Radio Coverage Prediction in Wireless Networks: A Bibliometric Study



Marianne Alfredine Omonlola Balogoun, Vinasétan Ratheil Houndji, Michel Dossou, and Anne-Carole Honfoga

Abstract The problem of predicting radio coverage is a fundamental step in the wireless networks design process and is nowadays very helpful in reducing drive tests for monitoring. Among the continuous flow of research in this area, a scientific contributions map becomes relevant to guide future researches correctly. This paper provides a bibliometric analysis and future research avenues to predict radio coverage. A structural insight is obtained on conceptual clarification, collaborations, top sources, authors, affiliations, most cited documents, and most cited countries. A total of 3134 documents have been analyzed: 49% are journal papers and 51% are proceedings papers. 60% of them are published during the last seven years. The majority of recent relevant works on the topic are focused on wireless communication systems, specifically 5G. The USA, China, and India are leading the way in research in this field. IEEE access, IEEE transactions on antennas, and propagation are the leading journals.

Keywords Wireless networks · Radio coverage prediction · Bibliometric study

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1 Introduction

Electromagnetic wave propagation is at the heart of several wireless networks used in our daily lives. Among the primary objectives of wireless network operators, coverage and capacity occupy a choice place. To provide optimized coverage and a higher capacity, the network coverage is usually evaluated [1]. During the network design, channel modeling provides sound theoretical guidance for communication systems design. This technique defines the process of characterizing the law of radio waves propagation in realistic environments [2]. Path loss or path attenuation is the most important parameter in channel modeling, especially in designing and analyzing the link budget of a telecommunication system. It represents the reduction in power density as the electromagnetic wave propagates in free space. In wireless communication and signal propagation, the signal may be attenuated due to propagation effects (reflection, refraction, diffraction, free space loss, aperture medium coupling loss, absorption) or terrain contours (environment, antennas height and location, distance between transmitter and receiver, propagation medium) [3]. Indeed, seven major path loss categories have been identified in the literature: Theoretical/Foundational Models, Basic Models, Terrain Models, Supplementary Models, Stochastic Fading Models, Many-Ray Models, and Active Measurement Models. For an accurate mapping of the extent of radio coverage existing and planned networks, researchers have developed various methods and approaches whose effectiveness is determined by the predictive power of the path loss model in many diverse environments and at distinct frequencies [4]. The introduction of machine learning (ML) approaches also provided competitive results with state of the art [1, 2, 5–8].

With the voluminous, fragmented, and controversial streams of research on this topic produced by the emphasis at this time on empirical contributions, bibliometric analysis is suitable for scientific mapping [9]. It gives many exciting overviews of the most relevant works, sources, countries, words, expressions, affiliations, authors, etc. To the best of our knowledge, there is no bibliometric study on this topic in the literature. This paper aims to deliver a bibliometric study to obtain a structural insight into different methods and several parameters involved in predicting radio coverage.

The rest of the paper is structured as follows: after Sect. 2 which presents the research methodology, Sect. 3 presents the highlights of this work. Sections 4 and 5 address respectively our results and discussions and the conclusion with some research directions.

2 Methodology

This paper presents the bibliometric study based on data extracted from Web of Science (WoS) [10] database. On July 31, 2022, bibliometrics data were picked from the WoS using this search string: (“radio coverage” OR “received signal strength” OR “radio wave propagation” OR “path loss”) AND (prediction OR prevision OR calculation OR computation OR forecasting OR evaluation OR estimation).

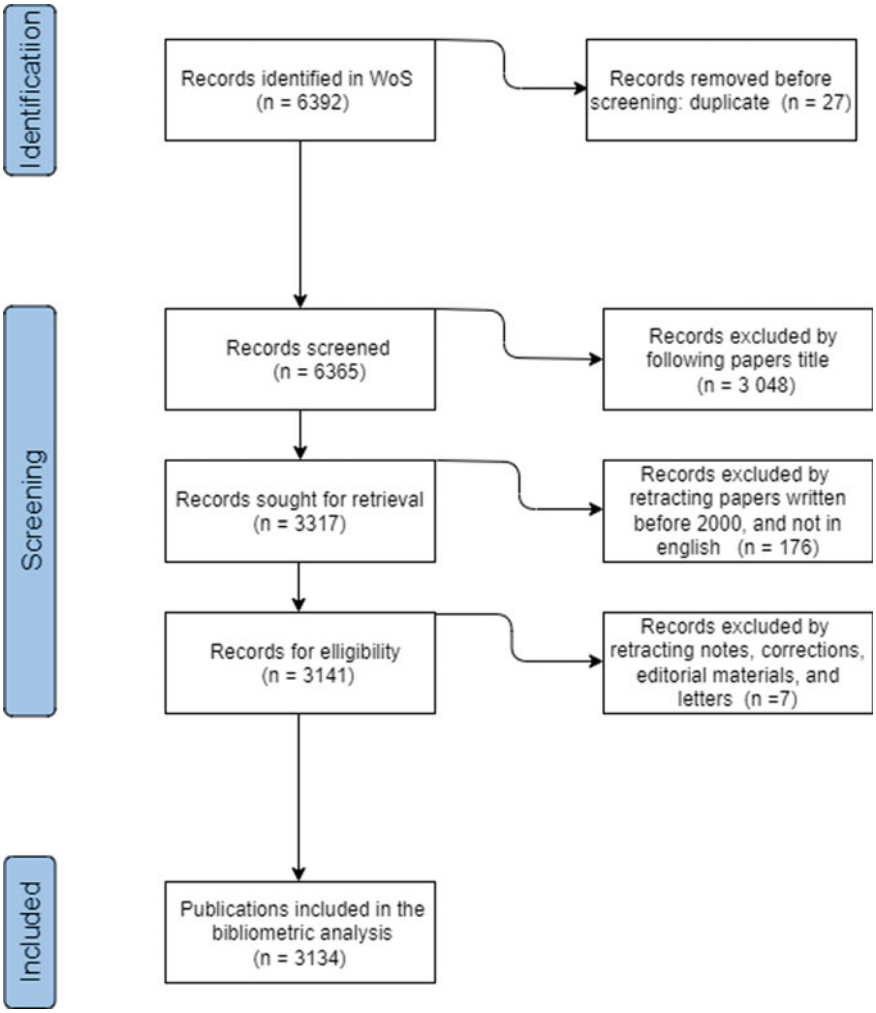

Fig. 1 PRISMA flow of selection process

Figure 1 shows the selection process using the Preferred Systematic Reviews and Meta-Analyses (PRISMA). In short, for further analysis, 6392 publications between 1984 and 2022 have been identified in WoS related to *radio coverage prediction*. A significant number of publications per year have been noticed between 2000 and 2022. A total of 3134 relevant publications have been identified from these publications including articles, article book chapters, article data papers, article early accesses, article proceedings papers, proceedings papers, and reviews. Furthermore, previously selected records were exported to plain text format files from WoS including authors, publication year, title, abstract, subject categories, and source journal.

Then, the relevant documents acquired could be effectively used to perform bibliometric analysis using biblioshiny. The last one is the shiny interface of the Bibliometrix library programmed in R for comprehensive science mapping analysis of scientific literature [9]. In addition, it facilitates integration with other statistical and graphical packages.

3 Highlights

This bibliometric analysis based on *radio coverage prediction* could help researchers to have a bibliometric overview of papers relative to this area of research. Our study shows the dynamics of research on *radio coverage prediction* between 2000 and 2022. The research works from 2015 to 2022 represent 60% of the considered documents. The recent interest in this theme is proven. It is explained by other prediction techniques and the apparition of 5G networks. Actually, most of the most cited documents in the field are about 5G and IEEE 801.1 is the standard widely used.

It also highlighted that prediction models vary according to different environments, transmitters frequencies, etc. In addition, Nigeria is the African country that contributes the most to scientific's production on this topic and has collaborated with China, Spain, etc. Nevertheless, research in this area remains poor in Africa on the need for empirical work. The USA is also very open to collaborating with other countries.

Grunwald et al. [4] worked on an overview of research on existing approaches (traditional and ML model-based) spanning more than 60 years till 2012. In the last decade, works in the same direction have not yet been done.

The topic is quite open to African researchers and scholars. Therefore, studying the possibilities in the African context to predict radio coverage will be helpful for wireless network design and supervision.

Today, it is shown that ML or deep learning gives competitive results with state-of-the-art [11]. So, machine learning approaches will help to predict radio coverage based on actual measurements of path loss (urban and rural areas, especially in forest-covered high hills or mountains [12]).

The deployment of Digital Terrestrial Television in Benin can be used to get true measurements to provide efficient machine learning algorithms to predict radio coverage as in [8].

Supplementary efforts such as [1] on predicting radio coverage for wireless networks to reduce long and costly drive tests can be made with other deep learning and machine learning models.

All path loss prediction models are based on works in the physical layer. Few works show advances in the application of machine learning in wireless communication with other layers such as the MAC layer, network layer, and application layer [13, 14] for other purposes like power control. Thus, to supervise the network, accurate predictions can be made by exploring additional pieces of information on others network layers.

4 Results and Discussion

This section presents and discusses the key findings from our bibliometric study.

4.1 Main Documents on Radio Coverage Prediction

Table 1 presents primary data collection information from the WoS database containing publications related to *radio coverage prediction*. After screening the data, 3134 documents were included in this study. Of these documents, 49% are articles and 51% are proceedings papers. They were written by 7971 authors, with 132 of them writing 151 documents alone. On average, these documents have been published for less than 8 years till 2022, indicating that there is recent activity in this research field.

Table 1 Main information about documents on *radio coverage prediction* in WoS

Description	Results
Main information about data	
Time span	2000:2022
Sources (journals, books, etc.)	1516
Documents	3134
Annual growth rate %	5.12
Document average age	7.32
Average citations per doc	10.43
References	49,995
Document contents	
Keywords plus (ID)	1812
Author's keywords (DE)	7294
Authors	
Authors	7971
Authors of single-authored documents	132
Authors collaboration	
Single-authored documents	151
Co-authors per documents	3.7
International co-authorship %	20.07
Document types	
Article	1476
Article; book chapter	7
Article; data paper	3
Article; early access	6
Article; proceedings paper	49
Proceedings paper	1577
Review	16

4.2 Annual Scientific Production

The total number of documents published each year in the period from 2000 to 2022 is shown in Fig. 2. After 2014, the annual production is at least 200, except in 2022. The 2022 papers number is justified by the fact that the year is still in progress. The highest production occurred in 2018 with 305 papers, followed by a small decrease in the number of papers published in the years 2019–2021, possibly due to the COVID-19 pandemic. Nevertheless, 60% of related works on *radio coverage prediction* have been published in the last seven years.

Annual scientific production of *radio coverage prediction* can be identified by considering key sources. The top 20 most relevant sources are shown in Table 2, with IEEE access being the most relevant source, having published 99 documents. This is followed by IEEE transactions on antennas and propagation with 87 documents, IEEE transactions on vehicular technology with 72, Wireless personal communications with 58, and IEEE transactions on wireless communications with 56. The growth dynamics of these first five sources is depicted in Fig. 3.

4.3 Source Growth Dynamics

Figure 3 shows that activity for "IEEE access" was minimal prior to 2015, but has since become the leading publication source. This is likely due to its creation in 2013 and its openness to various areas covered by "IEEE," giving it more chances to publish than other sources. Meanwhile, "IEEE transactions on antennas and propagation" has seen exponential growth and is the most suitable journal to publish research related to *radio coverage prediction*.

4.4 Top 20 Relevant Authors Based on the Number of Papers

The ranking of the 20 relevant authors who have the highest number of publications is shown in Fig. 4. Most of these authors are academics, but M. V. S. N. Prasad from the Radio and Atmospheric Sciences of Division National Physical Laboratory, which is a non-academic laboratory, is also included. The two first authors Bo Ai and Zhong, Zhangdui from the same Beijing Jiaotong University published 20 papers each on the topic. The fact that they have written so many documents on the subject until 2022 (see Fig. 5) shows that this field is interesting and still relevant. In addition, the authors in this shortlist are mostly from Asia, followed by Europa and Africa (especially Nigeria). The interest of these continents in the topic is highlighted. A look at Fig. 5 shows that Zhong, Zhangdui worked in the highest time span and Faruk Nasir from the University of Ilorin in Nigeria worked in the lowest time span. Further research can be performed to provide more empirical work.

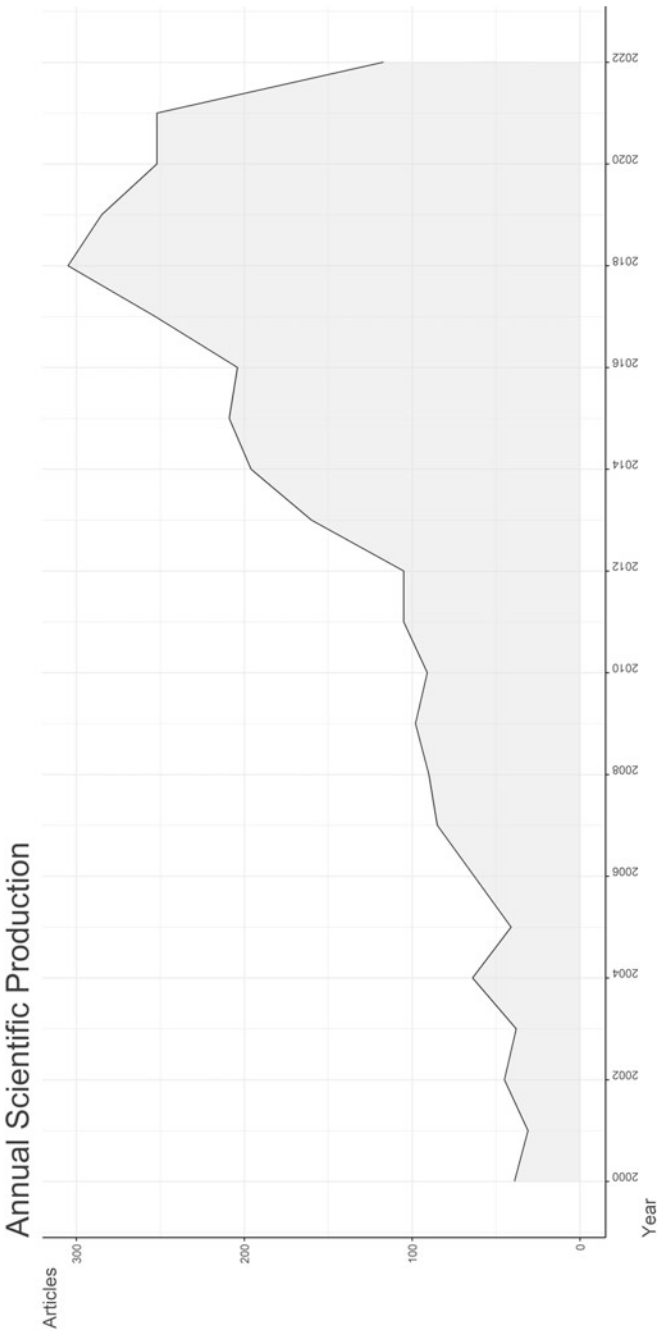

Fig. 2 Annual scientific production

Table 2 Top 20 most relevant sources

Sources	Articles
IEEE access	99
IEEE transactions on antennas and propagation	87
IEEE transactions on vehicular technology	72
Wireless personal communications	58
IEEE transactions on wireless communications	56
Sensors	50
IEEE antennas and wireless propagation letters	43
Radio science	27
IEEE journal on selected areas in communications	23
IEICE transactions on communications	23
IET microwaves antennas and propagation	22
IEEE antennas and propagation magazine	20
IEEE transactions on communications	20
IEEE internet of things journal	19
International journal of antennas and propagation	19
IET communications	18
Wireless communications and mobile computing	17
Microwave and optical technology letters	16
Wireless networks	16
EURASIP journal on wireless communications and networking	15

4.5 Top 20 Most Relevant Affiliations

Figure 6 displays the 20 most relevant affiliations. The Beijing Jiaotong University (China) leads the ranking with 66 publications, followed by the Beijing University of Posts and Telecommunications (China) with 62, etc. All of these affiliations are universities, and the four first are China's universities. The University of Michigan, the University of British, and the University of Toronto are the American universities on the shortlist. The University of Ilorin and Covenant University from Nigeria are the two African universities on this shortlist. The other affiliations are Asian and European, respectively.

4.6 Top 20 Most Cited Documents

Most globally cited documents are presented in Fig. 7. The two first most cited documents ([15] cited 1370 times and [16] cited 840 times) are both about radio coverage prediction in the microwave and millimeter-wave radio spectrum which corresponds

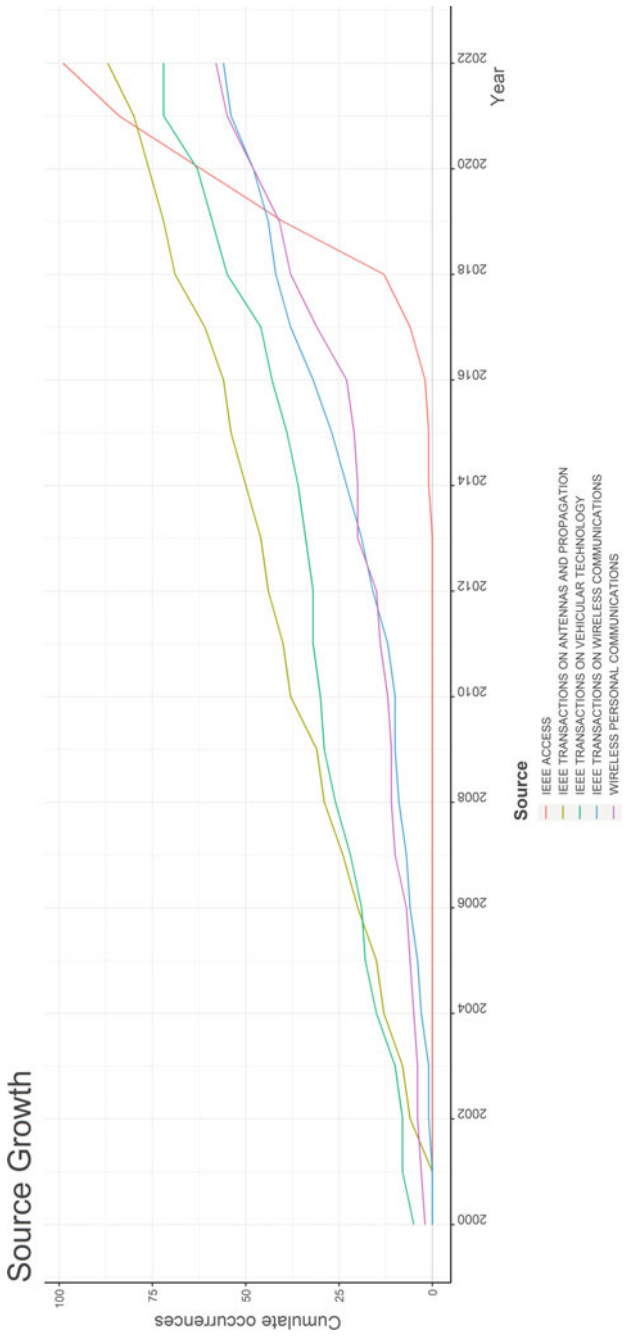

Fig. 3 Source growth dynamics

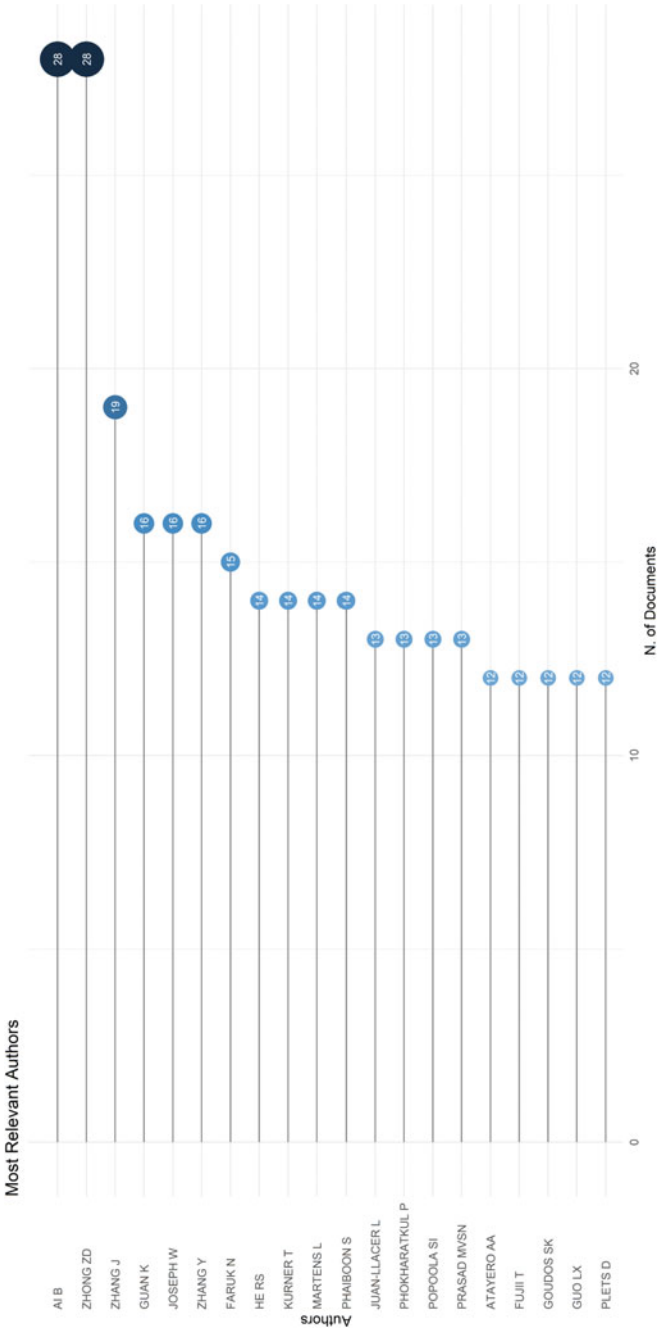

Fig. 4 Top 20 relevant authors

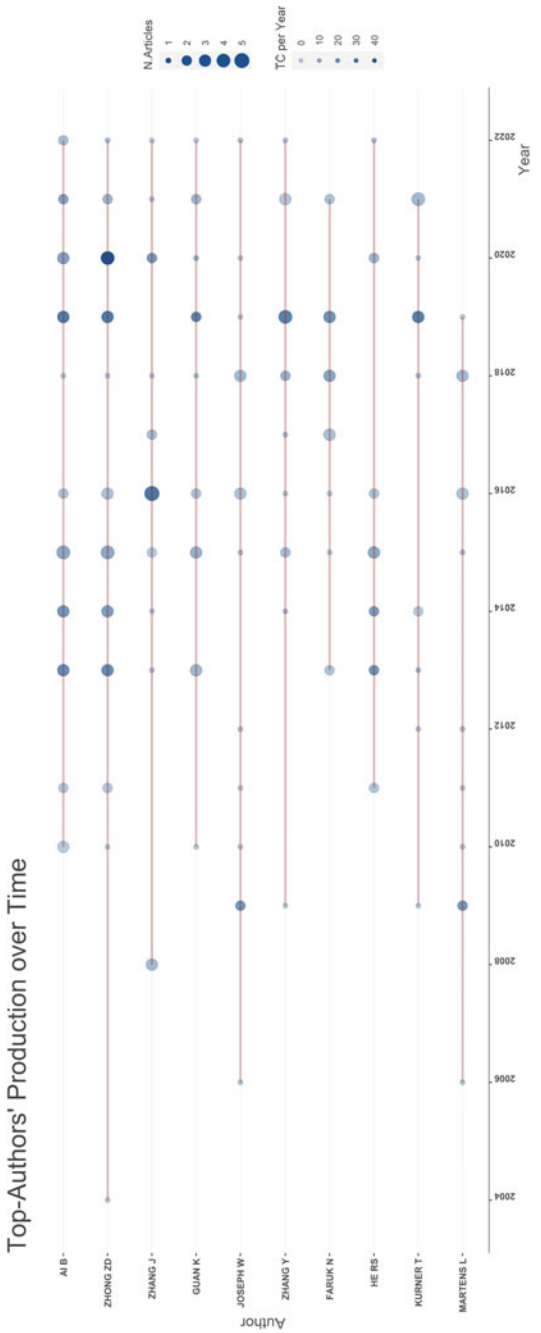

Fig. 5 Top 10 authors' production over time

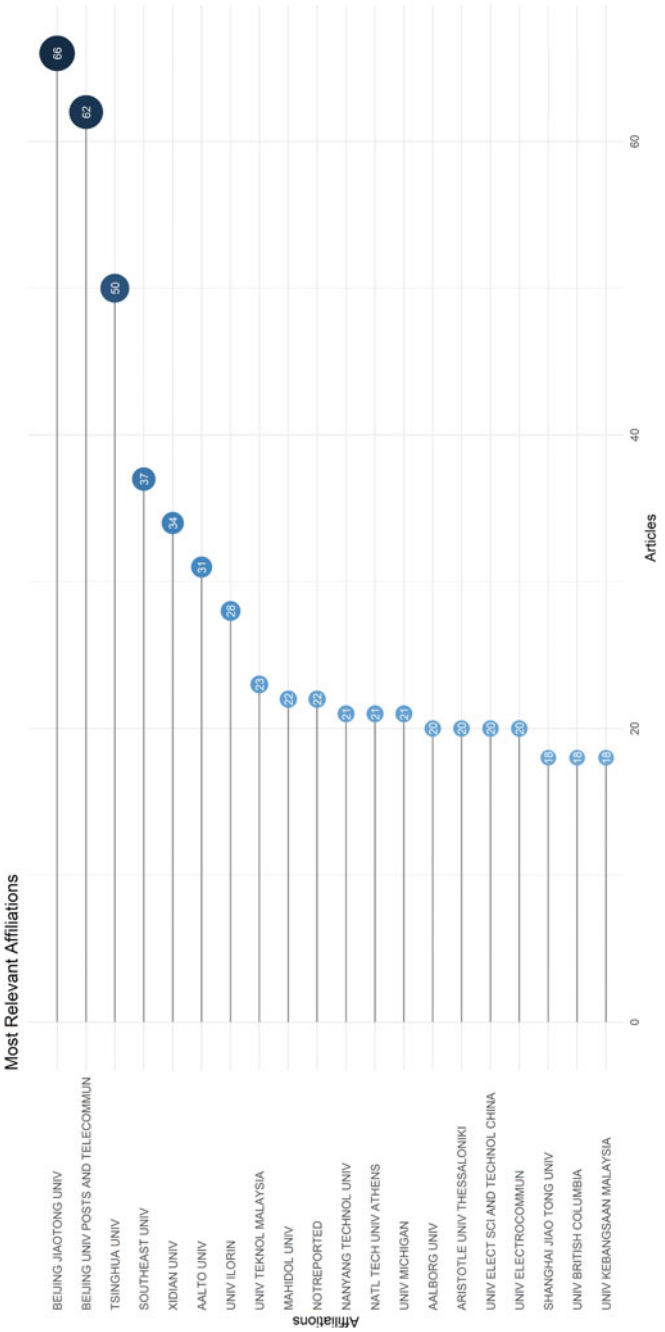

Fig. 6 Top 20 most relevant affiliations

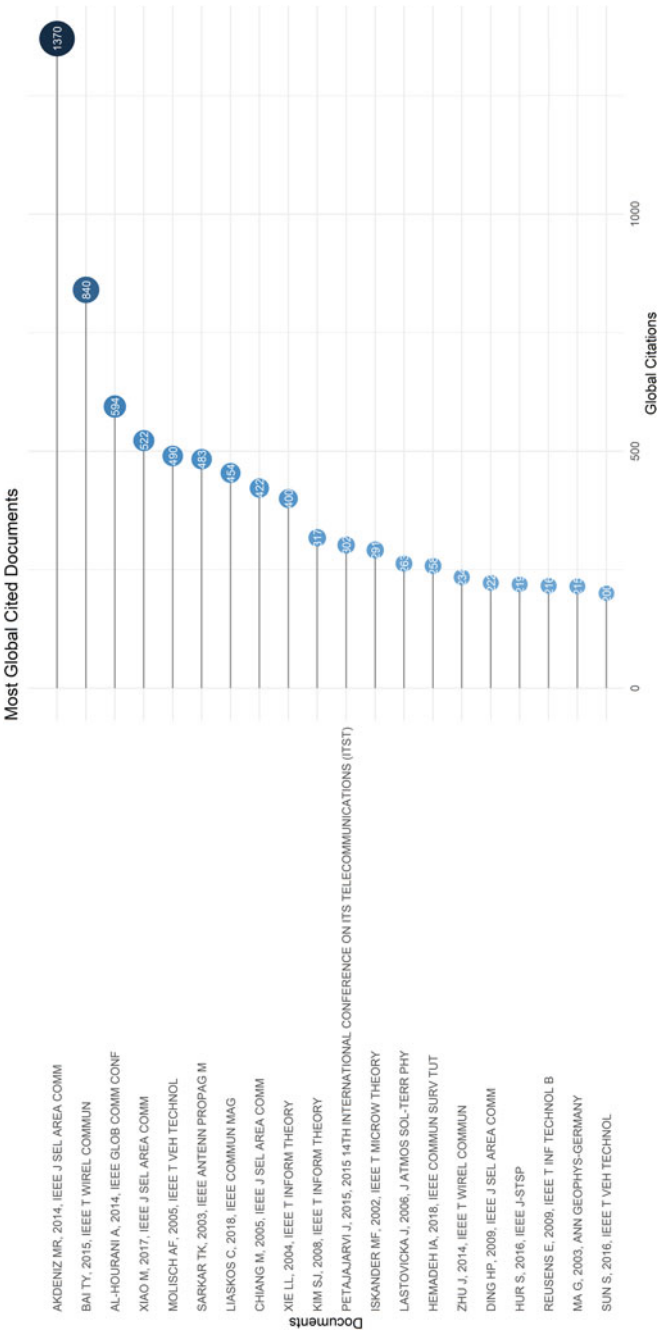

Fig. 7 Top 20 most cited documents

with 5G spectrum. In this shortlist, five documents are determined as not really relevant. The remaining papers have been ranged into six categories which are: mobile systems (1), all wireless communication systems (2), airborne wireless communication systems (3), terrestrial wireless communications systems (4), microwave and millimeter-wave radio spectrum (5), IoT (WBAN, LPWAN, UWB) (6).

Recent works are focused on all wireless communication systems in general. Especially microwave and millimeter-wave radio spectrum have been more studied. Table 3 presents the key objective per category of fifteen relevant papers of these twenty most cited qualitative method documents.

4.7 Top 20 Scientific Production on Radio Coverage Prediction

Table 4 shows the country's scientific production on *radio coverage prediction*. It is noticed that China is at the top of the list with 1119 documents. The second position is occupied by the USA with 811 documents. The third and fourth in rank are respectively India with 361 documents and Japan with 340. Other countries on this shortlist produced less than 300 documents. Asia and Europa countries are dominant and globally developed countries produce more than others.

4.8 Words Cloud Relative to Radio Coverage Prediction

Figure 8 presents the words cloud relative to *radio coverage prediction*. Table 5 is obtained by merging singular and plural words or expressions, and words with multiple scriptures. It shows the twenty words or expressions most used by authors in their documents. Understanding these keywords and the links between them will help to better understand the subject. Within these expressions, *model* appears 231 times. So the most important for radio coverage prediction are different prediction models. These models are designed using different approaches like purely theoretical modeling, empirically fitting often traditional statistical modeling or machine learning *algorithms*, etc. Indeed, during *wireless communication systems* design, the knowledge of *propagation channel estimation* is necessary. It includes *path loss* prediction which ensures good networks *performance* and a *capacity optimization*.

During *transmission* from antennas, the electric field is converted and transmitted as radio waves subject to phenomena like *diffraction* due to the *environment diversity*. In addition, the prediction through the *scattering* channel can be done for outdoor or indoor localization and at different frequencies. So, propagation models that estimate path loss based on the range are valid only for the modeling environment and its resemblers and usually do not provide accurate temporal and spatial information. However, ray-tracing models are specific to the 3D environment and

Table 3 Key objectives of most cited documents

Category	Author/date	Objective
1	Sarkar (2003)	To design a suitable receiver that will receive the transmitted signal, distorted due to the channel multipath and dispersion effects, and will decode the transmitted signal. An understanding of the various propagation models can actually address both problems
2	Phillips (2013) Liaskos et al. (2018) Kim et al. (2008)	To provide a literature survey and make an analysis of the works performed on this topic since 60 years. To make a fairly continuous research on path loss prediction methods and give future directions for research in this area. To propose a radical new approach, enabling deterministic programmable control over the behavior of wireless environments. To derive performance bounds and achievable rates and compare the relative for exchanging messages between two nodes over a shared half-duplex channel with the help of a relay for three protocols including the Gaussian case with path loss
3	Al-Hourani (2014)	To propose a statistical propagation model dependent on the elevation angle between the terminal and the platform for predicting the air-to-ground path loss between a low altitude platform and a terrestrial terminal on the urban environment properties
4	Iskander and Yun (2002)	To describe ray-tracing application, classical empirical models and statistical models, new challenges about propagation prediction and some new approaches for meeting these challenges
5	Sun et al. (2016) Hur et al. (2016) Hemadeh et al. (2018) Xiao et al. (2017) Akdeniz et al. (2014) Bai and Heath (2015)	To compare three candidates large-scale propagation models and provide one more suitable for the entire microwave and millimeter-wave radio spectrum use case. To present 28 GHz wideband propagation channel characteristics for millimeter-wave urban cellular communication systems and compare measurement data with ray-tracing data. To understand the millimeter-wave band's properties and present associated channel models while reporting on the main measurement and modeling campaigns. To present a comprehensive survey of millimeter-wave communications for future mobile networks by summarizing the recent channel measurement campaigns, modeling results, and discussing recent signs of progress. To derive detailed spatial statistical channels models to provide a realistic assessment of Mmwave micro-and picocellular networks in a dense urban deployment using recent real-world measurements at 28 and 73 GHz in New York. To propose a general framework to evaluate the coverage and rate performance in mmWave cellular networks
6	Reusens et al. (2009) Petajajarvi et al. (2015) Molisch (2005)	To discuss propagation channel and propose path loss models to evaluate energy efficiency of single-hop and multihop network topologies in wireless body area networks for remote health monitoring. To present an overview of ultrawideband propagation channels and to identify the key parameters for channel models and describe deterministic and stochastic models

appropriate to urban environment scenarios. Nowadays, machine learning or deep learning *algorithms* also are used.

Table 4 Top 20 scientific production countries

Rank	Region	Freq
1	China	1119
2	USA	811
3	India	361
4	Japan	340
5	UK	246
6	South Korea	211
7	Germany	197
8	Canada	191
9	Spain	160
10	Italy	155
11	France	146
12	Malaysia	133
13	Russia	122
14	Brazil	120
15	Turkey	119
16	Nigeria	113
17	Greece	109
18	Finland	85
19	Australia	70
20	Iran	70

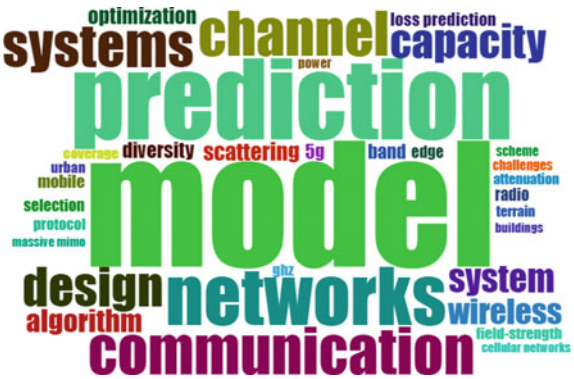

Fig. 8 Words cloud

Table 5 Most cited words

Words	Occurrences
Model	231
Propagation	200
Prediction	150
Systems	133
Networks	121
Path loss	100
Communication	87
Channel	83
Performance	78
Design	73
Capacity	64
Algorithms	57
Diffraction	55
Environments	52
Wireless	47
Channel estimation	41
Scattering	33
Optimization	31
Transmission	31
Diversity	29

4.9 Co-citation Network

The study of co-citation is explained as follows: When two authors are cited simultaneously, then the latter has a co-citation relationship. It is an important measure to assess the intellectual flow and development of research activities in a particular discipline. Figure 9 shows a co-citation relationship between 50 authors. These strong links in the co-citation network translate that authors keep an overview of most documents from 1968 to 2017. So, the authors highly assess the intellectual flow and development of research activities on *radio coverage prediction*. Two clusters are observed around Hata (1980) and Rappaport (2013). Their works are respectively about propagation loss in radio mobile services [17] and millimeter-wave mobile communications for 5G cellular [18]. These papers are references, and suitable results have been gotten.

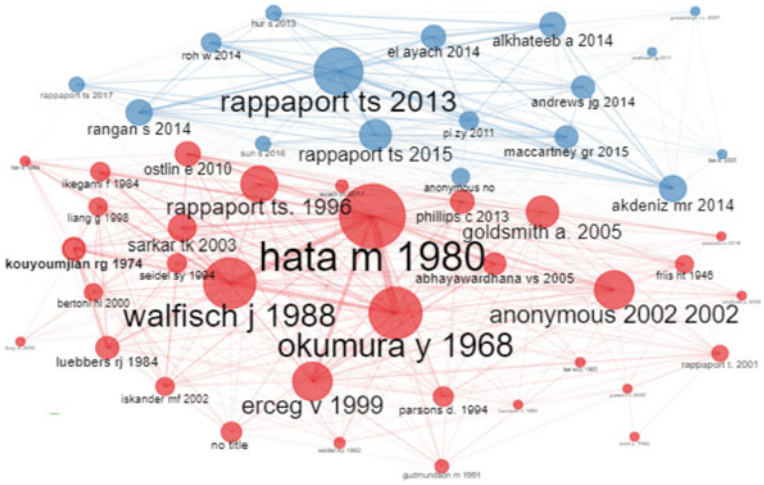

Fig. 9 Co-citation network

4.10 Conceptual Structure Map

Figure 10 displays the conceptual structure map. Two clusters are identified. This co-words analysis shows that most of the words displayed are nearby the concepts of *radio* and *power* and form the first cluster. The second cluster is around *urban* environment. This structure map also demonstrates that path loss prediction is part of both clusters.

4.11 Co-occurrence Network

Co-occurrence is the relation between two words or expressions when they appear simultaneously in the same area. This relation is shown in Fig. 11 with edges between keywords in documents related to *radio coverage prediction*. Two clusters have been identified. The first cluster is about propagation prediction models. The second cluster is about communication network system design.

4.12 Country Collaboration

Figure 12 shows the collaboration between countries. USA scholars and researchers strongly collaborated a lot with China ones in particular and collaboration is strong between America and Asia. Collaboration between African countries and others remains poor. Little collaboration is observed with Nigeria.

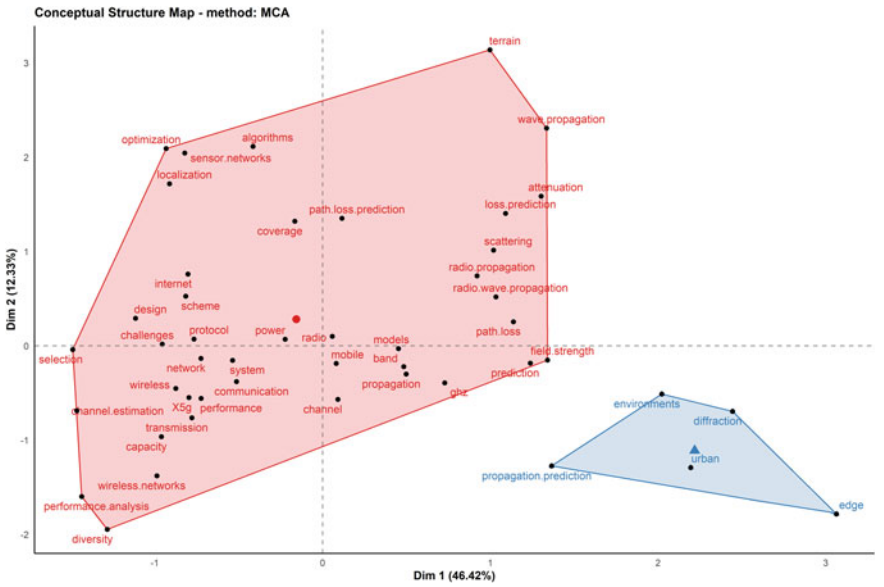

Fig. 10 Conceptual structure map

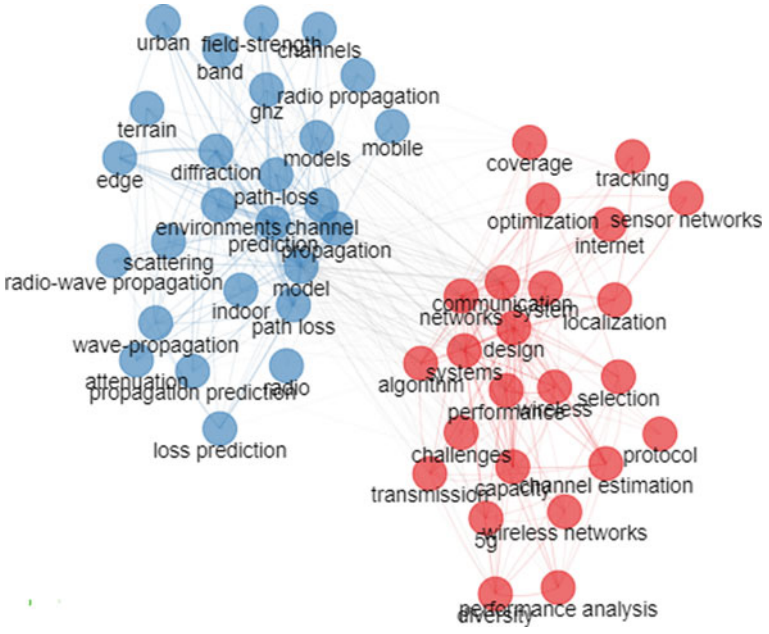

Fig. 11 Co-occurrence network

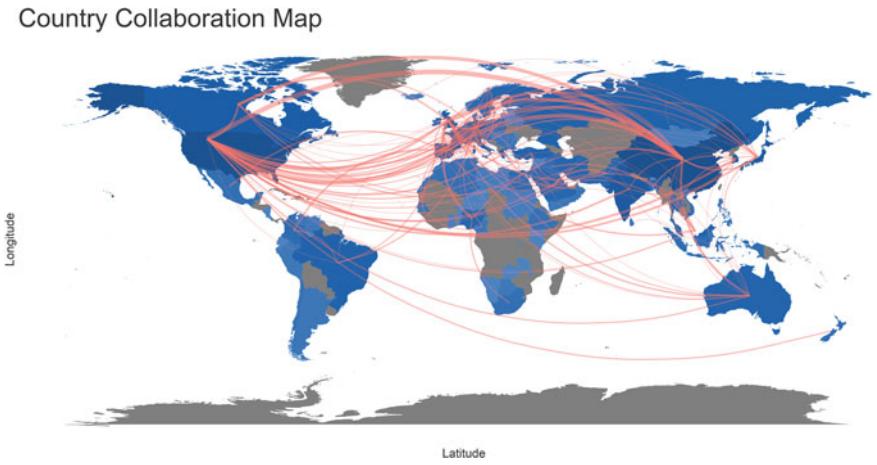

Fig. 12 Country collaboration map

5 Conclusion and Future Research Avenues

In this paper, bibliometric analysis of data extracted from WoS on radio coverage prediction has been presented. This analysis was conducted on 3134 documents identified from 2000 to 2022. Out of these publications, over 51% were proceedings papers and 49% were articles. The relevant parameters taken into account were the relevant publication sources, countries, words, expressions, documents, the main authors, and their affiliations. The results prove that interest in this topic has increased during the past seven years (2015–2022), as shown by the 60% of publications recorded. Additionally, it has been established that wireless communication systems, especially 5G, are the main field of research related to recent works on the subject. Within the top 20 relevant sources, five of them stand out: "IEEE access," "IEEE transactions on antennas and propagation," "IEEE transactions on vehicular technology," "Wireless personal communications," and "IEEE transactions on wireless communications." This study highlights that developed countries such as China and the USA are the most productive. As the research interest in African countries is not very noticeable, Nigeria is the only one among the top twenty productive nations. This bibliometric analysis constitutes a starting point for researchers working on this topic and is beneficial for conducting a thorough literature review on radio coverage prediction. African researchers should primarily concentrate on investigating topics related to radio coverage prediction and field measurements, in order to solve environmental issues such as broadcast network coverage and mobile network coverage. Future research can focus on measurement model-based path loss prediction in African environments. Accurate studies are needed in urban and mountainous contexts, and ray tracing models can be explored to provide spatial and temporal information to enrich machine learning models. Lastly, more work is necessary with a focus on monitoring, to reduce long and costly drive tests.

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