 https://doi.org/10.24191/jeesr.v25i1.004

Amplifying 23-Years Insights of Doherty Power Amplifier: A Review and Trend Analysis

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***Abstract*—Scopus database is used in this study to illustrate trends observed on the Doherty Power Amplifier (DPA) using bibliometric data from 2000 to 2023. This study adopts a bibliometric analysis of DPA using Biblioshiny, which comes from the R package of Bibliometrix. The application used in this study would decode information from the Scopus database and convert it into different graphical representations. A variety of DPA viewpoints are investigated, discussed, and found. The results of the bibliometric analysis provide important data on recent and upcoming trend articles in the field of power amplifiers. The analysis also offers significant information on its most productive authors, highly cited documents, keyword analysis results, most productive countries, and thematic map analysis, resulting in several potential research agendas for future studies. Future research is proposed to examine relevant publications in other well-known databases. This study is the first bibliometric study to utilize Biblioshiny to assess DPA trends.**

***Index Terms*—Bibliometrics analysis, Bibliometrix, Biblioshiny, Complementary metal-oxide semicondustor, Doherty Power Amplifier**

I. INTRODUCTION

Bibliometric analysis drastically enhances the value of a literature review by providing a transparent, systematic, and reproducible methodology. It enables the tracking of research areas and significant contributions without introducing bias, which is crucial for comprehensive support in the literature review process. In this research, we utilize "biblioshiny," a web-based tool from the R-package "Bibliometrix 3.0," for efficient extraction of primary bibliometric data [1]. The data for Bibliometrix 3.0 can be sourced from four major literature databases: Web of Science, Scopus, Cochrane Database of Systematic Reviews, and PubMed. To generate the results of the databases, the obtained data are inserted into the R-package “Bibliometrix 3.0”.

This manuscript is submitted on 13 February 2024, revised on 20 March 2024, accepted on 21 May 2024 and published on 31 October 2024. Naufal Adibah Mohd Farid, Mohd Faizul Md Idros, Abdul Karimi Halim and Abdul Hadi Abdul Razak are from the Electronics Architecture and Applications (EArA), School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia.

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William H. Doherty was an electrical engineer from the United States of America (USA) who invented a power amplifier (PA) design that provides extra efficiency surge at power backoff (PBO). Doherty Power Amplifier (DPA) which bears his name, has been extremely successful in mobile radio, both historically and even more lately. The DPA operates centered on the active load modulation standard. This principle optimizes the load impedance paths for both the carrier amplifier and peaking amplifier, adjusting them in response to changes in the incoming signal's amplitude. This adaptive approach enhances overall efficiency while preserving linearity. Nevertheless, a quarter-wavelength transmission line is integrated into its structure, introducing a frequency-dependent element that imposes a constraint on the bandwidth for load modulation. Consequently, the DPA exhibits a notably limited bandwidth [2].

Designers for PA were less interested towards the complex layout of DPA. They would rather opt for layouts that are more conventional and simpler. By employing mixed modulation techniques that involve both amplitude and phase/frequency manipulation, it becomes possible to substantially modify the output. This approach is particularly valuable when transitioning to new communication standards, especially those demanding high data rates that require modulations characterized by spectral efficiencies [3]. The current trends observed in studies related to DPA have changed in a positive manner over time, hence it is important for its architecture to adapt with more recent communication standards. Contemporary trends exert a significant influence on phasing out earlier generations of networks, paving the way for the cutting-edge Fifth Generation (5G) networks with Internet of Things (IoT) capabilities. The 5G wireless network is poised to enable extensive connectivity for billions of devices, thus opening up access to a multitude of innovative services.

Following this current trend, new methods have been created to satisfy the increasing needs for increased data rates, larger capacities, as well as broader bands of frequency, such as the millimetre wave (mm-wave), to assist the implementation of 5G across the globe. Massive Multiple Input/Multiple Output (MIMO), utilizing numerous antennas at both the transmitter and receiver terminals, has been recognized as a pivotal 5G technology aimed at augmenting data speed and optimizing spectrum utilization. Moreover, diverse wireless networks, including Long-Term Evolution (LTE), Wireless Local Area Network (WLAN), and Narrowband IoT (NB-IoT), necessitate a wide transmission power range to accommodate a range of communication scenarios. With these networks, devices can

frequently operate at low average output power.

To attain exceptional total efficiency and extend the battery lifespan, the Power Amplifier (PA) must demonstrate effectiveness not solely at peak power but also at deep Power Back-Off (PBO) levels, such as 12/18 dB or higher, as discussed in references [4,5]. The most power-consuming component in transceiver devices is PA. This is why most modern-day wireless communications, for example, Wireless Fidelity (Wi-Fi) and Long-Term Evolution (LTE), use complicated orthogonal frequency division multiplexing (OFDM) modulation to increase spectrum efficiency and handle large transmissions throughout their function [6]. To successfully amplify signals with a high peak-to-average ratio (PAPR), several PA designs have been developed throughout the years. For example, envelope tracking (ET), outphasing PA and DPA. The DPA architecture has developed one of the most frequently utilized PA designs in existing cellular base stations, which has been thoroughly researched by various scholars [7].

Although there are multiple studies and reviews that have elaborately described the uses of DPA, most of them have only placed focus on DPA's capabilities. Few of these studies have further focused on the development of DPA across the years. However, there is currently no published study that uses bibliometric techniques to record published DPA research. To explore trends pertaining to DPA, this study utilizes bibliometric analysis facilitated by Bibliometrix, an open-source tool integrated with the R package. The main aim of this paper is to examine the growth of recent literature concerning DPA. Consequently, this study is undertaken for the following purposes:

1. To analyze the year-by-year distribution and growth of research on DPA from the years 2000 to 2023.
2. To identify the most frequently referenced articles and their outreach over the stipulated timeframe.
3. To identify relevant authors, connections, and countries that contribute significantly to the body of literature on DPA.
4. To identify sources that are author-preferred, keywords, and contact methods.

Traditional trend analysis has always consisted of solely the naming and basic analysis of research using variable groups and theories. With bibliometric analysis, researchers are now able to perform network analysis on specific keywords and titles, leading towards developing a cluster area of study within the subject. Using research visualization and analysis, the researcher can present a concise overview of the earlier study's authorship, sources, and citations. The following scientific issues are addressed by this study:

1. What is the yearly publication trend pattern?
2. Who are the primary authors?
3. What are the publications with the most citations?
4. Which country is the most productive?
5. Which affiliations are the most productive?
6. What are the most popular research journals?
7. What are the most popular author's keywords?

This study is divided into six sections: Section One summarizes the significance of this study. Section Two summarizes previous research that had examined DPA databases. Section Three moves over the methods used in this study in great depth. Section Four presents the outcomes of bibliometric analysis in the form of charts, diagrams, and networks. Section Five contains debates concerning the analysis gathered from this study, while Section Six concludes the findings of this study.

II. Literature Review

There are currently 871 publications in Scopus database consisting related studies on "Doherty Power Amplifier". The earliest publication was recorded in the year 2000, which studied the 20GHz DPA with monolithic microwave integrated circuit (MMIC) for broadband digital systems, which was published on 11 June 2000. Studies on DPA have since shifted their focus to high efficiency and low distortion that would be suitable for wireless communication systems. Afterwards, studies on DPA evolved to improve other aspects of its architecture, such as its output power, linearity, voltage supply, and PBO efficiency. In the modern era of solid-state devices, high-frequency Power Amplifiers (PAs) have increasingly been designed to accommodate constant envelope-modulated signals, particularly phase and frequency modulations. These modulation schemes are considered the most suitable and direct options for optimizing PA power efficiency.

There is a constant drive for higher data rates with new mobile applications. Spectrally efficient modulation methods that were able to accomplish these rates would use high PAPR signals to increase the capabilities of PAs, which require a strong PBO performance from the PAs [8-10]. Several PAs, such as ET, outphasing [9] and DPA, are used for effective enhancements leading to high PAPR signals being transmitted. Considerable academic and economic resources have been dedicated to demonstrating Power Amplifiers (PAs) with enhanced Figure of Merit (FOM) for high Peak-to-Average Power Ratio (PAPR) and wide bandwidth signals. This pursuit aims to capitalize on the increased integration capacity and cost-effectiveness afforded by complementary metal-oxide semiconductor (CMOS) technologies. The escalating demand for higher data rates leads to the generation of radio frequency (RF) signals characterized by high PAPR, posing a significant challenge in the development of highly efficient linear PAs, as discussed in reference [11]. DPA is the most extensively researched and widely used PA due to its ease in circuit application and high efficiency over a broad voltage range [12,13]. Hence, numerous intricate Doherty Power Amplifier (DPA) design techniques have been employed across various research. These methods encompass uneven power drive, gate bias adjustments, harmonic tuning strategies, and the application of digital Doherty configurations utilizing digital signal processing for phase synchronization, as detailed in reference [14].

DPA is a well-known amplifier that is extensively used in PA designs. This PA comprises two amplifiers that aggregate their output power via a load-modulation network [15]. DPA could sustain high efficiency over a wide power spectrum [7]. High efficiency is essential in circuit designs because it can affect the entire circuit performance. A low-efficiency design will impair

circuit performance, leaving the circuit unable to meet the 5G IoT standards. Efficiency is highly reliant on the functioning of two PAs: carrier amplifier and peaking amplifier, which are also known as the primary and auxiliary amplifiers, as shown in Figure 1.

Both Power Amplifiers (PAs) need to be securely configured and precisely calibrated. When the output power nears a critical overload point, the peaking PA is engaged. To maintain high efficiency at lower power levels, it is common practice to deactivate the peaking PA, thereby providing the carrier PA alongside an open path and reducing power loss from the carrier PA, as discussed in reference [16]. Upon deactivation of the peaking amplifier, the Doherty Power Amplifier (DPA) operates in the low-power region, with efficiency primarily dependent on the carrier amplifier [17]. When the peaking amplifier becomes active, the DPA's efficiency is influenced by both the carrier and peaking amplifiers. Consequently, increasing the efficiency of traditional DPAs at Power Back-Off (PBO) levels becomes imperative, and one potential solution is to design the carrier amplifier as a harmonic-controlled amplifier, as proposed in reference [18].

Next, the power divider divides incoming signals into two sections, which are subsequently directed through 2 amplifiers with varying delays. Lastly, the circuit topology integrates the received signals [19]. Figure 2 illustrates the behaviors of the Doherty Power Amplifier (DPA), which are categorized into 2 operational sections: the low-power zone and the Doherty part. Upon reaching saturation and the initial efficiency peak in the key amplifier, the peaking amplifier is engaged, transitioning the DPA into the Doherty region. Subsequently, the second efficiency peak is attained at full output power, as elaborated in reference [20].

At present, there are still limitations that prevent DPA from being used for upcoming wireless transmission systems. Modulated signal forms require an ever-increasing PAPR (> 6 dB) to satisfy the constant need for higher data rates. This implies that DPA must work at a greater PBO (> 6 dB). Broadband operation is also needed, however, DPA's effectiveness at PBO diminishes as bandwidth increases. This modulation ensures a consistent drain voltage swing. Because of the narrowband $\pi/4$ transformer employed in a typical DPA design, bandwidth becomes limited. As a result, a method for achieving high efficiency at PBO without sacrificing bandwidth is critically wanted [21,22]. For optimal load modulation, the bias of peaking PA should be raised to match that of the carrier PA at a saturation power level. Peaking PA's adaptive bias control approach is effective in improving DPA's performance [23].

There are so many ways and methods that can be used to improve the limitations of DPA. For example, many methods can be used to expand the bandwidth of a circuit. Some of them use low-pass filter-based methods [24], short circuit stub-based methods, and transmission line-based methods. Low pass filter is placed at both carrier and peaking amplifiers via output terminals. This is to increase the DPA's operating bandwidth. The component within the low pass filter is then adjusted to attain good bandwidth. The second method for increasing DPA bandwidth can be done with the construction of short circuit transmission lines at the output ends of both carrier and peaking amplifiers. In order to achieve optimum frequency, improvements are made to the length and impedance of electricity within the short-circuit communication lines. The way that standard DPA is biased is like the bias found in carrier and peaking amplifiers. The third method for increasing DPA bandwidth is to link the two parts of transmission lines at the peaking amplifier's output terminal. The length and impedance of electricity for the added transmission lines are adjusted in this setup to achieve the greatest bandwidth. Both carrier and peaking amplifiers are then biased in the same way as traditional DPA [25]. Another method is to apply post-matching techniques or output compensations method on the DPA design. These solutions would add plenty of complexity to the circuit design and require more cost, thus a simpler method of increasing bandwidth is required [26].

A neutralization capacitor approach has been suggested to be implemented in the DPA design as a reliable method of improving to reduce inaccurate ground effect on sources, improving stability and increasing gain [27,28]. Other than improving bandwidth, one of the ways to increase efficiency is by using digitally managed data distribution. The concept behind this approach is to dynamically allocate power input to both the carrier and peaking amplifiers, a technique known as Digital Doherty Power Amplification (Digital DPA). The utilization of multiway amplification in methodologies like Envelope Tracking (ET), Chireix outphasing, or DPA represents one of the most widely accepted principles for enhancing amplifier efficiency. Although basic feedback methods such as a Cartesian loop are still used for narrow-band systems, the main technique for increasing linearity is now pre-distortion on either analog powered device (APD) or digital powered device (DPD).

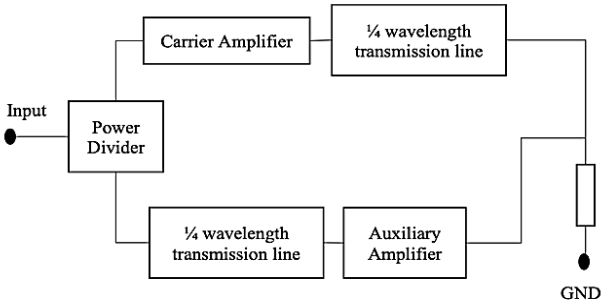

Fig. 1. Conventional DPA topology [7].

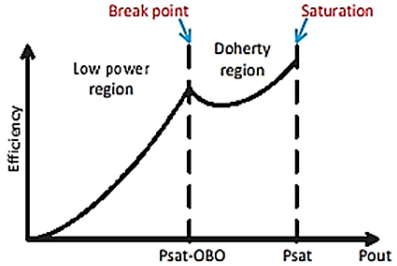

Fig. 2. DPA Behaviour [20].

It should be noted that in many instances, efficiency enhancement and linearization methods may be combined [29]. In the quest to enhance the output power performance and power efficiency of Doherty Power Amplifiers (DPA), designers may encounter challenges related to lossy output matching networks (OMNs) in transmission-line-based DPAs, leading to bulky chip sizes. To mitigate this issue, transformer-based OMNs are frequently employed in millimeter-wave Power Amplifiers (PAs). These transformers, equipped with lumped constant (LC) matching networks, exhibit impedance inverting properties while maintaining minimal insertion loss and compact size, as elaborated in reference [30]. Asymmetric DPAs and outphasing amplifiers are capable of operating over a wide dynamic range, leading to high saturation and excellent efficiency in high backoff conditions, as indicated in reference [31].

Two DPAs and a Chireix combiner form the hybrid amplifier, which uses the Doherty region in saturation and the outphasing zone in backoff. This design effectively broadens the high-efficiency backoff region. Nonetheless, both DPAs and outphasing amplifiers have inherent limitations in their backoff ranges. An asymmetric DPA can expand the backoff area at the expense of saturation and backoff efficiency. A reactance compensation method converts the DPA's backoff efficiency zone impedance into a resistive load, allowing the hybrid amplifier to prolong the backoff area. This adjustment allows the hybrid amplifier to extend the backoff region. Load-pull simulations for the DPA are used to estimate the backoff efficiency impedance, maintaining fixed input and output impedance at 50 ohms to optimize their original capabilities. Chireix combiners are optimized for hybrid amplifiers and represent the DPA's backoff region [32]. Figure 3 depicts the topology of the hybrid amplifier, illustrating a Chireix combiner connecting two identical DPAs in a hybrid Doherty-Chireix configuration.

Another issue that may arise from this hybrid is that the impedance at the Chireix combiner's input varies with phase, affecting the DPA's load impedance. Matching networks are utilized between the DPA and the Chireix combiner to alleviate this disadvantage [33]. Other than the Doherty-Chireix hybrid, there is also transformer-based Doherty hybrid. In lieu of the input power divider and 90-degree network, a transformer-based quadrature hybrid is utilized, leading to a more compact footprint and reduced losses. In traditional DPAs, 90-degree couplers have a big area and various coupling coefficient constraints. This design presents challenges when modifications are needed after determining the main frequency and characteristic impedance. In theory, the fusion amplifier divides the input signal into 2 equal output signals while introducing a 90-degree phase shift [34].

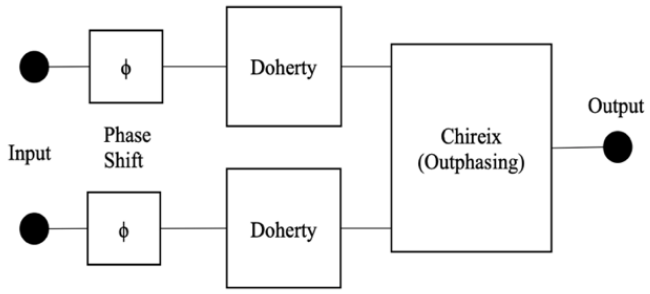

Fig. 3. Block Diagram of Hybrid Amplifier [33].

The selection of semiconductor technology for constructing power devices and amplifiers is primarily influenced by two key variables: the operating frequency and the power level. However, when multiple options are available, considerations such as cost, power efficiency, and linearity become more critical. In the context of base-stations, where high breakdown voltage and power density are essential, semiconductor devices like laterally-diffused metal-oxide semiconductor (LDMOS) and gallium nitride (GaN) high-electron-mobility transistor (HEMT) devices are commonly employed. LDMOS device, which is silicon-based, comes with low-cost and extremely excellent reliability and linearity behavior. On the other hand, even though GaN HEMT is a costlier option, it gives greater efficiency, particularly on silicon carbide (SiC) substrates. Because the bias voltage is equivalent across the two technologies, the optimal actual load is comparable. However, due to the reduction of capacitive effects, the fundamental characteristics of GaN devices allow for larger frequency operation and wider bandwidth. Other than LDMOS and GaN HEMT technology, silicon-based device technologies such as bulk RF Silicon on Insulator (SOI) CMOS are vital in RF phased-array integrated circuits (ICs). This preference arises from their remarkable level of integration and cost-effective manufacturing. Radio Frequency Silicon-on-Insulator Complementary Metal-Oxide-Semiconductor (RFSOI CMOS) device technology offers substantial benefits for high-performance Power Amplifiers (PAs). It can offer a high supply voltage (greater than 10%) along with large output voltage swings (drain voltage), as well as High-Q passive components (exceeding 20). These features contribute to increased output power and efficiency. Moreover, the reduced parasitic capacitance achieved through the use of a floating body in RFSOI device technology enables excellent gain and stability, leading to reduced power consumption in the driver stages, as highlighted in reference [35]. Q referenced in High-Q passive components means its Quality factor, where it is a ratio of the coil's inductive reactance at resonance to its resistance. The greater the value of Q, the greater will be its resonance curve and selectivity.

To the best of the researcher's knowledge, this study represents the first quantitative evaluation of research conducted on Doherty Power Amplifiers (DPAs). To achieve this evaluation, bibliometric techniques were employed in this study. Bibliometrics is a form of quantitative analysis technique used to evaluate the quantity of study work done in an area,

which must be specified by covering certain criteria such as year, scope, and keywords. This technique uses various indicators with numerous publication-related data to calculate the amount of study as recommended by bibliometricians over the stipulated years. Bibliometrics technique also can track the current trends of the targeted topics. This way, the study of the topics can be sort by a list of research papers that has the best method of improvement.

III. MATERIAL AND METHODS

Bibliometric indicators provide various advantages, including measurable measures of research effect, objective evaluation for funding and academic promotion, spotting developing trends within fields of study, and allowing comparison and collaboration among academics. Scholars often utilise four methods to perform bibliometric research, as in Figure 4. Such as defining the research goal, collecting data, analysing and visualising the data, and interpreting the findings and outcomes. Therefore, a bibliometric analysis of DPA research papers is presented in this study. Based on Figure 5, the flowchart provided is to show from the general PA based on application targeted for the study towards its architecture components, the topology, limitation, and method to improve performance. Therefore, this bibliometric analysis will collect data from database tool then the data will be analysed. From this, researchers able to know architecture components, method to improve DPA performance, the topology of the power amplifiers and also its limitation.

Statistics for this study were obtained from the Scopus database on 4 February 2023. Given that the Scopus database varies on a regular basis, the search and finding of filtering criteria were done concurrently [36]. Scopus is a database tool for obtaining academic knowledge. Scopus provides abstracts and citations by combining a large and well-managed database, enriched data, and pertinent scientific material from various fields in a unique manner [37,38]. Other than using Scopue, the databases can be obtained from other databases such as Pub Med, Science Direct, Web of Science [39] and others. Figure 6 depicts the flow diagram of the search strategy.

Using this strategy, 871 records are obtained from the Scopus database in the form of 'Bibtex' from the year 2000 to 2023. Data extraction utilised the usage of search strings, including: TITLE ("doherty power amplifier") AND (LIMIT-TO (LANGUAGE, "English")). This analysis is narrowed to cover the years from 2000 to 2023. The year is fixed to 2000 because the first document on this subject was found to have appeared in that year. Manual data filtering is used to eliminate unnecessary record entries. The collected data are then analyzed using the Bibliometrix 3.0 found in RStudio. Figure 4 shows the result of the database from Scopus.

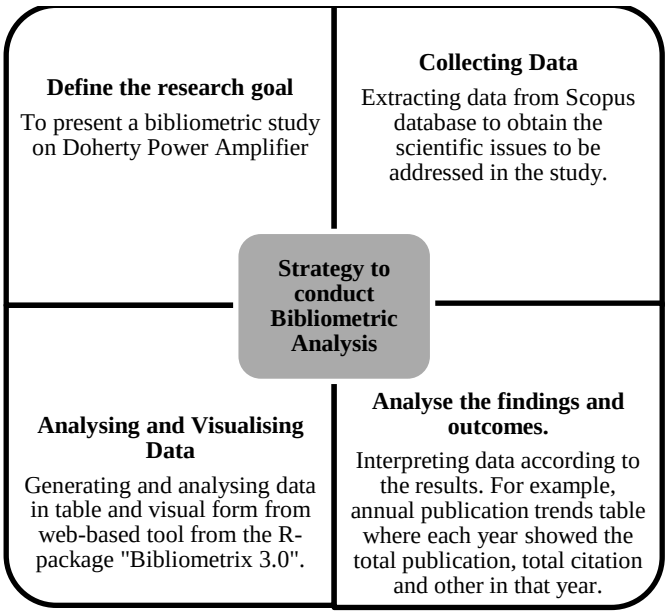

Fig. 4. Strategy to conduct Bibliometric Analysis.

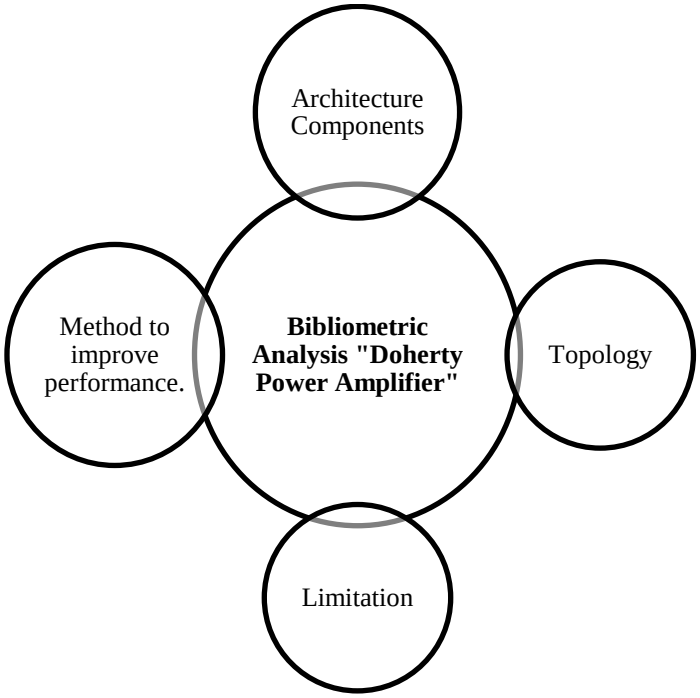

Fig. 5. Bibliometric Analysis of Doherty Power Amplifier.

IV. ANALYSIS AND RESULTS

4.1 Descriptive Analysis

DPA's study profile, including publication sources from 2000 to 2023 is covered in this section. The profile contains current publishing status; study patterns; highly cited papers; authors' profiles; nations and institutions; as well as sources of publication.

4.1.1 Annual Publication Trends

Table 1 shows the annual publication trends of DPA. This trend includes information from the 24 years consisting of

publication volume, citation volume, citation per manuscript, citation per year and year of citation. Figure 7 shows the total publication and total citation for annual publication trends. According to the information gathered in Table I and Figure 7, the years 2019 and 2022 have the highest total publications in DPA as compared to other years, with a total number of 87 publications in 2019 and 92 publications in 2022. The lowest number of publications was found in 2000, when the first paper about DPA was published. In 2012, the number of citations was recorded to be the highest from 2000 to 2023. This year saw a total citation of 1163 for DPA-related research.

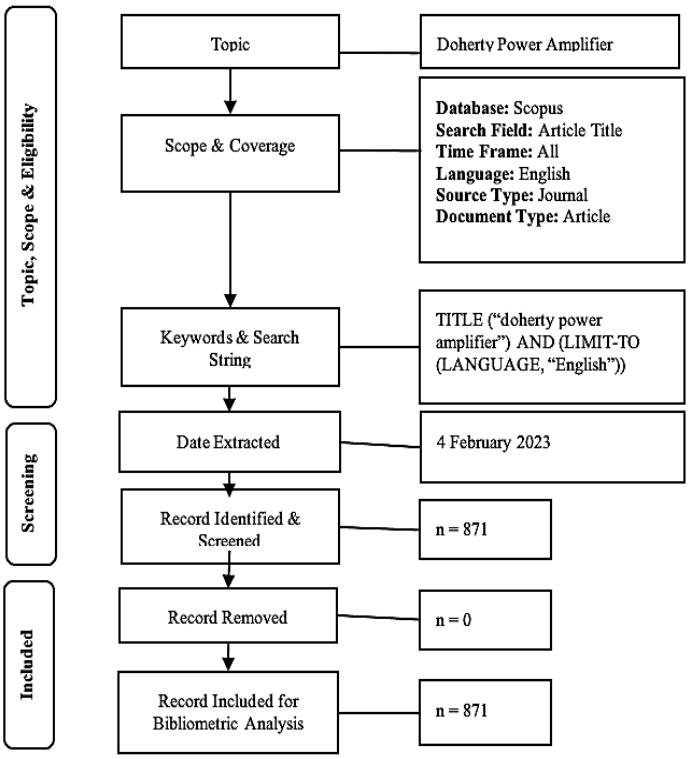

Fig. 6. Flow Diagram of the Search Strategy.

Figure 7 shows an exponential distribution with a slow increase in the early years of analysis and a rapid increase in the later years. Despite a drop in 2013, the yearly publishing pattern on DPA generally follows an upward trajectory. This rising tendency indicates that the topic of DPA has captured the attention of a growing number of scholars, academics, and researchers.

4.1.2 Most Productive Authors

All 871 records from the Scopus database showed manuscripts which have been published by 1435 authors. Of all these authors, 16 authors have been identified with single-authored documents. Table II shows the top 20 highly productive authors. The top three most productive authors are "Kim B" (TC = 1452, TP = 47), "Wang H" (TC = 626, TP = 26) and "Chen W" (TC = 612, TP = 33).

TABLE I. ANNUAL PUBLICATION TRENDS

Year	TP	TC	C/P	C/Y	Citable Years
2000	1	30	30	1.25	24
2003	3	33	11	0.52	21
2004	1	3	3	0.15	20
2005	6	361	60.17	3.17	19
2006	14	578	41.29	2.29	18
2007	13	261	20.08	1.18	17
2008	15	182	12.13	0.76	16
2009	24	410	17.08	1.14	15
2010	40	491	12.28	0.88	14
2011	38	626	16.47	1.27	13
2012	49	1163	23.73	1.98	12
2013	36	674	18.72	1.7	11
2014	46	808	17.57	1.76	10
2015	43	836	19.44	2.16	9
2016	57	946	16.6	2.08	8
2017	63	1058	16.79	2.4	7
2018	78	848	10.87	1.81	6
2019	87	923	10.61	2.12	5
2020	58	409	7.05	1.76	4
2021	84	262	3.12	1.04	3
2022	92	63	0.68	0.34	2
2023	8	1	0.12	0.12	1

Note(s): TP- Total publication; TC- Total Citations; TY- Total Year; C/P- Citation per doc; C/Y- Citation per year; PYS- Publication Year Start.

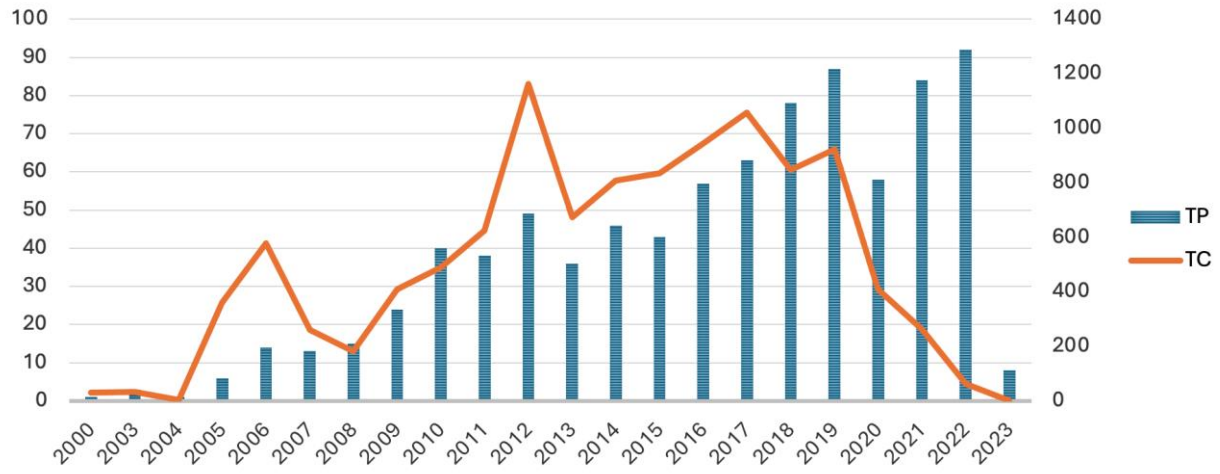

Fig. 7. Annual Publication Trends.

TABLE II. MOST PRODUCTIVE AUTHORS

Authors	h_index	g_index	m_index	TC	TP	PYS
KIM B	18	37	0.947	1452	47	2005
WANG H	14	25	1.077	626	26	2011
CHEN W	13	24	0.929	612	33	2010
COLANTONIO P	13	25	0.765	654	41	2007
GIANNINI F	13	25	0.765	641	33	2007
KIM J	13	16	0.684	881	16	2005
CAMARCHIA V	12	26	0.923	696	37	2011
GHANNOUCHI FM	12	27	0.706	762	30	2007
PIROLA M	12	26	0.923	705	29	2011
QUAGLIA R	12	26	0.923	719	30	2011
BOUMAIZA S	11	21	0.647	464	22	2007
FENG Z	11	21	0.786	470	23	2010
PIAZZON L	11	23	0.733	566	28	2009
PARK B	10	12	0.769	292	12	2011
RAWAT K	10	16	0.769	443	16	2011
CHO Y	9	12	0.692	417	12	2011
HE S	9	20	1	403	25	2015
KANG D	9	17	0.563	362	17	2008
LEE J	9	14	0.529	208	14	2007
YANG Y	9	16	0.563	269	26	2008

Note(s): TP- Total publication; TC- Total Citations; PYS- Publication Year Start.

TABLE III. MOST CITED PAPERS (LOCAL & GLOBAL CITATION)

Document	Authors	Year	Local Citations (LC)	Global Citations (GC)	LC/GC Ratio (%)
The Doherty power amplifier.	B. Kim, J. Kim, I. Kim, and J. Cha	2006	111	248	44.76
A Post-Matching Doherty Power Amplifier Employing Low-Order Impedance Inverters for Broadband Applications.	J. Pang, S. He, C. Huang, Z. Dai, J. Peng, and F. You	2015	73	115	63.48
The Doherty power amplifier: Review of recent solutions and trends.	V. Camarchia, M. Pirola, R. Quaglia, S. Jee, Y. Cho, and B. Kim	2015	72	168	42.86
A modified Doherty power amplifier with extended bandwidth and reconfigurable efficiency.	D. Gustafsson, C. M. Andersson, and C. Fager	2013	69	126	54.76
Broadband Doherty power amplifier via real frequency technique.	G. Sun and R. H. Jansen	2012	69	176	39.20
A broadband high-efficiency Doherty power amplifier with integrated compensating reactance.	J. Xia, M. Yang, Y. Guo, and A. Zhu	2016	63	96	65.63
Power efficiency and linearity enhancement using optimized asymmetrical Doherty power amplifiers.	J. Kim, B. Fehri, S. Boumaiza, and J. Wood	2011	59	129	45.74
A broadband Doherty power amplifier based on continuous-mode technology.	X. Chen, W. Chen, F. M. Ghannouchi, Z. Feng, and Y. Liu	2016	52	100	52.00
High-efficiency Doherty power amplifiers: Historical aspect and modern trends.	J. Esch	2012	51	5	1,020.00
High-efficiency Doherty power amplifiers: Historical aspect and modern trends.	A. Grebennikov and S. Bulja	2012	51	125	40.80

4.1.3 Most Cited Papers

Table III shows the papers that are most locally and globally cited. Global citations make it easier to calculate the number of yearly citations based on Scopus when data was obtained. Citations measure more on the frequency where each chosen article is referenced by the selected group of articles. The most cited articles were found by Kim B with a total of 111 local citations and 248 global citations.

4.1.4 Most Productive Countries

Table IV shows the top 9 countries that are most productive with research, their total publication, and the percentage of publications. The top 9 countries were the USA, China, Korea, Italy, Canada, Iran, Germany Japan, and Hong Kong. From Table IV, the USA and China became the top two countries with the highest number of publications, where the number of publications was recorded at 366 (42.8%) and 167 (19.5%) respectively.

TABLE IV. TOP 9 COUNTRIES TOTAL PUBLICATION

Country	TP	% of Publication
USA	366	42.8
CHINA	167	19.5
KOREA	75	8.8
USA	56	6.5
ITALY	29	3.4
CANADA	24	2.8
IRAN	23	2.7
GERMANY	18	2.1
JAPAN	17	2
HONG KONG	14	1.6

4.1.5 Most Productive Affiliations

Table V depicts affiliations that are most productive with the number of articles that were published. Table V also shows that the University of Electronics Sciences and Technology of China has the highest number of articles (163 articles), as compared to other affiliations found in the Scopus database. Sungkyunkwan University took second place with 112 articles.

TABLE V. MOST PRODUCTIVE AFFILIATIONS

Affiliation	Articles
University Of Electronic Science and Technology of China	163
Sungkyunkwan University	112
Pohang University of Science and Technology	95
Southeast University	87
Tsinghua University	76
Hangzhou Dianzi University	71
University Of Roma Tor Vergata	65
Pohang University of Science and Technology (POSTECH)	62
Ningbo University	52
University Of Calgary	46

4.1.6 Most Frequent Journals

Findings from the most popular research journal are presented in Table VI. Table VI shows IEEE Transactions on Microwave Theory and Techniques to have the highest number of publications, which is 99 publications, with the highest total citation of 4179 citations. This is followed by IEEE Microwave and Wireless Component Letters, which has 52 total publications and 997 citations.

TABLE VI. MOST FREQUENT JOURNALS

Source	h_index	g_index	m_index	TC	TP
IEEE Transactions on Microwave Theory and Techniques	39	62	2.053	4179	99
IEEE Microwave and Wireless Components Letters	21	29	1.235	997	52
IEEE MTT-S International Microwave Symposium Digest	15	22	0.625	788	74
IEEE Journal of Solid-State Circuits	13	18	0.722	688	18
Digest Of Papers - IEEE Radio Frequency Integrated Circuits Symposium	11	16	0.611	296	16
Asia-Pacific Microwave Conference Proceedings	9	14	0.474	238	33
IEEE Access	9	15	1.286	227	18
IEEE Transactions on Circuits and Systems I: Regular Papers	8	15	0.8	351	15
IEEE Transactions on Circuits and Systems II: Express Briefs	8	13	0.889	175	13
Digest Of Technical Papers - IEEE International Solid-State Circuits Conference	6	8	0.333	269	8

Note(s): TP- Total publication; TC- Total Citations.

4.2 Thematic Map Analysis

Biblioshiny was utilized to construct a thematic map, revealing the intellectual structure and emerging trends in DPA-related research [40,41]. Figure 8 shows a thematic map based on the authors' keywords. The analysis of bibliographic couplings between publications uncovered distinct categories representing diverse research areas [42].

Cluster 1 encompasses foundational research aimed at comprehending and identifying DPAs. Keywords such as "doherty power amplifier", "high efficiency", "broadband", "cmos", "millimeter wave", "transformer", "digital predistortion", "linearization", and "predistortion" indicated early investigations into capabilities, limitations, and potential applications. Notable research on DPA design was found from this cluster, producing high Power Added Efficiency (PAE) prototypes, and assessing design reliability through multiple samples [43].

Cluster 2 predominantly focuses on technological advancements to enhance DPAs. The term "third-order inter-modulation distortion (IMD3)" pertains to measuring third-order distortion products generated by nonlinear devices when exposed to two similar-frequency tones. A comprehensive simulation for IMD3 values was presented in this cluster, with a result comparison with previous work [44].

Cluster 3 suggests a broader exploration of DPAs, encompassing keywords like "cellular", "microwave power amplifier", "cmos integrated circuits", "digital", "polar modulation", "wimax", and "broadband matching networks". However, this extended scope also introduces complexity when assessing practical outcomes and value. An extensive study of DPA modifications was found in this cluster to broaden its bandwidth while preserving efficiency [45].

Cluster 4 addresses critical aspects of DPAs, including impedance, bandwidth, broadband amplifiers, heterojunction bipolar transistors (HBT), handsets, and efficiency. These aspects are crucial for ensuring the technology's efficiency and reliability in everyday applications. A proposed design demonstrated enhanced efficiency, bandwidth, and output PBO range through phase compensation, a critical element in DPA design [46].

In summary, while DPA research remains vital for conceptual and technological development, recent emphasis has leaned towards effectiveness and reliability rather than advanced concepts, practical applicability, and real-world implications.

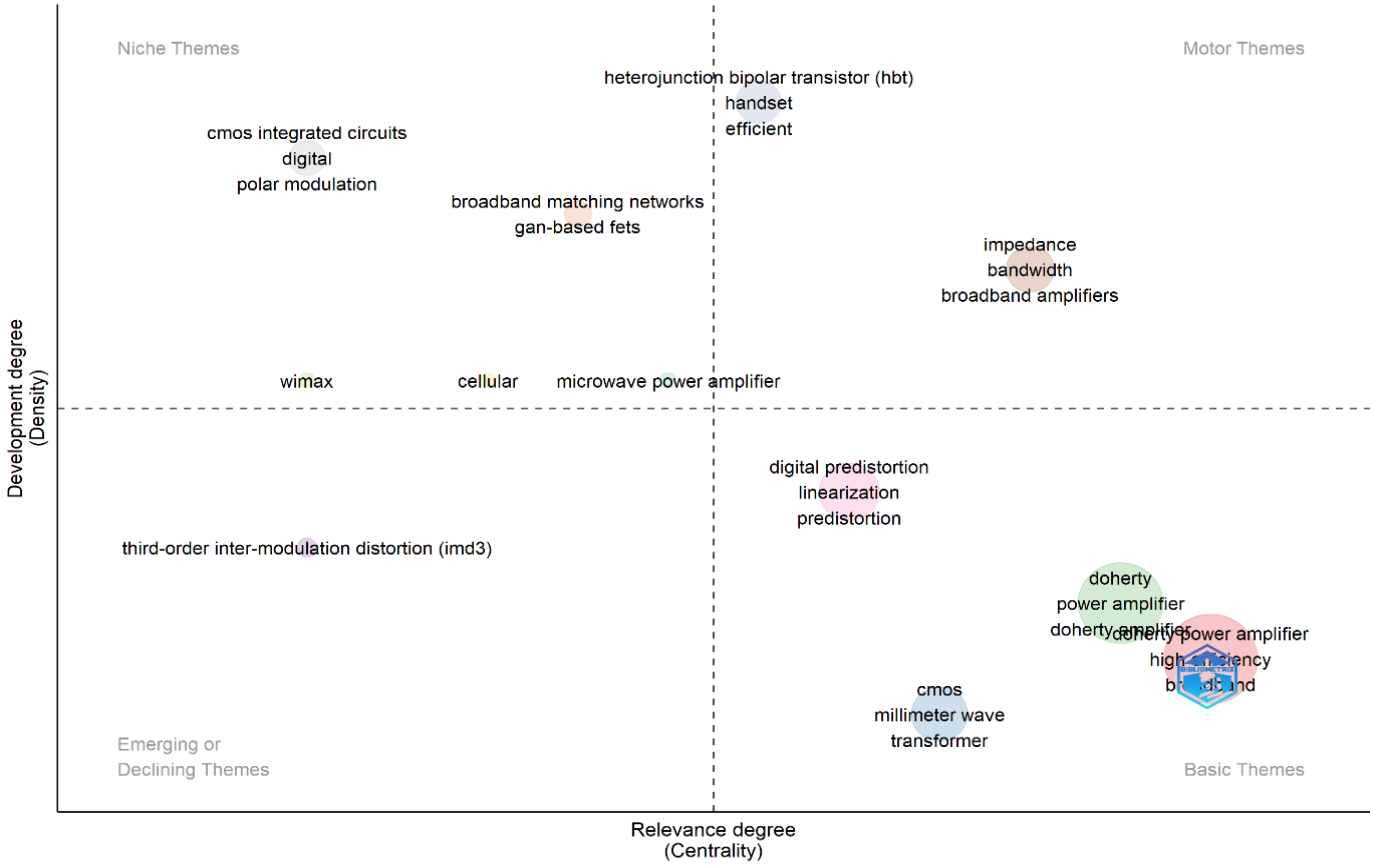

Fig. 8. Thematic Map of Author Keywords.

V. Discussion

With the fast-paced and continuously changing era of connectivity, improvements on PA designs are direly needed to be made, where these designs must continue to evolve and meet the people's needs. This study shows that PA, specifically DPA, shows a significant number of articles published in the field that contribute towards a greater need for new studies in the future. This contribution shows an increase over almost 2 decades, as seen in Figure 7. Similarly, as can be seen in Table 1, the highest number of publications for DPA was achieved in 2022 in comparison to other years analyzed in this study. This shows that the development of DPA is still being actively carried out by researchers from all around the world. From the Scopus database, publications on DPA have an annual growth rate of 9.46 percent. For primary authors contributing to these publications, it was found that the highest number of publications produced by a single author was 47 publications by Kim B. Kim B is also an author with the highest total citation among all other authors, which is 1452 citations. The second-highest total citation was by Wang H, with 626 citations. Compared Wang H to Kim B, it can be observed that the total citation from the works of Kim B was twice more than Wang H. Other than the best authors with high publications and citations, the country that is the most productive in producing publications is also recorded in Scopus database. This shows how well a country actively makes developments and develops its country. From Table 4, it can be observed that the USA and China are the top countries with the highest publications. The percentage of publications in the USA and China are 42.8 percent and 19.5 percent, respectively. Publications from the USA had almost reached the 50th percentile of total publications in the research area in comparison to other countries. However, the most productive affiliations were not from the USA, but from China. The University of Electronic Science and Technology of China has the most productive affiliation with 163 articles recorded in the Scopus database. This is followed by affiliations from Sungkyunkwan University, Korea and Pohang University of Science and Technology, with 112 and 95 articles respectively. Other than that, the most popular journal for this research area is IEEE Transactions on Microwave Theory and Techniques, which has 4179 total citations and 99 total publications. Second in place is

IEEE Microwave and Wireless Component Letters, with 997 total citations and 52 total publications.

From this study, it has been revealed that about 871 records were found on the Scopus database to be analyzed. The annual growth percentage of this title is about 9.46 percent within the timespan from 2000 to 2023. The analysis further shows annual publication trends (as depicted in Figure 7), where the highest recorded total publication is in the year 2022 with 92 publications. This number was about 10 percent of the total publications discovered within the year 2000 to 2023. However, the highest total citation was found from the year 2012. This study also revealed that the most productive authors on DPA were "Kim B" and "Colantonio P", who have the highest total publications recorded in the Scopus database with 47 and 41 total publications respectively. Other than that, it shows that "Kim B" also has the highest total citation recorded compared to other authors, with 1452 citations on publication. This author also has the highest rank for most cited paper, with 111 total local citations and 248 total global citations in the year 2006.

Further, The USA and China are the top countries that have the highest total publications, with 366 and 167 total publications respectively. The USA took first place with 42.8 percent of total publications produced compared to other countries. However, China has the most productive affiliations which is the University of Electronic Science and Technology of Science with 163 total publications. Coming second in place is Sungkyunkwan University in South Korea with 112 total articles being produced.

To figure out trends being observed in collaboration and co-citation analysis, network analysis was done in the area of research. This analysis is conducted where a cluster of studies for the same theme was connected to each other and formed a wide connectivity of the topic [47].

VI. Conclusion

This study has thoroughly plotted the development of DPA from the year 2000 to 2023 using bibliometric analysis using R Studio. This study has analyzed information obtained from the Scopus database, with an emphasis on important data, for example, publication year, article type, sources, and content of the document. Besides that, the bibliometric analysis offers important data on yearly publication patterns, mostly on the main term used, analysis on co-citation, network of co-citation, analysis on collaboration analysis, as well as co-occurrence network analysis. To conclude, this analysis focused on the bibliometric study of DPA development throughout the selected years based on the Scopus database. Findings from this study are hoped to enhance the understanding within academia on DPA's developments as the rapidly changing 5G technology continues to move with much higher efficiency and powerful data speeds. This study proceeds with several suggestions, which are based on its comprehensive bibliometric analysis of research relating to DPA. Findings from bibliometric analysis showed that most published studies are confined to developed and developing countries. Findings also suggested that efforts in future research should be directed towards the evolving 5G technology for other industries apart from telecommunications. Results from keyword analysis also highlighted contributions made by earlier studies in telecommunications, showing the significant role of 5G technology in creating an even more effective component in linking the entire world. This way, future studies are able to improve on the architecture components, topology, limitation and method to improve the performance of the power amplifier. For example, when advanced Doherty power amplifier were used in the appliances around the house, it will make our lives much easier. Same with occupations, when communications are improved which allows users to connect faster making their work done in a jiffy. Furthermore, the bibliometric analysis indicated that these technologies should be created for other economies as well. Other than that, future recommendation is to examine Doherty Power Amplifier topics in other databases than Scopus. Such as IEEE Xplore, Science Direct, Web of Science, Pub Med and others. Moreover, examining these databases into a bibliometrics study might help researchers to identify the best research papers that is related to their topics.

Acknowledgment

The authors would like to express their deepest appreciation to the Ministry of Higher Education Malaysia (MOHE) through the Fundamental Research Grant Scheme (FRGS/1/2019/TK04/UITM/02/28) for funding this research. This research is also supported by Universiti Teknologi MARA (UiTM).

VII. Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

VIII. Author Contribution

The authors confirm contribution to the paper as follows: ***conceptualization:*** *AHAR;* ***formal analysis and investigation:*** *NFMI and AKH;* ***writing–original draft:*** *NAMF;* ***writing–review & editing:*** *AHAR, NFMI and AKH. All authors reviewed the results and approved the final version of the manuscript.*

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