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PAPER

Global Growth and Trends of In-Body Communication Research—Insight From Bibliometric Analysis

Syifaul Fuada(✉), Guanghui Ma, Marcos Katz

Centre for Wireless Communications, Faculty of ITEE, University of Oulu, Oulu, Finland

syifaul.fuada@oulu.fi

ABSTRACT

A bibliometric analysis was conducted to examine research on in-body communication. This study aimed to assess the research growth in different countries, identify influential authors for potential international collaboration, investigate research challenges, and explore future prospects for in-body communication. A total of 148 articles written in English from journals and conference proceedings were gathered from the Scopus database. These articles cover the period from 2006 until August 2023. VOS Viewer 1.6.19 and Tableau Cloud were used to analyze the data. The analysis reveals that research on in-body communication has shown fluctuations but overall tends to increase. The United States, Finland, and Japan were identified as the leading countries (top three) in terms of publication quantity, while researchers from Norway, Finland, and Morocco received the highest number of citations. The University of Oulu in Finland has emerged as a productive institution in this field. Collaborative research opportunities exist with the countries mentioned above or with authors who have expertise in this topic. The dominant research topic within this field pertains to ultra-wideband (UWB) technology. One of the future challenges in this field is the exploration of optical wireless communication (OWC) as a potential communication medium for in-body devices, such as electronic devices implanted in the human body. This includes improving performance to meet the requirements for in-body communication devices. Additionally, this paper provides further insights into the progress of research on OWC for in-body communication conducted in our laboratory.

KEYWORDS

bibliometric analysis, VOS viewer, in-body communication, optical wireless communication, implants, in-body devices

1 INTRODUCTION

Wireless communication has made significant advancements in the healthcare industry [1], [2], providing numerous benefits to patients, doctors, and nursing staff [3]. This includes the ability to remotely monitor chronic diseases. In-body communication emerges as a promising wireless technology, enabling data transmission to and

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from in-body devices (e.g., implants, sensors, energy harvester devices, smart pills, etc.) [4]. Pacemakers, cardiac defibrillators, cochelar implants, insulin pumps, brain implants, and retinal implants are examples of implants that have pivotal applications in the healthcare field, specifically in wireless sensing networks. These devices capture bio-signals, convert them into signals, and wirelessly transmit them to external units for monitoring and identifying biological processes [5]. Additionally, in-body devices typically need to be controlled remotely, for instance to change settings, to install a new user profile, to request for sensor measurements, etc. Further exploration in this field is essential for advancing this technology. Given the profound implications of this technology, it is imperative to conduct a rigorous examination of existing research trends in order to identify and address any gaps in the current state of the art. This state-of-the-art study will cover various aspects, such as the feasibility of communication networks, the confidentiality of patient privacy data, the provision of power supplies for implants, and more.

Numerous methodologies exist for identifying current research trends, including classical and systematic literature reviews, meta-analyses, mapping analyses, and bibliometric studies [6]. Among these approaches, bibliometric analysis stands out for its unique capabilities, such as the rapid identification of research gaps and potential collaboration avenues [7]. As a quantitative technique, bibliometric analysis serves as a powerful tool for mapping the evolving landscape of specific research domains [8]. It aggregates data from various sources and presents it in a visual format, thereby facilitating data-driven conclusions and decision-making processes [9]. In recent years, bibliometrics has emerged as a preferred method for conducting literature reviews in various research fields. Some examples include corrosion in medical implants [10], e-health initiatives [11], future-oriented green communication [12], blockchain applications [13], smart healthcare systems [14], and the Internet of Things (IoT) in healthcare settings [15].

Moreover, in addition to its practicality in identifying emerging trends, bibliometric analysis also enables the evaluation of other factors, such as the performance of academic journals and the examination of the intellectual structure of a specific field based on existing scholarly literature. This analysis helps clarify the patterns that emerge during the process of field modernization. The data used in bibliometric analysis are typically objective and extensive, including various measurements such as publication count, subject matter, keywords, and citations. However, interpreting this data may involve objective assessment and subjective analysis using informed methodologies and techniques. When conducted correctly, bibliometric research can provide a solid foundation for advancing a field in innovative and impactful ways. It enables researchers to comprehensively understand the field, identify gaps in knowledge, explore new avenues for investigation, and position their expected contributions [16].

Remarkably, despite its growing relevance, no bibliometric studies have been undertaken to explore the landscape of in-body communication research. This study aims to address the research gap by conducting a comprehensive bibliometric analysis focused on in-body communication. The primary objective of this work is to provide readers with a comprehensive understanding of the growth of research on in-body communication. It aims to identify the leading country in this field, highlight potential collaborative opportunities, pinpoint forthcoming challenges, and offer unique insights from our own institutional research on this emerging subject. This research will utilize VOS Viewer, a meta-analysis tool that has the capability to examine the relationship between research articles in terms of specific themes and subjects [17]. Furthermore, this tool has the capability to present data on patterns in in-body communication and visually represent them through easily interpretable graphs.

2 METHODS

In this study, we conducted four stages (Figure 1) to perform a bibliometric analysis of in-body communications: data collection, visualization, analysis, and additional insights.

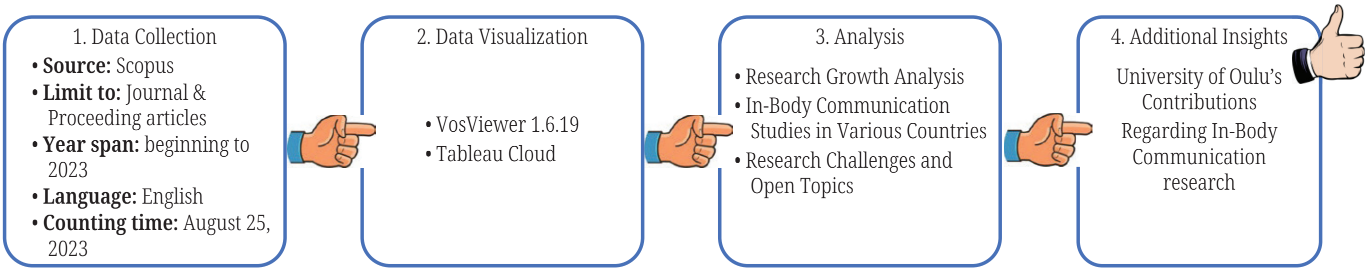

Fig. 1. Research phases of bibliometric analysis

The first phase of the study involved gathering academic articles from various sources. Nevertheless, for the purposes of this analysis, we exclusively focused on the Scopus database. This choice was made due to Scopus's established reputation for providing high-quality scholarly publications and its widespread usage in bibliometric studies [18–21]. Scopus is also commonly used by researchers for bibliometric analysis. Access to the Scopus Explorer was graciously facilitated by the University of Oulu through the campus intranet network. The data acquisition phase spanned from 2006 to the end of 2023. Our search strategy utilized the keywords "In Body Communication" and "In Body Wireless Communication," with the following search parameters: TITLE-ABS-KEY ("In Body Communication" OR "In Body Wireless Communication") AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "cp")) AND (LIMIT-TO (LANGUAGE, "English")). This search yielded a corpus of 148 articles, which included 52 journal articles (35.1%) and 96 conference papers (64.9%). All of the articles were sourced exclusively from English-language publications. Subsequent to meeting the search criteria, the data gathered, which includes key metadata such as authorship, citation counts, institutional affiliations, keywords, and abstracts, was exported in CSV format for further analysis.

Visualization tools are essential for conducting a thorough bibliometric analysis, and there are numerous software options available for this purpose. For this study, we selected VOS Viewer (version 1.6.19, released on January 23, 2023) [22] and the cloud-based version of Tableau, which can be accessed at https://www.tableau.com/products/cloud-bi. These platforms offer a wide range of data visualization techniques, allowing us to effectively present key findings and fulfill our research objectives. These include generating graphs that depict the temporal trajectory of in-body communication research from its inception to 2023, producing a geographical heatmap that quantifies the volume of research by country, and establishing interrelations between keywords extracted from the selected articles. To ensure methodological integrity and minimize potential bias caused by frequent database updates, all search procedures were performed on a single day, specifically on August 25, 2023 (match with the important date of author in [74]). As this research is limited to the analysis of secondary data and does not involve human subjects, informed consent was deemed unnecessary.

Through the analysis of this visual data, our objective is to gain an understanding of the research advancements in the field of in-body communication as well as to obtain valuable insights into future ideas and challenges within this domain. Additionally, we will provide a detailed description of the research progress on in-body communication conducted at the University of Oulu, specifically within the Centre for Wireless Communications. Our aim is to offer further insight into the contributions made by our institution to this field. It is important to acknowledge that our university is globally recognized as one of the leading authorities on this topic.

Our objective in analyzing this visual data is twofold: firstly, to gain a comprehensive understanding of the progress and innovations in the field of in-body communication; and secondly, to extract practical insights into potential challenges and research opportunities within this specialized domain. In addition to the broader analysis, this study will clarify the research contributions originating from the University of Oulu, specifically within the scope of the Centre for Wireless Communications. This focused analysis aims to shed light on the influential role played by our institution in this area of research, highlighting the global recognition of the University of Oulu as a leading authority on the subject.

3 RESULTS AND ANALYSIS

3.1 Analysis of research growth

Based on the information from Scopus, a total of 148 scholarly articles have been compiled on the topic of in-body communication since its inception until August 2023 (Figure 2). The initial research on this subject was published in 2006 in the *Proceedings of the 4th Asia-Pacific Conference on Environmental Electromagnetics* (CEEM 2006) by Wang and Su [23]. Wang was affiliated with the Nagoya Institute of Technology in Japan, while Su was affiliated with BeiHang University in China. This article has been indexed by Scopus and has been referenced 23 times. According to the Google Scholar database, it has been cited 36 times. Their study focused on a modeling approach to assess the feasibility of using ultra-wideband (UWB) systems for biomedical applications, particularly for wireless communication within the human body. The results obtained by conducting mathematical calculations on the UWB signal propagation channel and the proposed modulation indicate that the UWB system satisfies the necessary criteria for viability. It can be employed for wireless communication inside the body, as demonstrated by the observed bit error rate (BER) performance.

In the following year (2007), the proceedings featured four articles. One author, Higgins, affiliated with the United Kingdom, made the most significant contribution by authoring three of the articles [24–26]. Notably, these articles discuss the possibilities of wireless communication for electronic implants within the human body, a method referred to as "in-body communication," which relies on radio frequency (RF) technology.

In 2008, there was a dearth of scholarly publications addressing this specific subject matter. However, the following year saw a notable increase in the number of published articles, with the simultaneous release of five articles. "Path loss model for inhomogeneous human muscle tissue in the context of in-body communication," authored by Kurup et al. from Ghent University in Belgium and published in the electronics letter [27], was pioneering among them. The authors successfully developed a model to quantify the attenuation of signal strength within the muscle tissue of the human body, specifically for implants operating at a frequency of 2.4 GHz. This groundbreaking model serves as a valuable reference for designing and implementing in-body communication systems. The significance of this paper is evidenced by its recognition, with 37 citations in the Scopus database and 55 in the Google Scholar database.

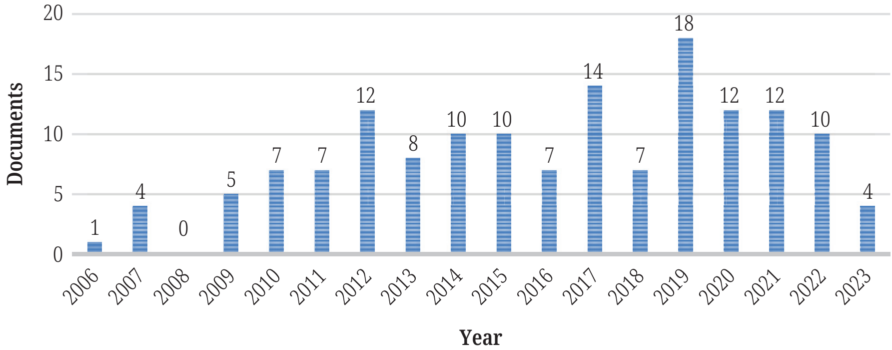

Fig. 2. Growth of in-body communication research as reflected in Scopus

During the period from 2010 to 2022, the number of publications relating to in-body communication varied but showed an overall upward trend. The highest number of publications occurred in 2022, totaling 18. These publications consisted of six journal articles and 12 proceedings articles. From 2019 to 2022, research on in-body communications primarily focused on the characteristics of UWB channels in RF communication, antenna design, and ultrasound. Furthermore, some authors have started to investigate near infrared (NIR) as a communication technology, as evidenced by [28–31]. As of now, in 2023, only four publications have been recorded. However, it is important to note that this data was collected up until August 2023, and there is still a possibility of an increase by the end of the year.

In Table 1 we have examined the top three authors in the field of in-body communication. The Scopus H-index, number of citations, total publications, current affiliation, country, and Scopus author ID of the individuals have been recorded. Balasingham and Iinatti were found to be the highest-ranked authors, with 11 and 10 publications, respectively. Kissi and Säreströniemi followed in second and third place, with nine and eight publications, respectively. The ranking based on the number of citations reflects the impact of the authors in the research area. Balasingham, with the highest number of citations and Scopus H-index, is regarded as the most prolific author. He currently holds the position of professor of medical signal processing and communications at the department of electronic systems, faculty of information technology and electrical engineering, Oslo University Hospital, and Norwegian University of Science and Technology. His research interests include robust short-range communications, wireless body area sensor networks (WBANs), microwave short-range sensing, localization and tracking of mobile sensors, and nanoscale communication networks.

Table 1. Top authors with the number of citations (counted on August 25, 2023)

Rank	Author	Citations	Total Publication	Scopus H-Index	Affiliation	Country	Scopus ID
I	Balasingham, I. (10)	4,271	308	33	Oslo University Hospital	Norway	6602773063
I	Iinatti, J. (10)	2,981	230	24	University of Oulu	Finland	3560731930
II	Kissi, C. (9)	158	22	8	Ibn Tofail University	Morocco	57207348180
III	Säreströniemi, M. (8)	286	53	9	University of Oulu	Finland	8394130300
IV	Bauch, G.	3,879	244	31	TU Hamburg	Germany	6701608210
IV	Hamalainen, M.	2,167	167	22	University of Oulu	Finland	7102722291
IV	Saito, K.	2,040	201	20	Chiba University	Japan	55576600100

(Continued)

Table 1. Top authors with the number of citations (counted on August 25, 2023) *(Continued)*

Rank	Author	Citations	Total Publication	Scopus H-Index	Affiliation	Country	Scopus ID
IV	Cardona, N.	1,629	188	22	Valencia Polytechnic University	Spain	6701536191
IV	Garcia-Pardo, C.	611	63	15			56644889700
IV	Leelatien, P.	41	13	3	Thammasat University	Thailand	36195806000
IV	Brumm, J.C.	32	8	3	TU Hamburg	Germany	57195568647

3.2 Mapping in-body communication research in various countries

This section provides a summary of the top five institutions that have demonstrated high productivity in the field of in-body communication, as indicated in Table 2. Our findings reveal that the University of Oulu in Finland, Oslo University Hospital in Norway, and the National School of Applied Sciences Kenitra in Morocco have emerged as the most productive institutions, with 16, 11, and 10 publications, respectively. The University of Oulu, in collaboration with the Centre for Wireless Communications, is one of the leading research centers and receives significant financial support from organizations such as the Academy of Finland (recently is named as Research Council of Finland), the Horizon 2020 framework program, and the European Regional Development Fund.

The rankings for the field of in-body communication in Finland and Norway, as displayed in Table 2, are influenced by the contributions of academics Balasingham, Iinatti, and Hamalainen, as listed in Table 1. Notably, the United States holds the top ranking in terms of the geographical distribution of scientific articles, as indicated in Table 3. This accomplishment has been achieved through numerous research partnerships with both domestic and international universities (as visualized in Figure 3), consolidating the United States' leading position. The figure demonstrates a strong research collaboration on the topic of in-body communication between Finland, Morocco, and the United States. Figure 3 was generated using the VOS Viewer software for co-author analysis (by country), with a minimum threshold of 10 country documents. Out of the 37 countries examined, only nine met this threshold requirement. Among those nine countries, only six displayed interconnections. Norway, Spain, and Belgium were not involved in collaborations with these six countries; therefore, they were not included in the visualization. The United States demonstrated connections with Morocco, Finland, Germany, and the United Kingdom, with respective link strengths of 10, 13, 1, and 1, resulting in a total link strength of 25. The link strengths between keywords indicate the frequency of co-occurrence in publications [32], [33]. While the overall link strength of the United States exceeds that of Morocco ($n = 20$), it is lower than Finland's ($n = 27$) due to Finland's higher number of research papers co-authored with other countries.

The top five countries in terms of productivity are the United States, Finland, and Japan, with 21, 18, and 17 publications, respectively. This implies that the topic of in-body communication is extensively investigated and widely recognized across three continents: North America, Europe, and Asia. This is evidenced by the presence of these countries in the list of the top ten publishing countries. Table 3 also shows the distribution of contributors from various institutions, categorized as university-based or non-based, in each country. For instance, Germany benefits from the contributions of university-based institutions such as the Technical University (TU) Hamburg, the University of Erlangen-Nuremberg, TU Berlin, TU Dresden, and TU Kaiserslautern, as well as non-university-based institutions like Nokia Bell Labs Germany and Advico Microelectronics GmbH. In Finland, the University of Oulu stands out as a significant influence in the research field of in-body communications.

Table 2. The top-five most productive institutions

Rank	Institution	Country	Number of Publications
I	University of Oulu	Finland	16
II	Oslo University hospital	Norway	11
III	The National School of Applied Sciences Kenitra	Morocco	10
IV	Centre for Wireless Communications, University of Oulu	Finland	9
IV	Ibn Tofail University	Morocco	9
IV	Norwegian University of Science and Technology	Norway	9
V	Chiba University	Japan	8
V	Valencia Polytechnic University	Spain	8
V	Purdue University	United States	8

Table 3. The top-five leading countries

Rank	Country	Number of Publications	Contributors	
			University-based Institution	Non-University-based Institution
I	United States 	21	Purdue University, University of Illinois, MIT, San Diego State University, Worcester Polytechnic Institute, Harvard University, Oregon State University, Texas A&M University, Virginia Polytechnic Institute and State University	Nokia Bell Labs United States, NEVA Electromagnetics, Massachusetts General Hospital
II	Finland 	18	University of Oulu	Nokia Bell Labs Finland, VTT Technical Research Centre of Finland
III	Japan 	17	Nippon Institute of Technology, University of Tsukuba, Chiba University, Tohoku University, Nagoya Institute of Technology, Keio University	National Institute of Information and Communications Technology
IV	United Kingdom 	14	Aston University, Queen Mary University of London, University of Warwick, Queen's University Belfast, Newcastle University	Toshiba Research Europe, Zarlink Semiconductor
V	Germany 	13	TU *Hamburg*, University of Erlangen–Nuremberg, TU Berlin, TU Dresden, TU *Kaiserslautern*	Nokia Bell Labs Germany, Advico Microelectronics GmbH

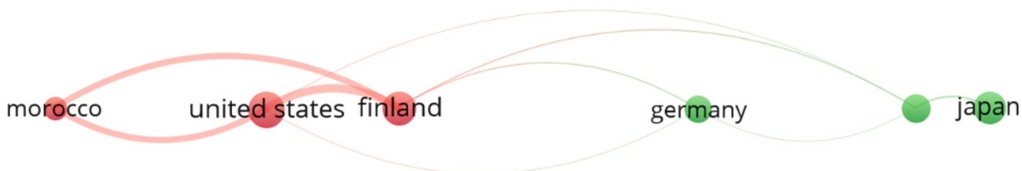

Fig. 3. Network visualization among country containing Morocco, United States, Finland, Germany, United Kingdom, and Japan

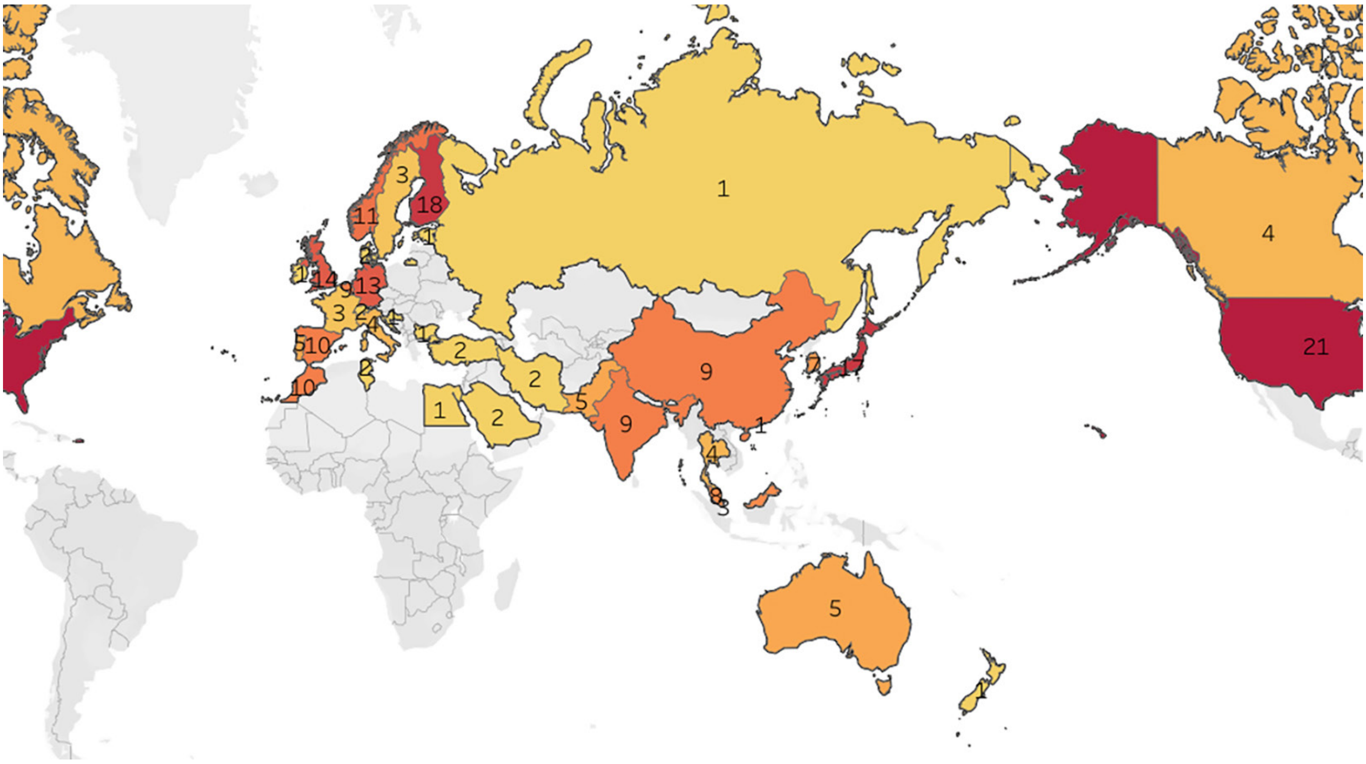

Fig. 4. Map showcasing the research publications in the field of in-body communication across different countries

In summary, our research findings suggest that the United States, Finland, and Japan offer the greatest opportunities for research collaboration in the field of in-body communication design and development. This is supported by the number of publications, as shown in Table 3. Regarding WBAN, or medical ICT, specifically in-body communication, there is potential for collaboration with Balasingham's research group at Oslo University Hospital and the Norwegian University of Science and Technology, as well as Iinati's research group at the University of Oulu (see Table 2). Both teams possess extensive expertise in this field, as demonstrated by the significant number of citations their articles have received (see Table 1). Subsequently, the data extracted from Table 3 is used to generate Figure 4, which visually depicts the global distribution of research studies conducted on in-body communication across different countries. This visual representation is constructed using the Tableau Cloud platform and presents the data on a geographic map. The map is shaded using a 15-level gradient, where a darker hue indicates a higher count of studies, while a lighter shade indicates a lower count. For instance, the United States is prominently displayed in a vibrant red color due to its significant number of publications, whereas Russia is represented in yellow owing to its low number of publications. It is noteworthy to mention that Finland holds a prominent position among countries conducting extensive research in the field of in-body communication on a global scale.

3.3 Mapping in-body communication research challenges and open topics

The examination of current research trends enables the analysis of research challenges. These trends can be identified by evaluating the frequency and relevance of keywords commonly used by researchers. Figure 5 displays the data on the relationship between keywords in in-body communication research from

2006 to the present. The data is presented in overlay mode [34], allowing us to analyze the most recent research by observing the color changes over the years. This data has been analyzed for the past 17 years to gain insights into the current research in this field. The creation of the keyword linkage map was made possible by the VOS Viewer 1.6.19 software, which utilized data from Scopus. This map, also known as a co-occurrence analysis of keywords, was used to investigate the most significant keywords and themes in the selected documents. In this study, a threshold of one occurrence was set to select keywords. This means that only keywords that appeared at least once in the selected documents were considered. As a result, 1258 keywords met this threshold. The size of the circle represents the number of keywords used, with larger circles indicating a higher number of keywords (see Figure 5).

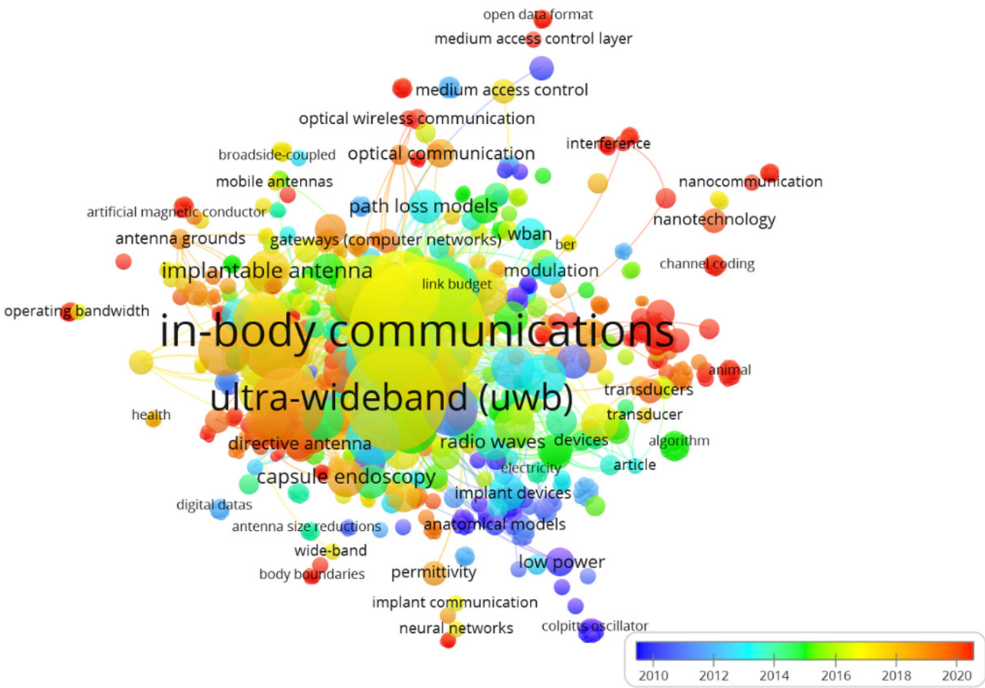

Fig. 5. Keywords in the field of in-body communication research

Through this analysis, it was discovered that several keywords were frequently used in the literature on in-body communication, such as: 1) UWB; 2) in-body communication; 3) WBAN; 4) wearable antenna; and 5) microwave antenna. This finding highlights the extensive amount of research that has been conducted and continues to be conducted in these specific areas. UWB technology has gained recognition as a promising choice for implant communication systems due to its numerous advantages, such as high data rates and simple transceivers [35]. This technology has been successfully employed in various medical monitoring applications [36], including tumor detection, heart rate and respiration monitoring, and glucose level monitoring. However, there are limitations to UWB technology, such as increased signal loss in biological tissues and vulnerability to temperature variations in biological tissues [31]. Nevertheless, the use of implantable antennas based on UWB technology for medical purposes is growing. This is because they have the ability to penetrate the human body and provide valuable health-related data using the parameters mentioned above [37]. The design of UWB antennas for implantable devices presents three primary challenges: limited antenna dimensions for implantation, the need for bio-compatibility, and the requirement for electrical isolation from the human body [38].

Additionally, we have identified the keywords that are least commonly found in the existing literature. This suggests that these specific areas deserve the attention of future researchers and require further investigation to bridge the gap. The keywords in question are: 1) medium access control; 2) optical communication or optical wireless communication (OWC); 3) wideband antenna; 4) 6G; 5) mobile antennas; 6) patch antennas; 7) algorithm; 8) neural networks; 9) implanted antenna; 10) low power; 11) anatomical model; 12) energy efficiency; 13) channel coding; and 14) orthogonal frequency division signify the absence of sufficient research in these domains, emphasizing the need for additional scholarly exploration. When examined on an annual basis, the red keywords represent the most recent research topics. OWC, also known as optical communications, stands out as a particularly recent research interest among these topics.

The inclusion of OWC as a communication core in the in-body communication system provides notable advantages compared to RF-based communication, which is commonly used in current implants [39]. OWC offers a reliable and energy-efficient solution, addressing concerns related to radio radiation in RF-based communications [39]. It also provides additional benefits such as wide bandwidth availability, absence of interference, improved data transmission rates, and enhanced data security and privacy for patients. The design and development of OWC-based in-body communication systems for biomedical applications necessitate further exploration to meet the requirements of medical systems that demand high-speed and secure data transfer, especially when communicating with implanted devices [39]. In researching in-body communication, various metrics such as reliability, security, throughput, energy, and latency should be considered as primary areas of focus [28]. Achieving low-latency communications on in-body devices for telemonitoring is crucial because there is a need for real-time data to enable immediate diagnostic and therapeutic interventions. Considering the critical role of in-body devices in supporting and saving lives, the importance of low-latency communication cannot be overstated. It is crucial to ensuring timely treatment. It should be acknowledged that compromises may need to be made regarding the latency of the communication link for data offloading as it becomes feasible to schedule diagnostic procedures.

Over the next decade and beyond, the implementation of OWC in implantable communication technology is expected to have a significant impact on key technological developments in the field of biomedical applications [5]. In conjunction with advancements in OWC and various complementary technologies, numerous research findings have emerged to address various obstacles. One of these endeavors is to enhance communication efficiency by reducing the BER [40].

3.4 University of Oulu's contributions to in-body communications research topics

The implementation of technology in the healthcare sector is crucial for enhancing the well-being of individuals and saving lives during critical health circumstances. The utilization of implantable electronic devices in the human body has become a prominent area of interest in biomedical and telecommunication engineering. It plays a crucial role in remotely monitoring specific bodily functions, providing appropriate interventions for health conditions such as cardiac issues, and serving as a diagnostic tool to promptly address various health concerns. Several technologies currently available in the medical field include pacemakers, brain stimulators, defibrillators, smart pills, insulin pumps, cochlear implants, and others. These devices can be externally controlled, allowing medical staff to wirelessly change their settings. Ultrasound [41], or RF technology, can be used to facilitate this communication link.

However, communicating with electronic devices implanted in the human body presents various challenges due to the unique characteristics of the human body as a medium [31]. Unlike indoor, outdoor, or underwater channels, the human body, as a channel in this context, contains a complex arrangement of tissues such as skin, fat, blood, melanin, bones, and water. Each of these various tissues possesses unique dielectric properties [42], as well as distinct absorption and scattering coefficients [43]. Developing an in-body communication system will enable the integration of these devices with other wireless devices, ultimately leading to the realization of the smart hospital concept in the future [44]. In the future, it is expected that crucial medical ICT functions, such as diagnostics, treatment, wireless communication, activation, inhibition, and monitoring of cellular activity, among others, will be performed by utilizing a thorough understanding of bio-tissues as a medium for transmission [45].

The Centre for Wireless Communications, under the University of Oulu, has made significant contributions to the field of in-body communications research. Professor Jari Iinati's work, as reflected in the Scopus database, primarily focuses on the RF spectrum, specifically antenna design, channel characteristics, and propagation [46], [47]. In addition to RF research, Professor Marcos Katz and his team have also explored the optical spectrum [45]. The experiments conducted on pork ex-vivo samples demonstrate that, compared to UWB, optical-based communication through biological networks experiences less power loss [31]. Professor Katz's team has investigated OWC at short distances to establish highly secure links within the body or between the body and external devices. The use of optical technology in in-body communication applications is believed to ensure secure data exchange, particularly due to the confidential nature of patient health data [48]. The optical channel in biological tissues also presents challenges, such as scattering, attenuation, and complex media composed of different tissues. Therefore, the selection of an appropriate wavelength is crucial. Figure 6 depicts the progress in cutting-edge research on in-body communication using light as a communication medium. All experiments were conducted using an artificial phantom, actual bones, and fresh porcine samples. The artificial phantom used in the study was created at the University of Oulu [49], [50]. The research was conducted in two phases: the initial investigation phase (2019–2021) and the optimization phase (2022 onward).

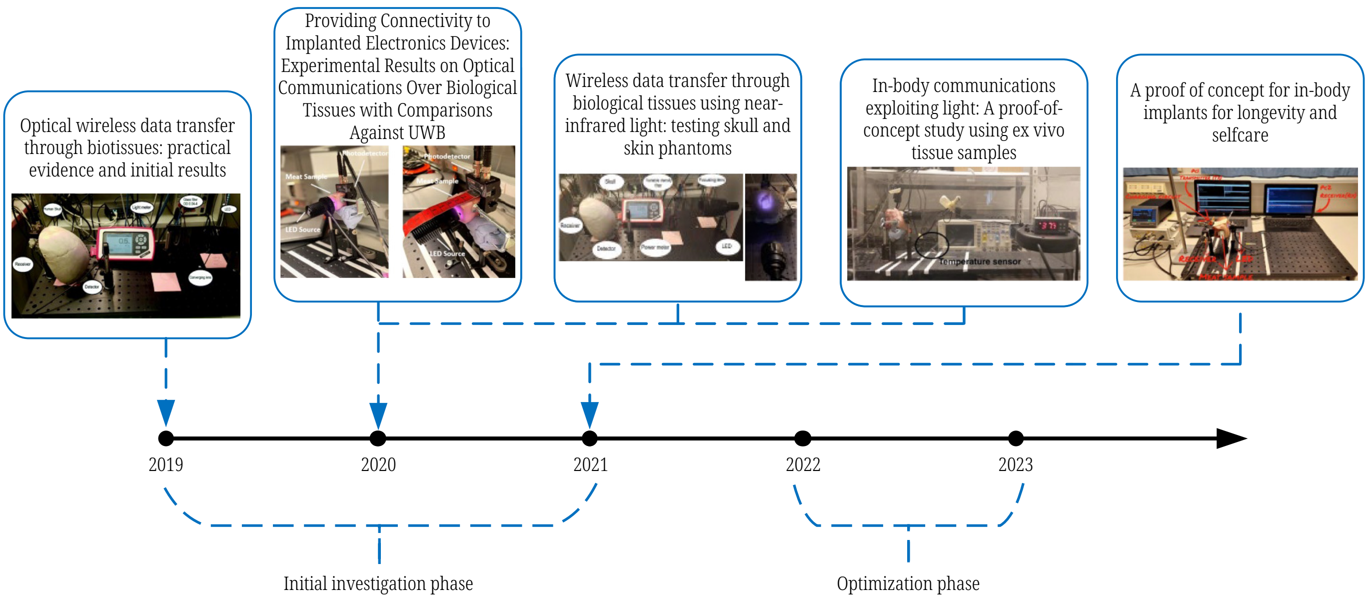

Fig. 6. The research timeline focuses on the exploration of in-body communication exploiting light as a medium at the Centre for Wireless Communications, University of Oulu, Finland

The utilization of RF techniques poses challenges related to frequency interference, patient privacy concerns, and security. On the other hand, ultrasound technology, such as that used in ultrasound sonography (USG), is considered safe because it has a limited interaction distance with implants. However, its data transmission rate is lower compared to RF and optical approaches. Beginning in 2019, Professor Katz's team conducted experiments utilizing NIR light and a straightforward communication link [29]. The propagation of the NIR spectrum (around 800–1000 nm) in biological tissue is relatively efficient due to its radiation being less influenced by the main obstacles: absorption and scattering characteristics [51]. The findings are promising, demonstrating the ability to transmit data through a bio-tissue-mimicking phantom at close distances. This was achieved by considering parameters such as tissue depth and LED input current. The thickness of different tissue types in relation to optical density and transmitted power were clearly observed. Subsequent experiments adhered to the optical transmission power outlined in the ANSI.Z136.1-2007 standard, which governs laser safety (2W/cm^2 for a 1-second exposure at a wavelength of 830 nm). Exceeding the maximum limits of received power and electrical current can easily harm biotissue. Therefore, preserving tissue health is a concern that should be given careful consideration during the experiment. The study successfully demonstrated the reception of data at a rate of tens of kilobits per second (kbps) [30]. This rate is considered adequate for the majority of electronic medical implants currently in use. It offers additional benefits, such as improved security, privacy, and safety, which may not always be found in conventional RF communication. Additionally, the team conducted extensive research considering various factors such as the power delivery standard, the amount of current in the LED transmitter, the temperature of the tissue sample, the test scenarios (from outside to inside the body or vice versa), and modulation. The results of the measurements indicate that effective communication can be achieved on a pork tissue sample that is four centimeters thick, with a minimum data rate of 100 kbps [28], using Gaussian Minimum Shift-Keying (GMSK) modulation. The NI USRP-2920 was used for digital signal processing (DSP).

Ongoing studies are being conducted to meet the increasing demands of telecommunication advancements, which require higher data rates. The current state-of-the-art (e.g., 100 kbps) is suitable for many implant communication applications nowadays, including telemonitoring, medical imaging transmission, and uploading or downloading medical profiles or statistics, as evidenced by previous work [28]. But maybe not for cases involving high-bandwidth data, such as the transmission of high-quality images and videos in real-time. At least 1 Mbps will be considered satisfactory for facilitating future implant communications. Achieving a high level of throughput is crucial in the in-body communication system. Accordingly, techniques to achieve higher data rates for numerous future scenarios are essential. One potential solution could be the use of smart pills or other in-body sensors that transmit live streaming video. To achieve this, various potential approaches can be explored to improve throughput and coverage. These include using suitable modulation schemes (such as On-Off Keying, Pulse-Position Modulation, Pulse Width Modulation, Binary Shift Phase Keying, Quadrature Phase Shift Keying, and Quadrature Amplitude Modulation, beyond GMSK), OFDM technique, energy and spectral efficient transmission strategies, advanced modulation schemes, employing multibeam transmission with multiple-input multiple-output (MIMO) techniques, implementing pre-equalizers and post-equalizers, optimizing LED bias-point, and utilizing other methods. It is important to note that all efforts to enhance system performance must also adhere to safety limits, such as the maximum allowable received power and electrical current on the LED. Surpassing these limits may potentially damage biological tissue. To this end, preserving tissue health is an additional concern that should be carefully considered. Additionally, energy harvesting is also a crucial consideration in this context.

The implementation of in-body communication, especially in implanted devices, faces a significant obstacle due to its dependence on battery power. Currently, most implants use batteries that have a limited lifespan, which necessitates replacement surgery when they reach the end of their life [52], [53]. This process imposes physical, psychological, and financial burdens on patients [54]. To address these challenges and prolong the lifespan of implanted devices, it is essential to have a continuous supply of energy. Energy harvesting methods offer a promising solution for powering devices within the body [52], [55]. By significantly extending battery life, these methods have the potential to enhance user comfort. Energy harvesting has emerged as a prominent subject of investigation within the field of in-body communication. This line of research focuses on converting various available energy sources, such as human motion, body heat, and external sources such as visible light or near-infrared, into usable energy for implanted devices [56].

When designing an in-body communication system, it is crucial to prioritize data security issues. Then, incorporate high-capacity power banks and utilize energy-harvesting mechanisms. OWC can effectively enhance data security by reducing vulnerability to remote hacking. Furthermore, photovoltaic cells can be an excellent energy-harvesting device to power in-body devices [54], [57]. In 2021, Prof. Katz's research team investigated simultaneous optical wireless transmission and energy harvesting through tissue using a single beam of the NIR spectrum for the first time [58]. This concept enables both wireless connectivity and power supply for in-body devices simultaneously. The experiment involved transmitting image files to a tissue-mimicking phantom, which lasted for 28 minutes. Energy harvested from photovoltaic cells was subsequently stored in coin batteries using a single beam of NIR light. Within this 28-minute timeframe, the battery received sufficient charging to sustain the in-body device for up to four hours. Although it is feasible to demonstrate data transmission and energy harvesting for in-body devices using a NIR-based single-beam approach, there are challenges to energy harvesting because commercially available photovoltaic cells are not designed to harvest energy from narrow-band NIR light. Instead, their utilization is primarily optimized for the visible light spectrum (wideband), such as sunlight or artificial illumination sources (e.g., flashlights, white LEDs, etc.). Consequently, only a small amount of energy can be harvested.

Further studies are required to optimize the harvested energy. One approach is to increase the transmission power. However, it is essential to comply with regulations, including the maximum limits for transmitter LED current and optical received power. This is because high-power simultaneous data transmission could potentially harm the tissues. Exploring pulse-based transmission techniques is particularly interesting because they enable transmission at a high power level for a very short duration, thereby reducing the potential risk of tissue damage. Ensuring privacy and security in the wireless connection of in-body devices, for instance Pacemakers, is of utmost importance due to their vulnerability to hacking [75]. Hackers can exploit this vulnerability such as manipulating the Pacemaker's operations, creating severe threats to patients [76]. Using sophisticated cryptographic techniques becomes necessary to ensure the security and privacy of these devices and safe to the patients. However, implementing such techniques consumes considerable energy, which is limited within these devices. Energy harvesting techniques can mitigate this concern by providing sufficient power for additional functions, specifically encryption and decryption mechanisms during data transmission. In summary, using energy harvesting will enhance the daily operational cycles with multiple benefits for in-body devices.

The enhancement of optical links is also essential. Previous research has indicated that data transmission is restricted to a depth of 3 cm [28]. The minimum optical distance should be extended to a depth of at least 5 cm. The skin comprises several layers, including the epidermis, dermis, and hypodermis. It has been observed that wavelengths ranging from 600 to 950 nm are more favorable because they experience minimal absorption across all layers of the skin, unlike other wavelengths [59]. Investigating different wavelengths within the range of 750–950 nm is necessary to determine the most suitable option for optical wireless data transmission. This is because the light data needs to penetrate a depth of at least 5 cm.

4 DISCUSSION (STRENGTH AND LIMITATION OF THE STUDY)

To the best of our understanding, this study represents the first investigation of bibliometric analysis conducted on peer-reviewed literature concerning "in body communications" or "in body wireless communications." In order to assess the current state of research in this domain, two widely utilized visualization tools, namely Tableau Cloud and VOS Viewer, were employed to analyze recent advancements and identify areas of focus within this field. Furthermore, we provide a comprehensive overview of the research advancements conducted within our institution, the Centre for Wireless Communications at the University of Oulu, to provide additional contextual understanding of the study of in-body communications.

Nevertheless, it is important to acknowledge certain limitations in our study. Firstly, our data was solely obtained from the Scopus database, excluding other prominent databases such as Web of Science, Dimensions, PubMed, and others. Additionally, we exclusively considered articles published in journals and conference proceedings. However, we contend that the quantity of collected data was sufficient to provide an accurate representation of the current state of research on in-body communication. This is because the Scopus database is widely utilized for bibliometric analysis, as demonstrated by various authors in different fields [60–66]. While the Scopus database is used to search for relevant research, it is important to note that there are numerous journals that are not included in this database. Consequently, publications originating from these unindexed journals may have been missed [15].

It is important to note that our study only included articles in English, potentially overlooking relevant articles published in other languages. Additionally, due to the continuous updating of the database, our study may have overlooked some recent influential papers. Moreover, our study solely focuses on the trend of in-body communication research and does not provide a comprehensive bibliometric analysis. This analysis would include examining the most prolific journals and proceedings, identifying highly cited articles on the topic, and analyzing co-authorship by authors and countries. The ranking of established academic journals holds great importance as it facilitates the dissemination of research findings among researchers and scholars within their respective fields of specialization [67].

Furthermore, our search in Scopus was limited to only two keywords, "in-body communications" and "in-body wireless communications," resulting in a restricted number of articles. We counted a total of 148 articles. To gather a more extensive dataset, it would be beneficial to include other relevant keywords [68], as they are highly essential, such as "implant," "implantable biomedical device," "implantable medical device," "implantable medical electronic," "implantable device," and "implantable electronic device" in our literature search. By using relevant keywords, Scopus can offer a more precise count and retrieve articles that may not explicitly mention "in body communication." This helps to increase the pool of articles available for analysis. A bibliometric review is a valuable method for summarizing large amounts of data and gaining insights into the intellectual structure and emerging trends within a specific research topic or field. This method is particularly useful when conducting a review with a large dataset that would be impractical to review manually. However, in cases where the focus of the review is narrow and the dataset can be managed through manual review, the systematic review method may be more appropriate [7]. In our study, we obtained a dataset of 148 articles from Scopus. Although this dataset is relatively small, it can still be effectively analyzed using bibliometrics. The decision to utilize bibliometrics in this study was driven by the aim of identifying collaboration opportunities and trends within the acquired dataset [69]. Visualizing bibliometric analysis results offers valuable insights for fostering academic collaboration, particularly in research activities, by highlighting active countries, institutions, and researchers. Previous studies on various topics have also utilized datasets of a similar size, consisting of 148 data points, after implementing a rigorous filtering process based on specific criteria. For instance, references [70–72] utilized this dataset size to analyze Halal Destination research, investigate the impact of corruption on foreign direct investment attractiveness, and perform a Board Capital analysis, respectively. Therefore, the utilization of bibliometric methodology in our ongoing study on in-body communication research is in accordance with established practices in the field.

In subsequent studies, it is crucial to utilize appropriate tools, such as Open Refine software, for processing data obtained from Scopus before analyzing it using VOS Viewer. This will facilitate the clustering of keywords with similar meanings, thereby eliminating any potential bias in the selection of keywords [69], [73]. In addition to Open Refine, there are various alternative options available, including Cloudingo, Datameer, Talend Data Fabric, Dataloader.io, *Alteryx,* Compare, and Demand Tools, among others.

5 CONCLUSION

The analysis of research on in-body communication, spanning from its inception in 2006 until 2023, was conducted using a bibliometric approach. Currently, we are in the initial stage of exploration and have solely relied on data from the Scopus database. The findings indicate that research on in-body communication has experienced fluctuations, with an overall upward trend from the early years to 2023, despite a decline in 2008. The leading countries conducting research on this topic are the United States, Finland, and Japan. Meanwhile, the University of Oulu in Finland, Oslo University Hospital in Norway, and the National School of Applied Sciences Kenitra in Morocco have been identified as institutions with a significant number of publications in this field. Opportunities for research collaborations could be pursued at the University of Oulu or by collaborating with the author who has the highest number of citations and expertise in this field. The University of Oulu has made significant contributions through its research and efforts in the field of in-body communication. Among all the articles on in-body communication, the dominant theme found was UWB. The future of in-body communication research presents a clear challenge in the need to investigate OWC as the primary method of communication for implantable electronic devices. Additionally, it is crucial to develop optimization techniques to enhance the performance of optical communication links and improve the independent functioning of systems by implementing energy harvesting techniques.

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8 AUTHORS

Syifaul Fuada received a B.A. in Electrical Engineering Education from Universitas Negeri Malang (UM), Indonesia, and an M.Sc. in Electrical Engineering option Microelectronics from the School of Electrical Engineering and Informatics, Institut Teknologi Bandung (ITB), Indonesia. He was with the University Center of Excellence at Microelectronics (PUI-PT Mikroelektronika) ITB from 2016–2018 as a main researcher. He is a lecturer at the Program Studi Sistem Telekomunikasi Universitas Pendidikan Indonesia (UPI). He is pursuing a doctoral degree at the Faculty of Information Technology and Electrical Engineering (FITEE), Centre for Wireless Communications (CWC), University of Oulu, Oulu, Finland. His research interests include Optical Wireless Communications and medical ICT (E-mail: syifaulfuada@upi.edu or syifaul.fuada@oulu.fi).

Guanghui Ma earned his Bachelor's degree in Electrical Engineering from Xi'an Jiaotong University, China, in 2016. He then achieved a Master's degree in Engineering with first-class honours from the University of Melbourne in 2018. Dr. Ma completed his PhD at Monash University, Australia. Currently, Dr. Ma is conducting research at the Centre for Wireless Communications in the University of Oulu, Finland. His work predominantly centres around the evolution of 6G network architecture, Internet of Things (IoT), visible light communications, and the integration of heterogeneous optical and RF networks (E-mail: guanghui.ma@oulu.fi).

Marcos Katz received the B.S. degree in electrical engineering from the Universidad Nacional de Tucumán, Argentina, in 1987, and the M.S. and Ph.D. degrees in electrical engineering from the University of Oulu, Finland, in 1995 and 2002, respectively. He has worked in different positions at Nokia, Finland, from 1987 to 2001. From 2001 to 2002, he was a Research Scientist with the Centre for Wireless Communications, University of Oulu. From 2003 to 2005, he was a Principal Engineer with the Advanced Research Laboratory, Telecommunications Research and Development Center, Samsung Electronics, Suwon, South Korea. From 2006 to 2009, he has worked as a Chief Research Scientist with VTT, the Technical Research Centre of Finland. He has been a Professor with the Centre for Wireless Communications,

University of Oulu, since December 2009. He has written and edited six books in different areas of mobile and wireless communications. He has written more than 200 publications and holds more than 50 patents. He has served as the Chair of Working Group 5 (on short-range communications) for the Wireless World Research Forum (WWRF), from 2008 to 2012 (E-mail: marcos.katz@oulu.fi).