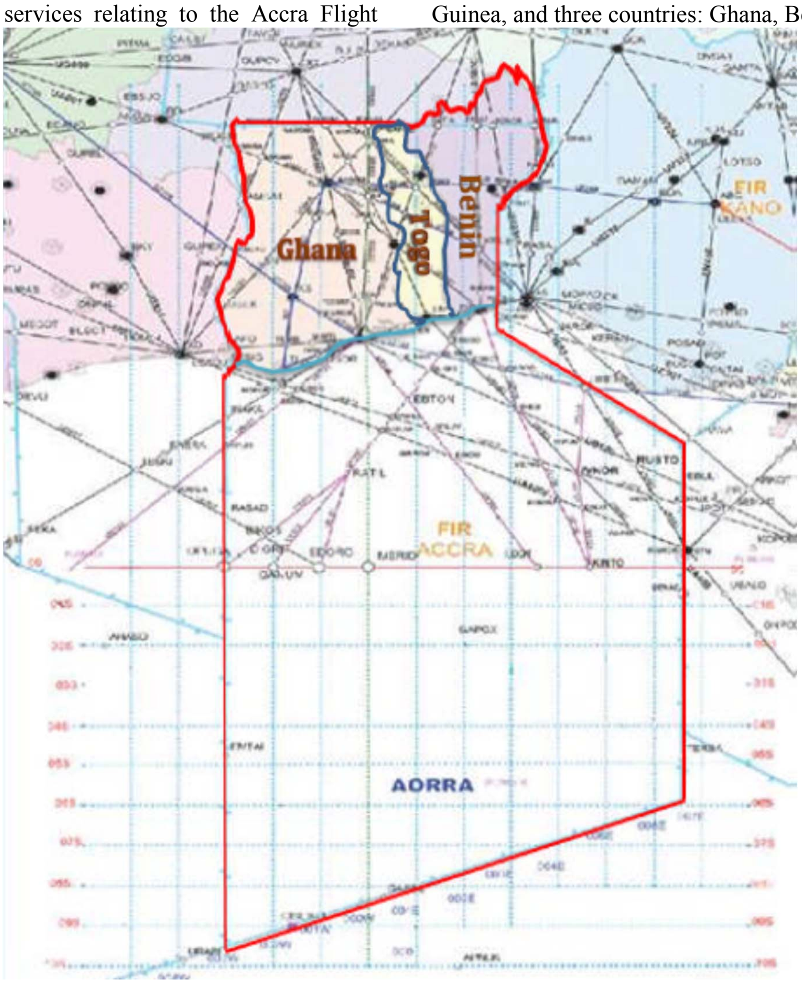


Figure 1. Ghana Civil Aviation Authority delegated airspace [5]

There are numerous systems that allow the pilot to check and control various parameters regarding the navigation of the aircraft. Some among them rely on the support of ground base systems. GCAA is responsible for maintaining these ground bases radio navigational aids, which assist the aircraft positioning throughout its defined route [5].

Two of the most significant guidance systems that pilots rely on are the Instrument Landing System (ILS) and the VHF Omnidirectional Range (VOR) and. The VOR (108 – 117.975 MHz) allows the aircraft to receive guidance relative to fixed ground locations during its flight, playing a significant part on the end-route radio navigation.

The VHF is a radio navigational system that propagates over relatively shorter distances in all directions and based on ground. VHF transmits two types of signal, one is insensitive to phase variation while the others varies according to phase variations. These two signals are received and well interpreted by the aircraft to provide reliable communications. VOR communication systems are universal.

The ILS localiser (108 – 111.975 MHz) assists the pilots during the approach and landing procedures, and for operations with low visibility. Both of these systems transmit signals in the VHF band, comprised within 108 MHz and 137 MHz.

The ILS on the other hand help to provide an accurate estimate of the position of the aircraft at a given time. It works in combination with a glide path to provide the timely location of the aircraft especially when approaching landing.

The constant increase of air trips implies the need to have precise systems that can supply uninterrupted flows of accurate information to aircrafts regarding their position and path. Failure of communication systems between ground navigation systems and flights may not necessarily come from the system's intrinsic parameters but may be due to interference from radio wave propagating in the same band of frequency with significant magnitude. Interference connotes a combination of two or more electromagnetic waves propagating at close frequencies that leads to misinformation especially with sensitive systems like flight communication systems.

Unfortunately, in Ghana, radio navigation systems are vulnerable to interference originated from FM broadcasting stations that are transmitting in a neighbouring frequency band. Ghana National Communication Authority (NCA) statistics report 471 radio stations operating in Ghana in 2017 [6]. FM broadcasting signals could be regarded as noisy, considering the overview of ILS, LOC and VOR, but since both aeronautical navigation systems use precise frequencies to provide critical guidance to aircrafts, it makes them prone to interference.

This paper investigates the impact of FM audio broadcasting stations on aeronautical radio Navigational aids, namely VOR and ILS. Various scenarios have been considered to quantify the severity of the interference and possible perturbations in the aeronautical radio navigation system.

The rest of the paper is structured as follow: section two presents the mathematical models of deriving the interference effect and a simulation approach to test different scenarios. This section is followed by the simulation result and analysis sections. Finally, section four presents the discussion and section VI, the conclusion.

II. Methodology

A number of literatures [2], [7]–[13] indicated that intermodulation interference is the major cause of interference on Navigational aids systems due to undesired signals originating from FM radio broadcast station. Specifically, there is likely occurrence of interference between FM broadcasted signals and ILS or VOR. This interference may have different level of disturbances leading to undesirable effects ranging from background audio to distorted reception between the ground station and air devices. These disturbances can also affect the integrity of the signals being exchanged and lead to miscommunication. The effects of these interferences are severe during landing phase and their negative impacts cannot be overemphasized. More details on the possible nuisance of negative effects of interferences on aeronautic and navigational systems can be found in [14].

The methodology is therefore concerned with the analytical modelling of the intermodulation distortion and the method of assessing interferences on the ILS and VOR systems using the Ghana Civil Aviation Authorities Air Navigation system as a case study

A. Modeling the Intermodulation Distortion

Intermodulation distortion consists of the amplitude modulation of a number of signals containing different frequencies, and it is mainly caused by nonlinearity in a system. In other terms, Intermodulation distortion is a multi-tone distortion product that results from the presence of multiple signals at the input of a non-linear device. The negative aspect of IMD is the creation of additional frequency components that are not harmonic frequencies and generally termed as spurious emissions.

The noisy signals generated as a consequence of the non-linearity of the device can be mathematically estimated based on the knowledge of the original signal using advanced mathematical series like Volterra series [15], [16] or Taylor series [16], [17].

Intermodulation is produced by non-linear systems capable of generating harmonics in response to sinusoidal input which explain the fact that from an input of a single frequency f_n components, the output contains a number of signals, frequency multiples of the input frequency signal ($f_n, 2f_n$, $3f_n$, ...). The Intermodulation phenomenon arises when the input to a non-linear system is made of more than two frequencies. To illustrate the intermodulation concept, let's consider an input signal made of three differently frequencies namely (f_n, f_m and f_p) which can be modelled as follow

$$I(t) = M_n\, sin(2\pi f_n + \theta_n) + M_m\, sin(2\pi f_m + \theta_m) + M_p\, sin\big(2\pi f_p + \theta_p\big) \quad (1)$$

Where M and n represent the amplitudes and phases of the various frequencies

The output function O(t) can be obtained after passing it through a non-linear function H as follow

$$O(t) = H\big(I(t)\big) \quad (2)$$

O(t) will contain the three fundamental frequencies (f_n, f_m and f_p) and in addition frequencies that are linear combinations of the fundamental frequencies in a summarized form below:

$$K_n f_n + K_m f_m + K_p f_p \quad (3)$$

Where K_n , K_m and K_p are arbitrary integers with possible negative or positive values. They are known as the intermodulation products (IMP)

In general, considering an input signal with a random number R of frequency components $f_n, f_m \dots f_r$, the output signal will contain in addition to the fundamentals, a number of frequencies defined below

$$K_n f_n + K_m f_m + \dots + K_r f_r \quad (4)$$

Where K_n, K_m and K_r are arbitrary integers.

Additionally, the order of intermodulation product is an important parameter to consider. It is defined as the sum of the absolute values of the coefficients as illustrated by the formula below

$$O = |K_n| + |K_m| + \cdots + |K_r| \quad (5)$$

Considering the input signal of three different frequencies (f_n, f_m and f_p), the third order modulation products occur where

$$|K_n| + |K_m| + \big|K_p\big| = 3. \quad (6)$$

In many radio and audio applications, and more specifically in the aeronautical navigation systems, only the 2nd and 3rd order Intermodulation products are considered owing to their proximity to the fundamental frequency and considerable magnitude. The graph below, illustrates a third order distribution intermodulation. Subsequently, for a two-tone input signal with fundamental frequencies F_1 and F_2, the considered intermodulation frequencies will be respectively $2f_1 - f_2$ and $2f_2 - f_1$.

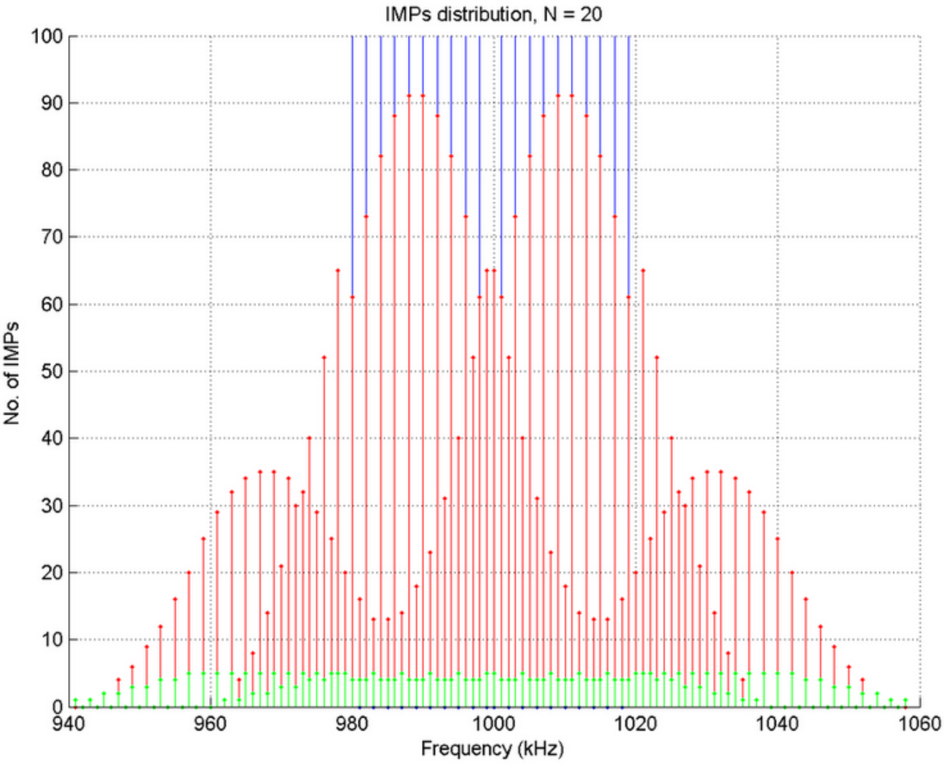


Figure 2. Distribution of third-order intermodulation: in blue the position of the fundamental carriers, in red the position of dominant IMPs, in green the position of specific IMPs.

The type of inference dealt with in this paper is not the direct type whereby two different systems propagate directly on the same frequency, rather the transmit frequencies for the aeronautical system and FM radio are different. However, the intermodulation of the FM radio waves due to the presence of non-linearity causes strange frequencies with significant magnitude that affect the aeronautical system, a type of interference known as type B1 interference.

B. Intermodulation Analysis Software v.10

Frequency Intermodulation Analysis software v.10 was used to facilitate the computation. It is interactive computer software, developed with a 3rd Order Frequency Intermodulation formula using Java programming language to carry out intermodulation computations in an efficient and less time-consuming manner. The software requires as input all transmitter frequencies (e.g. Frequencies of FM station) and the Upper and lower limits of the protected frequency band. The protected frequency is the band protected from interference and in this study concerned with the Localizer and VOR, the protected frequency range is 108 to 117.975MHz. The numbers of times a single FM frequency is involved in intermodulation products causing interference in the aeronautical band is termed as a **Hit**. The software is a handy l tool which aids the efficient practical troubleshooting process in identifying the offending FM radio stations in the case of any harmful interference on the Navigational Aids /Instrument Landing system.

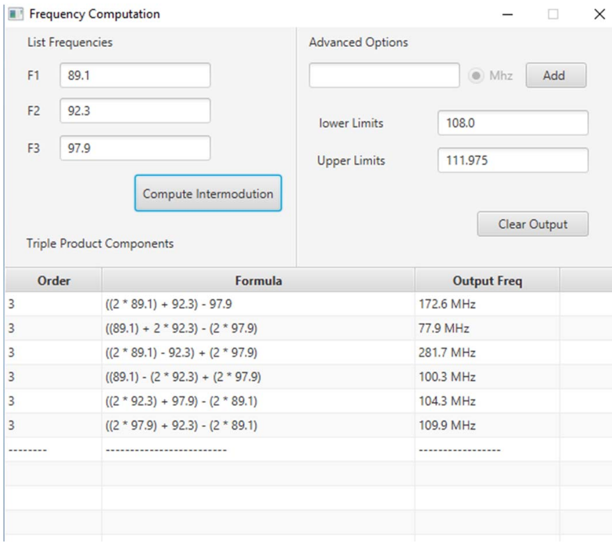


Figure 3. screen shot of Intermodulation Analysis Software v.10

C. Simulation of IMP with Matlab software

With the help of Matlab software, a two-tone sinusoid with preset frequencies can be created, sampled at a specific rate. The signal was made nonlinear by passing it through a polynomial function and adding noise using. The Third-order intercept point function (toi) can then be computed and the intermodulation products occurrence can be verified respectively at the frequencies at $2F_1 - F_2$ and $2F_2 - F_1$. The periodogram of the signal can also be obtained with Matlab using a Kaiser window. A complete program was developed in Matlab to perform the investigation of a double-tone signal with frequencies 98.9 KHz, 87.9 KHz, sampled at a rate of 96 KHz with 1000 samples. The resulting power spectral diagram, obtained using a Kaiser windows with ß= 38, are illustrated in Figure 5 and 6 respectively

D. Experimental Approach

This paper was concerned with the third order intercept of a dual tone input signal for which all the frequency of FM stations in Accra have been fed to the intermodulation analysis software. Results indicated the number of hits and the same assessment was reconducted in some few cases using Matlab software that led to the plotting of power density graphs.

IV. RESULTS

This section presents the results of the Intermodulation product assessments carried out using the Intermodulation software and the Matlab software to determine the possibilities of potential harmful interference affecting Air Navigation Services at Kotoka International Airport.

The summary of the overall results of the Intermodulation Assessment carried out in the Greater Accra is presented in the Table below. The list of FM station and their various frequencies is attached in Appendix A Scenario 1: This scenario considers the localizer for which the frequency was set to 109.9 MHZ. Additionally, the FM frequencies for the double tone signals are presented in Table 1

Table 1. Frequencies of the double tone signal used for the intermodulation test with respect to the Localizer

S/N	FM1	FM2
1	98.9	87.9
2	99.3	88.7
3	99.7	89.5
4	100.9	91.9
5	101.3	92.7
6	102.1	94.3
7	102.3	94.7
8	107.1	104.3

Table 2 below shows the summary of the simulation results indicating the number of intermodulation products and hits obtained

Table 2 Summary of the 3rd order intermodulation distortion assessment considering the localizer (109 MHz) used at Kotoka International Airport

Region	No of FM stations	Number of Computations (Inter-modulation products)	Number of Hits found in 108-117.975 MHz	Total intermodulation products (HITS)
		Two Signal ($2f_1$-f_2)	Two Signal ($2f_1$-f_2)	
Greater Accra	52	40	8	8

The second scenario is similar to the first one but was done with respect to the VOR system that operate at a frequency of 113.1 MHz. In this second scenario the frequencies considered for the double tone signal are listed in Table 3.

Table 3. Frequencies of the double tone signal used for the intermodulation test with respect to the VOR

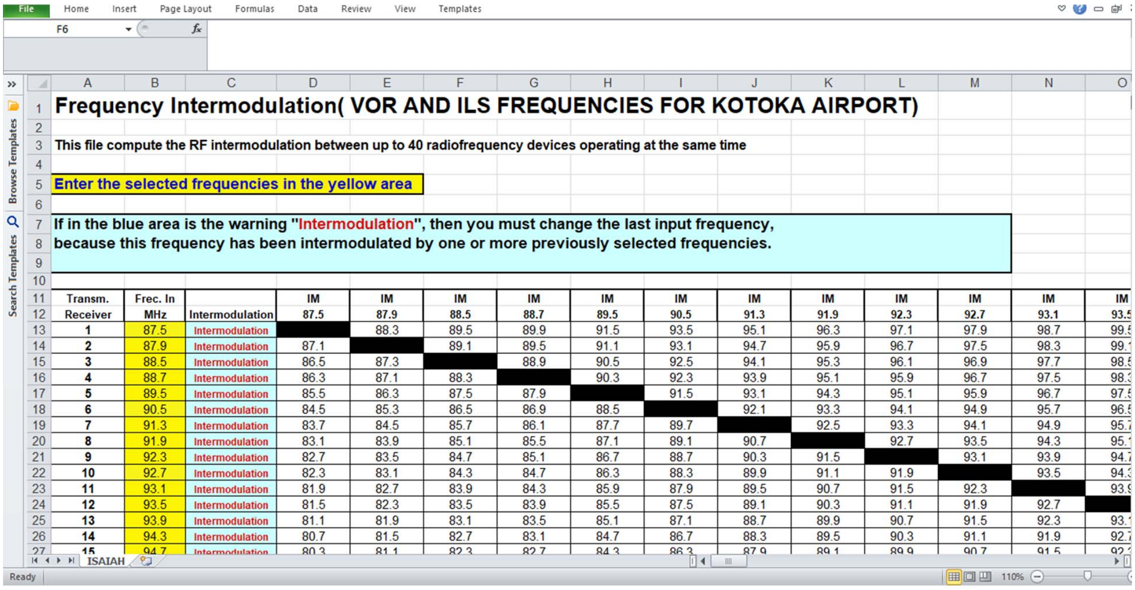
S/N	FM1	FM2
1	100.5	87.9
2	100.9	88.7
3	101.3	89.5
4	102.7	92.3
5	103.1	93.1
6	103.5	93.9
7	103.9	94.7

Table 4 below shows the summary of the simulation results indicating the number of intermodulation products and hits obtained, considering the VOR system.

Table 4 Summary of the 3rd order intermodulation distortion assessment considering the VOR (113.1 MHz) used at Kotoka International Airport

Region	No of FM stations	**Number of Computations (Intermodulation products)**	**Number of Hits found in 108-117.975 MHz**	Total intermodulation products (HITS)
		Two Signal ($2f_1$-f_2)	**Two Signal ($2f_1$-f_2)**	
Greater Accra	52	40	7	7

Additionally, some manual computation of 3rd order intermodulation product computations were done from greater Accra using a programmed sheet in Microsoft Excel as illustrated in Figure 4 below



Frequency Intermodulation(VOR AND ILS FREQUENCIES FOR KOTOKA AIRPORT)

This file compute the RF intermodulation between up to 40 radiofrequency devices operating at the same time

Enter the selected frequencies in the yellow area

If in the blue area is the warning "Intermodulation", then you must change the last input frequency,
because this frequency has been intermodulated by one or more previously selected frequencies.

Transm. Receiver	Frec. In MHz	Intermodulation	IM 87.5	IM 87.9	IM 88.5	IM 88.7	IM 89.5	IM 90.5	IM 91.3	IM 91.9	IM 92.3	IM 92.7	IM 93.1	IM 93.5
1	87.5	Intermodulation		88.3	89.5	89.9	91.5	93.5	95.1	96.3	97.1	97.9	98.7	99.5
2	87.9	Intermodulation	87.1		89.1	89.5	91.1	93.1	94.7	95.9	96.7	97.5	98.3	99.1
3	88.5	Intermodulation	86.5	87.3		88.9	90.5	92.5	94.1	95.3	96.1	96.9	97.7	98.5
4	88.7	Intermodulation	86.3	87.1	88.3		90.3	92.3	93.9	95.1	95.9	96.7	97.5	98.3
5	89.5	Intermodulation	85.5	86.3	87.5	87.9		91.5	93.1	94.3	95.1	95.9	96.7	97.5
6	90.5	Intermodulation	84.5	85.3	86.5	86.9	88.5		92.1	93.3	94.1	94.9	95.7	96.5
7	91.3	Intermodulation	83.7	84.5	85.7	86.1	87.7	89.7		92.5	93.3	94.1	94.9	95.7
8	91.9	Intermodulation	83.1	83.9	85.1	85.5	87.1	89.1	90.7		92.7	93.5	94.3	95.1
9	92.3	Intermodulation	82.7	83.5	84.7	85.1	86.7	88.7	90.3	91.5		93.1	93.9	94.7
10	92.7	Intermodulation	82.3	83.1	84.3	84.7	86.3	88.3	89.9	91.1	91.9		93.5	94.3
11	93.1	Intermodulation	81.9	82.7	83.9	84.3	85.9	87.9	89.5	90.7	91.5	92.3		93.9
12	93.5	Intermodulation	81.5	82.3	83.5	83.9	85.5	87.5	89.1	90.3	91.1	91.9	92.7	
13	93.9	Intermodulation	81.1	81.9	83.1	83.5	85.1	87.1	88.7	89.9	90.7	91.5	92.3	93.1
14	94.3	Intermodulation	80.7	81.5	82.7	83.1	84.7	86.7	88.3	89.5	90.3	91.1	91.9	92.7
15	94.7	Intermodulation	80.3	81.1	82.3	82.7	84.3	86.3	87.9	89.1	89.9	90.7	91.5	[illegible]

Figure 4. RF Intermodulation result for 40 radiofrequency devices operating simultaneously

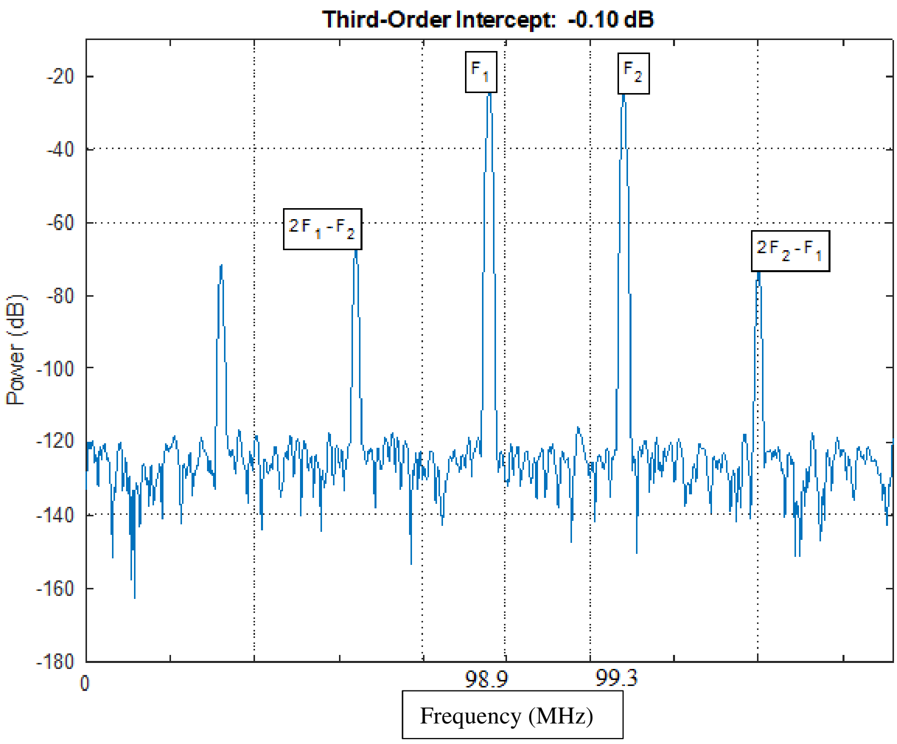


Figure 5. Spectrum showing 3rd order harmonic intermodulation products for 98.9 MHz and 99.3 MHz

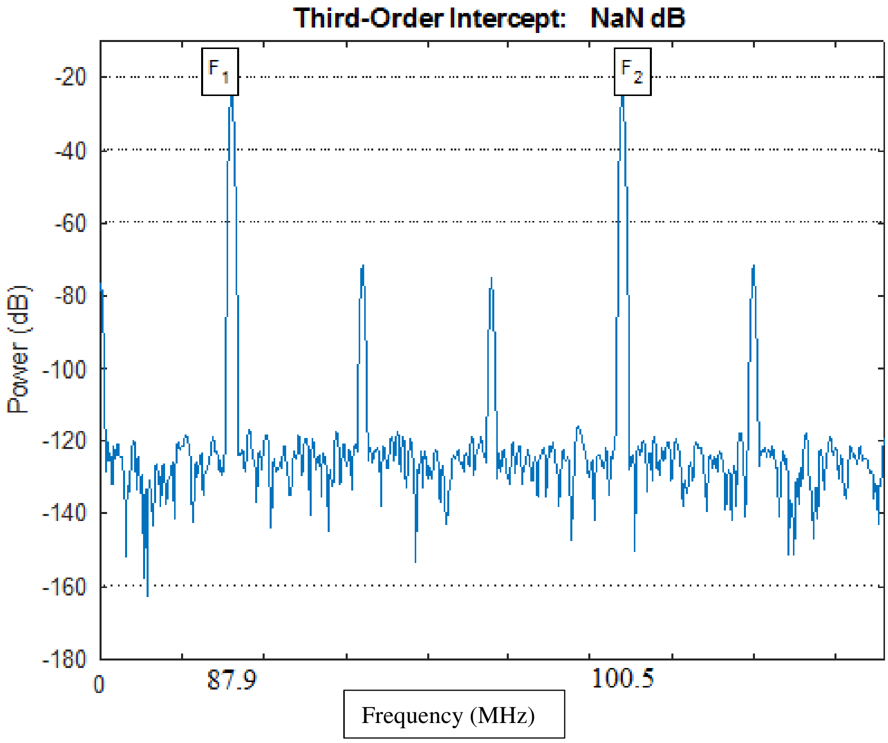


Figure 6. Spectrum showing 3rd order harmonic intermodulation products for 87.9 MHz and 100.5 MHz

Furthermore, the following two graphs, evidence the 3rd order intermodulation distortion phenomenon and the possibility of hits for some selected frequencies using the Matlab software. The first graph shows the third order intercept with a magnitude of -0.1 dB for two frequencies closed to each other namely 98.9 KHz and 99.3 KHz while the second one shows no intercept for other two frequencies a bit disparate (87.9 KHz and 100.5 KHz)

Predominantly, there is a high susceptibility of an Interference occurring within the Greater Accra region specifically in the environs of the Localizer and VOR stations which are located at the KIA Airport in Accra, because the number of possibilities of 3rd order harmonic intermodulation products generated is very great, resulting from a combination of signals from two or three FM radio Broadcast stations. Greater Accra regions has a higher number of FM Frequencies and therefore there is a great potential number of intermodulation products generated with a high possibility of interference occurring in the aeronautical band. This is further illustrated by the power density spectral plot obtained with the Matlab simulation software.

V. Discussion

From the analysis of the results, it can be concluded that there is a high score of 3rd harmonic distortion causing interference in the aeronautical band which becomes critical for the safe operation of flight especially in the taking off and landing stages.

This problem can be addressed by imposing specifications that regulate the operation of the FM broadcast station within some limits that will reduce the third harmonic distortion emanating from the intermodulation problem. There is a need to cross-check the requirement of NCA for co-location of FM stations and factors considered to decide on the maximum transmit power in order to ascertain if these factors take into consideration the third harmonic distortion and probably provide a revised scheme if necessary.

Moreover, the situation encountered in Ghana is a bit different since majority of these FM broadcast stations operate beyond the limits of transmit power imposed unto them by the local regulation agency, in this case the National Communication Authority (NCA). There is lack of monitoring and enforcement on the FM stations operation limit.

The implications of these findings for the aviation safety are crucial to the point that, there is a need to implement measures to mitigate the interference identified in order to forestall any undesired consequences. This can be done through the implementation of band pass filters [8], [11], [18] by the FM Radio station to suppress the undesired 3rd harmonic intermodulation component which has the tendency to interfere with the Air Navigation communication systems.

VI. Conclusion

In summary, this paper presented a thorough assessment of possible interferences on the aeronautical navigation system at the Kotoka international airport of Ghana due to the operation and co-location of FM broadcast stations in Accra, Ghana. It was established that due to the presence of non-linear system, the phenomenon of intermodulation was developed from a system having two or more inputs leading to the propagation of signals at special frequencies other than the fundamentals with considerable magnitude that can perturbate other systems. More specifically, this paper considered the effect of dual tone input signal and estimated analytically and by simulation, the effect of the 3rd harmonic intermodulation distortion on the aeronautical system. The likelihood of occurrence of several hits was found, explaining the perturbation of the aviation aeronautical communication system by the FM broadcast stations in the Greater Accra region. The study has severe implications on safety of flight especially during the take-off and landing stages and could lead to crashes if care is not taken. In view of these findings, a number of recommendations have been made to mitigate the effects of the intermodulation problem and these include the following: all FM radio broadcast station should implement band pass filter (cavity filters) in order to reject the 3rd harmonic frequencies likely to be generated due to their operation and prevent possible formation of intermodulation interference; the operators of the FM radio broadcast stations should also ensure that they operate within the specifications, inhibiting all harmonic signals that emanate from their systems; the National Communication Authority (NCA) should ensure that these FM radio broadcasting stations operate within specification by appropriate filtering of harmonic signals associated with their operations.

References

[1] ICAO, "The World of Air Transport in 2015," 2015.

[2] M. Macdonald and M. House, "Annual Analyses of the EU Air Transport Market," UK, 2017.

[3] UNWTO, "Global Report on Aviation Responding to the needs of new tourism markets and destinations," 2012.

[4] ICAO, "Strategic Objective - Air Navigation Capacity and Efficiency — Global Air Navigation Priorities," 2015.

[5] GCAA, "Aviation Statistics," *Ghana Civil Aviation Authority*, 2019. [Online]. Available: http://www.gcaa.com.gh/web/?p=126. [Accessed: 17-Feb-2019].

[6] NCA, "Authorised FM Radio Stations as at Third Quarter of 2017," *National Communications Authority*, 2019. [Online]. Available: https://www.nca.org.gh/media-and-news/news/authorised-fm-radio-stations-as-at-third-quarter-of-2017/. [Accessed: 17-Feb-2019].

[7] Y. Kim, P. Park, S. Ahn, J. Jo, S. Park, and C. Park, "Network coverage knnnjvnwk," pp. 6–10, 2017.

[8] I. Gasulla, J. Sancho, J. Capmany, J. Lloret, and S. Sales, "Intermodulation and harmonic distortion in slow light Microwave Photonic phase shifters based on Coherent Population Oscillations in SOAs.," *Opt. Express*, 2010.

[9] D. Ishibashi and N. Kuga, "Analysis of 3rd-order passive intermodulation generated from metallic materials," in *Proceedings of 2008 Asia Pacific Microwave Conference, APMC 2008*, 2008.

[10] J. C. Pedro, "On the use of multitone techniques for assessing rf components' intermodulation distortion," *IEEE Trans. Microw. Theory Tech.*, 1999.

[11] A. T. Alastalo and V. Kaajakari, "Third-order intermodulation in microelectromechanical filters coupled with capacitive transducers," *J. Microelectromechanical Syst.*, 2006.

[12] P. Stavroulakis, "Interference analysis and reduction for wireless systems," *IEEE Communications Magazine*. 2004.

[13] P. L. Lui, "Passive intermodulation interference in communication systems," *Electron. Commun. Eng. J.*, 1990.

[14] ITU, *Radio Regulations Articles*. 2016.

[15] W. van Drongelen, "Volterra Series," in *Signal Processing for Neuroscientists*, 2018.

[16] L. F. Yang and C. K. Chen, "Analysis of bilinear systems via taylor series," *Int. J. Syst. Sci.*, 1987.

[17] S. Boyd, L. O. Chua, and C. A. Desoer, "Analytical foundations of volterra series," *IMA J. Math. Control Inf.*, 1984.

[18] E. A. Wan and R. Van Der Merwe, "The unscented Kalman filter for nonlinear estimation," in *IEEE 2000 Adaptive Systems for Signal Processing, Communications, and Control Symposium, AS-SPCC 2000*, 2000.