Understanding the Internet of Nano Things: overview, trends, and challenges

Comprendiendo la Internet de las Nano Cosas: visión general, tendencias y desafíos

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RESUMEN

A través de los años, los avances tecnológicos han llevado a un rápido crecimiento de entornos inteligentes (oficinas, hogares, ciudades, etc.). El aumento de entornos inteligentes sugiere la interconectividad de las aplicaciones y el uso de la Internet. Por esta razón, surge lo que se conoce como Internet de las cosas (IoT, por sus siglas en inglés). La ampliación del concepto IoT brinda acceso a la Internet de las nano cosas (IoNT, por sus siglas en inglés), un nuevo paradigma de redes de comunicación basado en nanotecnología y IoT, en otras palabras, un paradigma con la capacidad de interconectar dispositivos a nano escala a través de redes existentes. Este nuevo paradigma denominado IoNT se presenta al mundo como una opción para diversos campos de aplicación. Por lo tanto, surgen nuevos desafíos y oportunidades de investigación. En consecuencia, este trabajo tiene como objetivo investigar el estado del arte y analizar las tendencias para el uso de IoNT, su aplicación y los desafíos futuros en diferentes campos de interés social, debido a que IoNT se presenta como una opción para la investigación con las capacidades necesarias para involucrarse en muchos campos del bienestar social. Se concluye que la literatura actual de IoNT está prevalecida por las tecnologías, las aplicaciones se enfocan en el cuidado de la salud y no se dispone de una estandarización internacional en cuanto a la privacidad, seguridad o la arquitectura de las nano redes.

Palabras Clave: *Internet de las nano cosas, Internet de las cosas, nanotecnología, nano redes, nano comunicación.*

ABSTRACT

Over the years, technological advancements have led to rapid growth of smart environments (offices, homes, cities, etc.). The increase of intelligent environments suggests the interconnectivity of applications and the use of the Internet. For this reason, arise what is known as the Internet of Things (IoT). The expansion of the IoT concept gives access to the Internet of Nano Things (IoNT). A new communication networks paradigm based on nanotechnology and

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IoT, in other words, a paradigm with the capacity to interconnect nano-scale devices through existing networks. This new paradigm so-called IoNT is presented to the world as an option for various fields of application. Therefore, new challenges and research opportunities have arisen. Consequently, this work aims to investigate state of the art and analyze trends for the use of IoNT, its application and future challenges in different fields of social interest, because IoNT is presented as an option for research with the capacities needed to get involved in many fields of social welfare. It is concluded that technologies prevail current IoNT literature, applications are focused on health care, and there is no international standardization regarding privacy, security or architecture of nano-networks.

Keywords: *Internet of Nano Things (IoNT), Internet of Things (IoT), Nanotechnology, Nano-Networks, Nano Communication.*

1. INTRODUCTION

New technological trends such as the Internet of Things (IoT) have shown that computers are not the only ones with a gateway to the Internet and that there are various devices and objects with this access capability. It has become the most important research topic in the last 10 years (Akyildiz, Pierobon, Balasubramaniam, & Koucheryavy, 2015), whose objective is based on everyday objects having identification, detection, interconnection and processing capabilities to communicate with each other and with services through the Internet to solve a specific and useful need of people (Whitmore, Agarwal, & Da Xu, 2015).

Therefore, IoT has given researchers a thorough view of the interconnection of objects to the Internet, and with it, the Internet of Nano Things (IoNT) has emerged. IoNT adds a new scale in IoT incorporating nano-sensors in the devices, which in turn allows it to connect and communicate through the nanotechnology network with internet.

This new paradigm of communication networks will have an impact in almost all fields of our society, from health to the protection of the environment. Therefore, there are nano-scale properties that require new solutions for communication and that must be provided by the information and communication sciences (Akyildiz & Jornet, 2010b).

The focus of this work is based on the study of the current state of IoNT, which links two approaches where there have been significant advances in recent years such as IoT and nanotechnologies. The aim of this work is to investigate state of the art and analyze trends in the use of IoNT, its application and future challenges in different fields of social interest.

This document specifies the methodology used in section two. Then, we offer the conceptual bases of the study, detailing the definitions and characteristics of IoNT, the capabilities, and possibilities of IoNT in the third and fourth section. In addition, we present the analysis of trends and challenges of IoNT for its use and application in different fields of social interest according to the classification of the literature, emphasizing that current research is based on the dissemination of technologies and that communication aspects are the main challenges that the IoNT systems face. Finally, the conclusions are addressed.

2. METHODOLOGY

This work is carried out from a qualitative methodology in which research on state of the art and an analysis of IoNT trends is carried out. A search, review, and evaluation of the bibliography related to research topics are carried out. The above allows to establish state of the art, determine definitions, characteristics, and possibilities of IoNT. Also, it enables the creation of a series of criteria for the analysis of IoNT trends and challenges

Kitchenham´s work (Kitchenham, 2004) was considered for the selection of the bibliographic material, where several composures were established, such as research questions, keywords, search strings, inclusion and exclusion criteria and selected articles.

2.1. Research Questions

The research questions are based on the stated objective. They will be used for the evaluation of the documents found, responding to the goal of the investigation: RQ1-what is IoNT? RQ2-What are the characteristics of IoNT? RQ3-What are the practices related to IoNT? RQ4-What are the possibilities and trends of IoNT?

2.2. Search Strategy

The search strategy defines the sources of information, keywords and search strings used to locate the bibliographic material. The databases selected were IEEE Xplore, ScienceDirect and Springer Link they have various documents (articles, books, conferences, etc.) with the support of the scientific community (Martínez, 2016). In the same way, Google Scholar search engine was used to carry out inquiries of other documents.

The keywords used were: Nanotechnology, Nanosensors, Nanonetworks, Communication, Internet of nano things, Architecture, Applications, Challenges and they were combined for convenience with logical operators to make the search strings: Nanotechnology "Internet of nano thing", Nanosensor "Internet of nano things", Architecture "Internet of nano things", Applications "Internet of nano things", Challenges "Internet of nano things".

2.3. Inclusion/Exclusion Criteria

The criteria consist of descriptions by which the articles must be considered to download and subsequently apply the research questions. In the inclusion criteria, the articles included will be those with a description of IoNT Characteristics, proposals for IoNT applications, new communication paradigms, proposed devices based on nanotechnology and challenges and IoNT opportunities. The exclusion criteria were the language and incomplete text.

2.4. Selected Articles

In the localized literature, actions were carried out such as reading the title, abstract, and keywords. Subsequently, the inclusion/exclusion criteria and research questions are applied, whose purpose is to obtain information relevant to the research topic. The search provided a total of 269 articles. After applying the inclusion/exclusion criteria and research questions with an answer "yes" 47 articles were selected. Table 1 shows the chosen items.

TABLE 1

Selected articles from the search, review, and evaluation process of the bibliographic material.

ID	AUTHORS	TITLE
D-1	El-din & Manjaiah (2017)	Internet of Nano Things and Industrial Internet of Things
D-2	Nayyar, Puri, & Le (2017)	Internet of Nano Things (IoNT): Next Evolutionary Step in Nanotechnology
D-3	Dabhi & Maheta (2017)	Internet of Nano Things-The Next Big Thing
D-4	Llopis-Lorente et al. (2017)	Interactive models of communication at the nanoscale using nanoparticles that talk to one another
D-5	Gandino, Celozzi, & Rebaudengo (2017)	A Key Management Scheme for Mobile Wireless Sensor Networks
D-6	Balasubramaniam, Jornet, Pierobon, & Koucheryavy (2016)	Guest editorial special issue on the internet of nano things
D-7	Akkari et al. (2016)	Distributed Timely Throughput Optimal Scheduling for the Internet of Nano-Things
D-8	Ali, Aleyadeh, & Abu-Elkhair (2016)	Internet of Nano-Things Network Models and Medical Applications
D-9	Jarmakiewicz, Parobczak, & Maslanka (2016)	On the Internet of Nano Things in healthcare network
D-10	OTEC, IBEC, & VHIR (2016)	BENCHMARKING INTERNACIONAL

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D-11	Afsharinejad, Davy, Jennings, & Brennan (2016)	Performance analysis of plant monitoring nanosensor networks at THz frequencies
D-12	Ali & Abu-Elkheir (2015)	Internet of nano-things healthcare applications: Requirements, opportunities, and challenges
D-13	Dressler & Fischer (2015)	Connecting in-body nano communication with body area networks: Challenges and opportunities of the Internet of Nano Things
D-14	Miraz, Ali, Excell, & Picking (2015)	A review on Internet of Things (IoT), Internet of Everything (IoE) and Internet of Nano Things (IoNT)
D-15	Akyildiz, Pierobon, Balasubramaniam, & Koucheryavy (2015)	The internet of Bio-Nano things
D-16	Bhargava, Ivanov & Donnelly (2015)	Internet of Nano Things for Dairy Farming
D-17	Stuerzebecher, Fuchs, Zeitner, & Tuennermann (2015)	High-resolution proximity lithography for nano-optical components
D-18	Loscri, Marchal, Mitton, Fortino, & Vasilakos (2014)	Security and privacy in molecular communication and networking: Opportunities and challenges
D-19	Balasubramaniam & Kangasharju (2013)	Realizing the internet of nano things: Challenges, solutions, and applications
D-20	Jornet & Akyildiz (2013)	Graphene-based Plasmonic Nano-Antenna for Terahertz Band Communication in Nanonetworks
D-21	Dressler & Kargl (2012a)	Security in nano communication: Challenges and open research issues

D-22	Dressler & Kargl (2012b)	Towards security in nano-communication: Challenges and opportunities
D-23	Jornet & Akyildiz (2012b)	The Internet of Multimedia Nano-Things in the Terahertz Band
D-24	Jornet & Akyildiz (2012a)	The internet of multimedia Nano-Things
D-25	Smith et al. (2012)	Design and fabrication of nanoscale ultrasonic transducers
D-26	Maynard (2012)	Nano-technology and nano-toxicology
D-27	Kalkan & Levi (2012)	Key distribution scheme for peer-to-peer communication in mobile underwater wireless sensor networks
D-28	Hung, Hsu, Shu, & Wen (2012)	On the performance of a rapid synchronization algorithm for IR-UWB receivers
D-29	Akyildiz, Jornet, & Pierobon (2011)	Nanonetworks: A New Frontier in Communications
D-30	Sorkin & Zhang (2011)	Graphene-based pressure nano-sensors
D-31	Wu et al. (2011)	High-frequency scaled graphene transistors on diamond-like carbon
D-32	Takeuchi & Mora (2011)	Divulgación y formación en nanotecnología en México
D-33	Akyildiz & Jornet (2010a)	Electromagnetic wireless nanosensor networks
D-34	Akyildiz & Jornet (2010b)	The Internet of nano-things
D-35	Gregori & Akyildiz (2010)	A new NanoNetwork architecture using flagellated bacteria and catalytic nanomotors
D-36	Liu, Lai, & Ho (2010)	High Spatial Resolution Photodetectors Based on Nanoscale Three-Dimensional Structures

D-37	Záyago-Lau & Foladori (2010)	La nanotecnología en México: un desarrollo incierto
D-38	Atakan & Akan (2010)	Carbon nanotube-based nanoscale ad hoc networks
D-39	Parcerisa (2009)	Molecular communication options for long range nanonetworks
D-40	Parcerisa & Akyildiz (2009)	Molecular communication options for long range nanonetworks
D-41	Rutherglen & Burke (2009)	Nanoelectromagnetics: Circuit and electromagnetic properties of carbon nanotubes
D-42	Akyildiz, Brunetti, & Blázzque (2008)	Nanonetworks: A new communication paradigm
D-43	Kaviani, Sadr, & Abrishamifar (2008)	Generation and detection of nano ultrasound waves with a multiple strained layer structure
D-44	Hegg & Lin (2007)	Nano-scale nanocrystal quantum dot photodetectors
D-45	Foladori & Invernizz (2006)	La nanotecnología: una solución en busca de problemas
D-46	Djenouri, Khelladi, & Badache (2005)	A survey of security issues in mobile ad hoc and sensor networks
D-47	Britto & Castro (2012)	Nanotecnología, hacia un nuevo portal científico-tecnológico

Source: Authors' elaboration, 2018

Therefore, from the search, review, and evaluation process of the bibliographic material was collected a total 47 articles to build state of the art; identifying characteristics, applications, and capacities for their later analysis in which the possibilities and IoNT trends in various fields social welfare are exposed.

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3. IONT FEATURES

IoNT has emerged mainly from the new technological trends that have arisen in recent years, resulting from the search for new research spaces and emerging technologies to produce hardware devices at scale. Therefore, to understand IoNT, it is necessary to know the primary definitions, understand how nano-things are communicated, describe their architecture and present the application domains.

3.1. Purpose of IoNT

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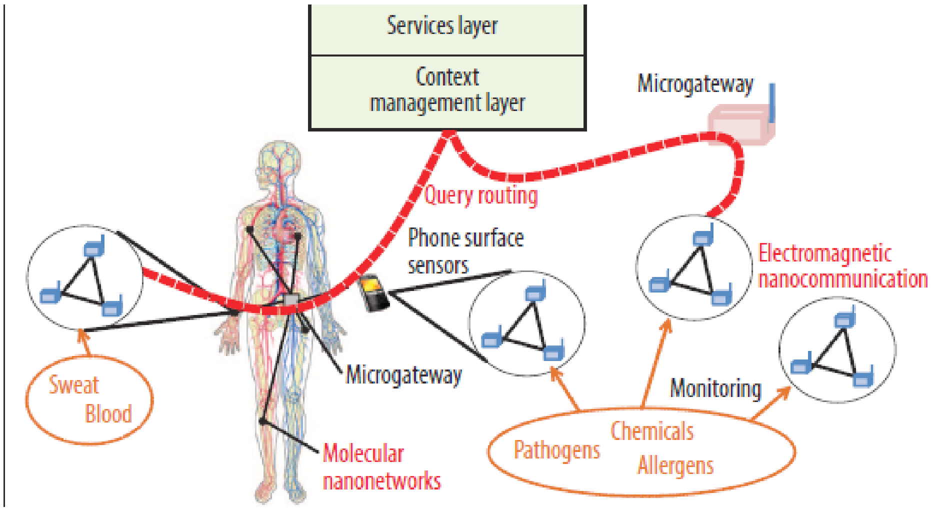
By Nayyar, Puri, & Le (2017), the first concept of IoNT was proposed by Akyildiz & Jornet a paper entitled "The Internet of Nano-Things" in 2010. Describing the term of IoNT as "The interconnection of nanoscale devices with existing communication networks and ultimately the Internet defines a new networking paradigm that is further referred to as the Internet of Nano-Things" (Akyildiz & Jornet, 2010b, p. 58). Similarly, Miraz, Ali, Excell, & Picking (2015) presents to IoNT as one extension of the Internet of everything, but where you have the possibility of incorporating nano-sensors in various objects and using nano-networks.

Moreover, in Balasubramaniam & Kangasharju (2013) it is mentioned that these miniature sensors, interconnected through nano-networks, could obtain fine-grained data within objects and from hard-to-access areas, leading to the discovery of novel insights and applications. That is, the purpose of IoNT consists of the capacity to interconnect diverse types of devices developed at a nano-scale in a communication network, where it allows the collection of data in places with difficult access.

Figure 1 illustrates the definitions presented for IoNT, show the interconnection which is established between different devices, as are nano-sensor through nano-networks, with the aim provide essential information within complex-to-access areas. For example, on-body nano-sensors could provide electrocardiographic and other vital signals, while environmental nano-sensors could collect information about pathogens and allergens in a given area. (Balasubramaniam & Kangasharju, 2013).

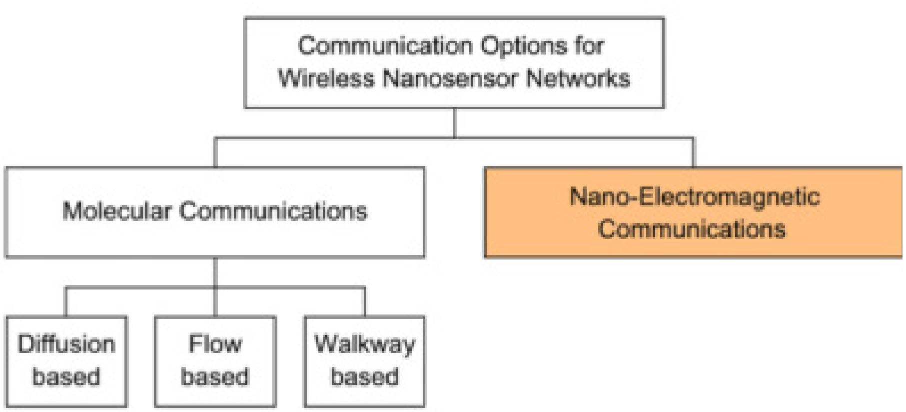
FIGURE 1
Nano-communication



Source: Taken from Balasubramaniam & Kangasharju (2013, p. 63).

In Akyildiz, Brunetti, & Blázzque (2008), for 2008 the works of literature that be referred to a term of nano-networks figured as electronic components with the capacity of interconnection within a nano-scale chip. However, defined the term as nano-networks "are not a simple extension of traditional communication networks at the nano-scale. They are a complete new communication paradigm, in which most of the communication processes are inspired by biological systems found in nature" (Akyildiz et al., 2008, p. 2266). Figure 2 shows two alternatives in nano-scale communications. These are molecular communications and nano-electromagnetic communications (Akyildiz & Jornet, 2010b).

FIGURE 2
Communications in wireless nanosensor networks



Sourcee: Taken from Akyildiz & Jornet (2010a, p. 4).

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Molecular communication is a new approach to communications between nano-machines (Gregori & Akyildiz, 2010), it is inspired by the communication mechanisms that occur between living cells (Parcerisa, 2009). It is defined as the transmission and reception of information encoded in molecules (Akyildiz & Jornet, 2010b). As well as in molecular communication the authors Akyildiz & Jornet indicate that nano-electromagnetic communication is defined as the transmission and reception of electromagnetic (EM) radiation from components based on novel nano-materials (Akyildiz & Jornet, 2010b).

3.2. IoNT Architecture

This new paradigm of networks based on the intercommunication of nano-devices requires a series of components to form an IoNT architecture model. Figure 3 shows two models of IoNT architecture proposed by Akyildiz & Jornet (2010b); On the left side, intracorporal nanotechnologies for sanitary applications and on the right side, the architecture for interconnected offices.

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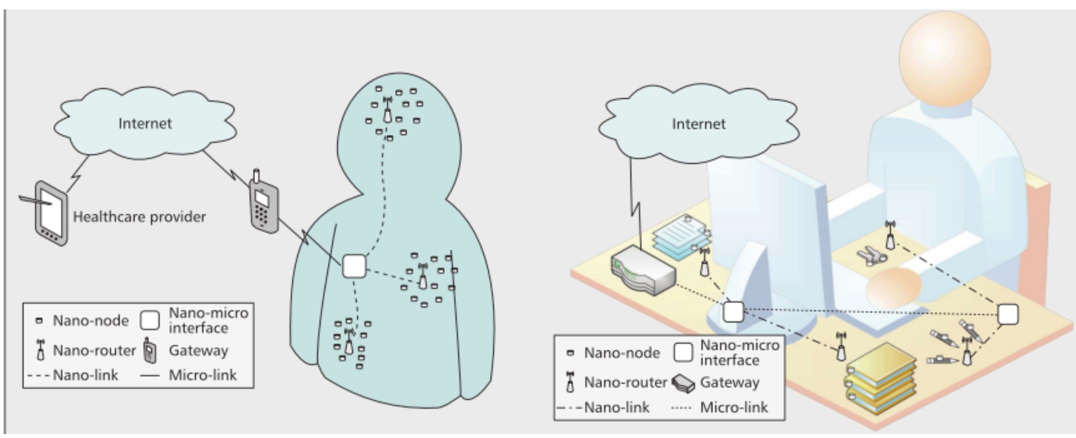
The components of the network architectures shown in Figure 3 are the same for both healthcare applications and offices, among which are: Nano-node, Nano-router, Nano-micro interface, and Gateway.

FIGURE 3
Network architectures for IoNT



Sourcee: Taken from Akyildiz & Jornet (2010b, p. 59).

In Nayyar et al. (2017), Dabhi & Maheta (2017) and Akyildiz & Jornet (2010b) the authors express that the Nano-node, Nano-router, Nano-micro interface and Gateways components are part of the IoNT architecture regardless of the type of application. Also, they describe the terms in the following way:

a. **Nano-Nodes:** They are considered as "the smallest and simplest nanomachines which perform various tasks like computation and transmission" (Nayyar et al., 2017, p. 6). Therefore, the biological nano-sensors inside the human bodies and the nano-machines integrated into diverse things, as they can be; books, keys or paper folders are examples of nano-nodes (Akyildiz & Jornet, 2010b).
b. **Nano-Routers:** "They act as aggregators of information coming

from nano-nodes" (Dabhi & Maheta, 2017, p. 10603). The nano-routers can control the behavior of nano-nodes through the exchange of simple control commands (on / off, sleep, read value, etc.) (Akyildiz & Jornet, 2010b).

c. **Nano-Micro Interface devices:** "Perform the undertaking of accumulation of data originating from nano- switches and transmit it to the microscale and bad habit versa" (Dabhi & Maheta, 2017, p. 10603).

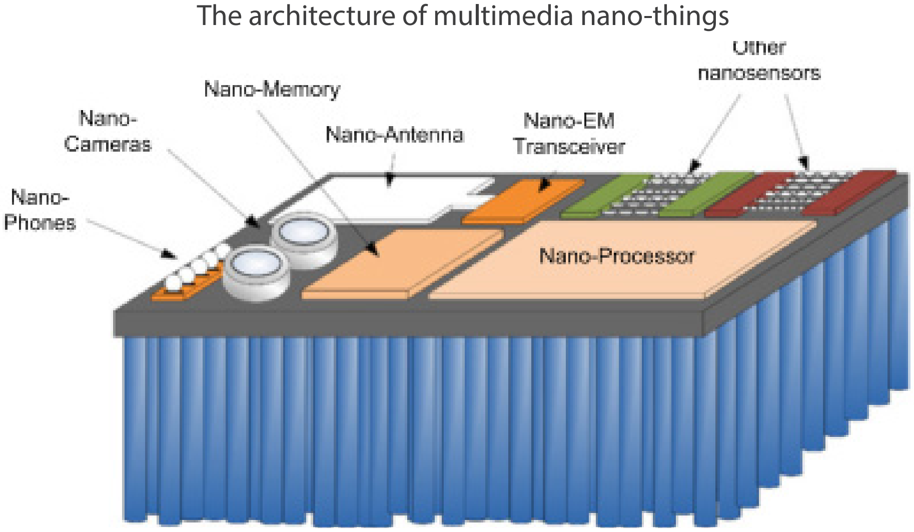
d. **Gateway:** "It enables the remote control of entire nano things network over the Internet" (Dabhi & Maheta, 2017, p. 10603). For example, in an intrabody network, a smartphone can send the information it receives from a nano-micro interface placed on our wrist to a doctor (Akyildiz & Jornet, 2010b).

3.3. IoNT domains

IoNT contains two domains: Internet of the Nano-Things Multimedia (IoMNT) and Internet of the Bio-Nano Things (IoBNT) (El-din & Manjaiah, 2017), also, the architecture of the nanodevices can be different, depending on the capabilities that it provides nanotechnology. In Jornet & Akyildiz(2012a), IoMNT is specified as "The interconnection of pervasively deployed multimedia nano-devices with existing communication networks and ultimately the Internet defines a novel communication paradigm that is further referred to as the Internet of Multimedia Nano-Things" (p. 242) .

The vision or perspective of multimedia nano-things concludes that nano-components have to be integrated into a single device (Jornet & Akyildiz, 2012a). As seen in Figure 4, a single device is made up of different nano-components (nano-cameras, nano-phones, nano-antenna, etc.). Moreover, this device must be tiny of at least a few cubic micrometers (Akyildiz & Jornet, 2010a; Akyildiz, Jornet, & Pierobon, 2011).

FIGURE 4
The architecture of multimedia nano-things



Sourcee: Taken from Jornet & Akyildiz (2012a, p. 244).

Next, some particularities of the architecture of IoMNT are described:

e. **Nano-Cameras:** photo-detector designed at nano-scale which is of great importance in telecommunications. It allows the detection of signals and acquisition of optical images (Liu, Lai, & Ho, 2010).
f. **Nano-Phones:** Consist of ultrasonic transducers with nano-scale dimensions (Smith et al., 2012).
g. **Scalar nano-sensors:** They are able devices of a new generation of sensors (Sorkin & Zhang, 2011). A nanosensor "is not just a tiny sensor, but a device that makes use of the novel properties of nanomaterials to identify and measure new types of events in the nanoscale" (Jornet & Akyildiz, 2012a, p. 7), such as the physical characteristics of chemical compounds, viruses, bacteria and even cancer cells.
h. **Nano-Processor:** High-performance transistors (Wu et al., 2011). They are smaller and can work at high frequencies. However, "the complexity of the operations that a nano-processor will be able to handle depends on the number of transistors in the chip, thus, on its total size" (Akkari et al., 2016, p. 1204).
i. **Nano-Memories:** In Jornet & Akyildiz (2012a), it is indicated that these memories are not yet ready and available for the nano-devices. Nano-materials and new manufacturing processes are considered as the starting point for their development, using single-atom memories, where each bit of information requires only one atom.
j. **Power Nano-systems:** This type of batteries requires new models or techniques that allow energy storage in a very different way than conventional batteries. There is a studied technique based on the piezoelectric effect, where vibrational energy is converted into electricity (Jornet & Akyildiz, 2012a).
k. **Nano-Antennas and Nano-Transceivers:** The use of nano-materials has generated that many investigations can be made and with this the possibility of manufacturing nano-antennas. These antennas are much more compact than the traditional antennas, they are based on graphene and have the chance of working on the frequency of the Terahertz band (Jornet & Akyildiz, 2013).

The capabilities of multimedia, processing, data storage, energy, etc., of the nano-devices, will not always be the same, these capacities vary according to their size (Jornet & Akyildiz, 2012a).

On the other hand, the IoBNT domain has the perspective on biological structures. It is mainly based on biological cells. IoBNT is defined as "uniquely identifiable basic structural and functional units that operate and interact within the biological environment" (Akyildiz et al., 2015, p. 33).

Figure 5 shows how the comparison of elements by a biological cell with the features or components that make up an electronic device is carried out. For example, the nucleus of the cell with the control unit and the cytoplasm with the memory.

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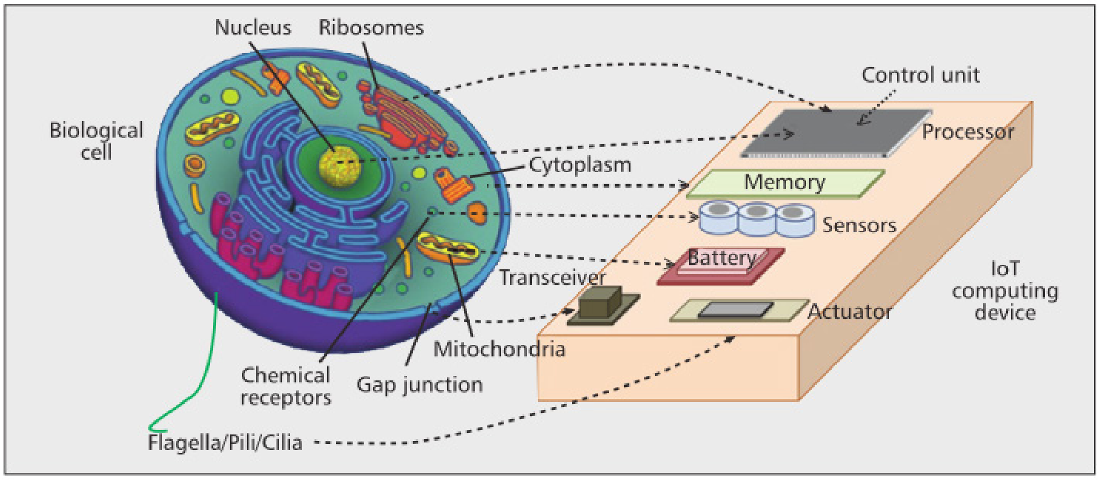
FIGURE 5
Elements of a biological cell and IoT components



Sourcee: Taken from Akyildiz et al. (2015, p. 33).

Next, some particularities of the architecture of IoBNT are described:

a. **Control Unit:** "The nucleus can be considered as the control unit of the cell" (Akyildiz et al., 2008, p. 2264). The genetic instructions are those that are packaged in the DNA molecules of the cells (Akyildiz et al., 2015).
b. **Memory Unit:** "Contains the values of the embedded system data, would correspond to the chemical content of the cytoplasm, i.e. the interior of the cell, comprised of molecules synthesized by the cell as a result of DNA instructions" (Akyildiz et al., 2015, p. 33).
c. **Processing Unit:** It concerns the molecular machinery that, through DNA molecules, generates other molecules with types and concentrations dependent on the instructions are given (Akyildiz et al., 2015).
d. **Power Unit:** It corresponds to the deposit in the cell of the molecule Adenosine Triphosphate (ATP), which is synthesized by the cell from energy provided by an external environment and provides power so that the biochemical reactions of the cell can be generated (Akyildiz et al., 2015).
e. **Transceivers:** It falls on the chains of chemical reactions, through these the cells exchange information molecules. (Akyildiz et al., 2015).
f. **Sensing and actuation:** Consist of the ability of the cell to recognize external molecules or physical stimuli (Akyildiz et al., 2015).

4. CAPABILITIES AND POSSIBILITIES OF IONT

This section takes a tour of the leading possibilities and capabilities of IoNT, including nanotechnology; directly responsible for IoNT systems.

The concept of nanotechnology was proposed for the first time in 1974, in a paper in which it was explained that nanotechnology was based on the processing, separation, consolidation, etc., of materials by an atom (Akyildiz et al., 2011). Nayyar et al. (2017) defines the most basic concept of nanotechnology as the engineering of functional systems at the molecular scale. It can manipulate matter in tiny scales or manometric scale (Foladori & Invernizz, 2006; Záyago-Lau & Foladori, 2010).

The Ministry of Science, Technology and Productive Innovation of the government of Argentina (Observatorio Tecnológico [OTEC], Instituto de Bioingeniería de Cataluña [IBEC], & Fundació Hospital Universitari Vall d'Hebron– Institut de Recerca [VHIR], 2016) indicates that nanotechnology will have an essential attribution on products and services worldwide, mainly in nanotechnological fields such as Nano-biotechnology, Nano-analytical, Nano-materials, Nano-optics, Nanoelectronics, and Nanochemistry.

In short, nanotechnologies are new, are expanding at high speeds (Llopis-Lorente et al., 2017; Maynard, 2012), and will transform the world's leading products and services. For Takeuchi & Mora (2011) in a period of between 10 and 20 years, a significant part of the industrial production, medical care, and interaction with the environment will change due to the use of new technologies. So, the possibilities and capabilities of IoNT will increase, due to its dependence on nanotechnology.

4.1. Security in nano-things

IoNT is vulnerable to all types of attacks, either physical or through wireless technologies, given that this type of device does not meet with constant vigilance (Dressler & Fischer, 2015; Dressler & Kargl, 2012a; Jornet & Akyildiz, 2012a; Loscri, Marchal, Mitton, Fortino, & Vasilakos, 2014). The attacks can occur to acquire private data through the theft of sensors, interrupt applications controlled utilizing computers or modify the communication links in the nano-networks.

In Jornet & Akyildiz (2012a, 2012b) there are three dimensions to be investigated to find greater security and privacy in IoNT. These dimensions are: new mechanisms for authentication, guarantee the integrity of the data and guarantee the confidentiality of the user. Also, Dressler & Fischer (2015) shows the existence of new security methods among nano-communications, especially the connections between IoNT and IoT. These security aspects mentioned are nano-communication security, security objectives and security mechanisms for IoNT systems. The security objectives are a series of concepts that guarantee the security of communication systems (Dressler & Kargl, 2012b). They are made up of "confidentiality, integrity, and availability" (Dressler & Kargl, 2012a, p. 6184).

4.2. Security mechanisms for IoNT systems

One way to increase the security of IoNT systems is to consider the following mechanisms to establish secure communications in nano-sensor networks:

g. **Key management:** The establishment of symmetric keys is called key management (Gandino, Celozzi, & Rebaudengo, 2017). In Wireless Sensor Networks (WSN), symmetric key cryptography is considered, mainly due to the low power in the batteries of these nodes (Kalkan & Levi, 2012).

h. **Performance and scalability:** The security and privacy in the nano-communication systems present significant challenges regarding the performance and scalability of the participating nodes (Dressler & Kargl, 2012a).
i. **Access control and authentication:** Authentication is a prerequisite to guarantee the objective of confidentiality (Dressler & Fischer, 2015). Each of the messages that want to be sent to a nano-communication system must go through a gateway and be authenticated.
j. **Secure localization:** In IoNT, many of the applications will need to know the location of the nano-sensors to perform specific jobs (Dressler & Kargl, 2012b).
k. **Intrusion detection:** Due to some problems that classical cryptography methods could present, it is essential to make the necessary arrangements to detect and react to attacks. In Dressler & Kargl (2012b) indicated that a strategy to counteract a denial of service attacks consists of implementing an intrusion detection system in the entry node to the nano-communication system and that it is fail-safe.

4.3. Protocols for nano-networks

Unique features provided by nanotechnology characterizes the nano-scale devices. They also present a series of drawbacks regarding communication, mainly to establish a network connection of multiple nano-devices. Next, is shows preliminary ideas for the creation of network connections of various nano-scale devices. This is elaborated from information collected in Akyildiz & Jornet (2010b).

l. **Channel Sharing:** Develop impulse-based communications (Ali & Abu-Elkheir, 2015). "We think of asynchronous MAC protocols, in which a nano- node willing to send a packet can just transmit it and wait for some type of acknowledgment" (Akyildiz & Jornet, 2010b, p. 61).
m. **Addressing of nano-machines:** Implement addressing schemes that capture and exploit the hierarchy of the network. Investigate strategies for the discovery of neighbors that exploit the high directivity of the terahertz antennas to determine the relative location and orientation between the nano-objects simultaneously (Jornet & Akyildiz, 2012a).
n. **Information routing:** A communication system based on impulses must be defined and assume that the nano-nodes know the distance between them. For example, different nodes at the same distance from the nano-router will have the same ID. The neighbors of these nodes, who might not have heard the nano-router, will take a higher ID and broadcast it. Therefore, other nodes will have higher IDs. (Akyildiz & Jornet, 2010b).
o. **Reliability issues:** "End-to-end reliability in nanonetworks and the IoNT has to be guaranteed both for the messages going

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from a remote command center to the nano- nodes, as well as for the packets coming from the nanomachines to a common sink" (Akyildiz & Jornet, 2010b, p. 62).

p. Network association and service discovery: New solutions are needed for network association and network discovery (Akyildiz et al., 2015). With a hierarchical network structure, it is not necessary to notify the entire network of the existence of a new nano-node, it would only be required to inform the nearest nano-router or nano-micro interface (Akyildiz & Jornet, 2010b).

4.4. Applications of IoNT

The possibilities offered by the new techniques for the collection of fine-grained information by IoNT allows to increase the existing applications and to venture into new fields in contrast with IoT. Here are some applications of IoNT:

q. Multimedia: It focuses on the construction of devices such as photo-detectors (Liu et al., 2010) and acoustic nano-transducers (Smith et al., 2012) to produce multimedia content with high resolution (El-din & Manjaiah, 2017). The nano-multimedia systems have their focus in various fields such as health, biological attacks, forensic science and industrial process control (Jornet & Akyildiz, 2012a).

r. Biomedical: "Nanosensors now are used for Bio-Nano field for delivering a drug in specific devices ofhuman body when it has any problem and monitor the level of a specific substance"(El-din & Manjaiah, 2017, p. 114). Examples of these nano-sensors can be intracorporal health monitoring and drug delivery (Akyildiz et al., 2011).

s. Military: "The IoNT can use nanosensors that have the ability to detect the presence of a chemical composite in a concentration as low as one molecule" (El-din & Manjaiah, 2017, p. 114). The extent of nano-networks in this field can be of various sizes, for example, in a battlefield the demand for a nano-network interconnection is dense (Akyildiz et al., 2008) while monitoring the health status of soldiers through nano-body sensors the area is much smaller (Jarmakiewicz, Parobczak, & Maslanka, 2016).

t. Industrial: IoNT could improve manufacturing processes and quality control procedures of many companies or organizations (Akyildiz et al., 2008). One of the trends on the part of nanotechnology is based on touch technology. Therefore, IoNT could be applied to boost the sensitivity of touch on air surfaces through nano-sensors that detect movements and convert them into signals (El-din & Manjaiah, 2017).

u. Environmental: There is the possibility of monitoring and controlling chemical compounds that release and exchange plants (El-din & Manjaiah, 2017).

The paradigm of IoNT and its high capacity of application in different fields have managed to transform the day to day of people, boosts the economy and above all offers the possibility of continuing research in various areas (Balasubramaniam, Jornet, Pierobon, & Koucheryavy, 2016). The breadth of the capabilities and opportunities of IoNT in the world indicates that the IoNT market is planning a high economic investment, with an approximate of $

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9.69 billion by the year 2020 (Dabhi & Maheta, 2017).

5. AN ANALYSIS OF CHALLENGES AND TRENDS FOR IONT

The analysis of the study was done by grouping the literature analyzed and then by defining criteria. Table 2 shows the categories and classification of the criteria for each of the categories

TABLE 2
Categories and classification criteria

CATEGORIES	CRITERIA
Perceptible	Hardware
	Software
	Architecture
Applications	Healthcare
	Industrial
	Environmental
Challenges	Security
	Privacy
	Communications

Source: Authors' elaboration, 2018.

5.1. Application of criteria

Then, the application of criteria in the selected literature for the study is carried out. It is necessary to highlight that 26 publications were chosen from the results provided by the application of the research questions RQ2 or RQ4 with "yes" answer. Because these provide direct contents and referring to characteristics, possibilities, and challenges of IoNT. Table 3 presents the 26 publications that will apply the criteria that will determine trends (technologies and applications) and IoNT challenges.

TABLE 3
List of publications for the application of criteria

ID	AUTHORS
D-1	El-din & Manjaiah (2017)
D-2	Nayyar et al. (2017)
D-3	Dabhi & Maheta (2017)
D-6	Balasubramaniam et al. (2016)
D-7	Akkari et al. (2016)
D-8	Ali et al. (2016)
D-9	Jarmakiewicz et al. (2016)
D-11	Afsharinejad et al. (2016)
D-12	Ali & Abu-Elkheir (2015)
D-13	Dressler & Fischer (2015)
D-14	Miraz et al. (2015)
D-15	Akyildiz et al. (2015)
D-16	Bhargava et al. (2015)
D-18	Loscri et al. (2014)
D-19	Balasubramaniam & Kangasharju (2013)
D-20	Jornet & Akyildiz (2013)
D-22	Dressler & Kargl (2012b)
D-23	Jornet & Akyildiz (2012b)
D-24	Jornet & Akyildiz (2012a)
D-29	Akyildiz et al. (2011)
D-33	Akyildiz & Jornet (2010a)
D-34	Akyildiz & Jornet (2010b)
D-35	Gregori & Akyildiz (2010)
D-38	Atakan & Akan (2010)
D-40	Parcerisa & Akyildiz (2009)
D-42	Akyildiz et al. (2008)

Source: Authors' elaboration, 2018.

Then, in the following sub-sections, the analysis of the literature for each of the categories

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and their respective criteria is provided.

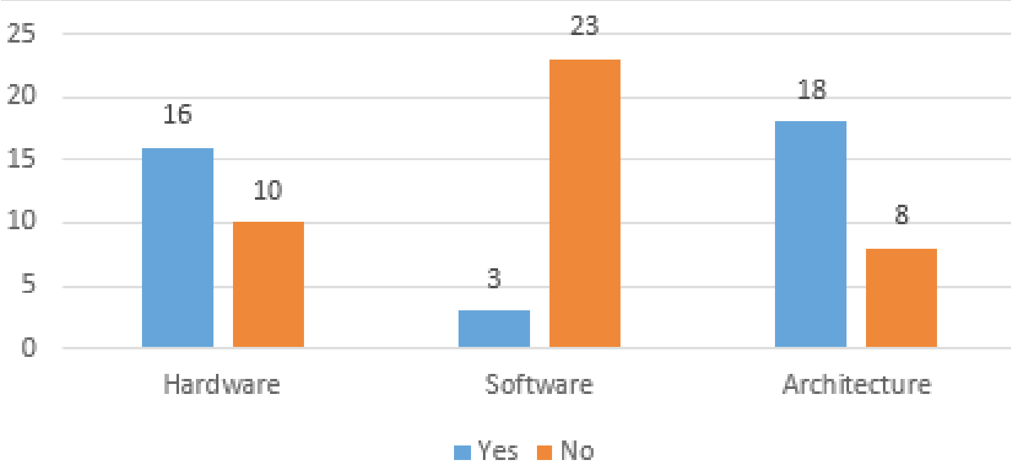
5.1.1. Technology IoNT

The category of technologies contains the criteria that the IoNT information systems depend on in their combination. The application determines the focus and trends of the selected publications, this is established through the "yes" or "no" responses that each work contains in each criterion.

Figure 6 illustrates the results of the application of the criteria, highlighting that the publications are more focused on providing details regarding the types of hardware and architectures of the IoNT systems on the implementation of software for the administration of the systems. This could be happening because industrial systems have a very critical security parameter, and that is that they must guarantee and protect people's lives. Therefore, the field of software development would be progressing very slowly because it is not clear how data will be protected when this network is connected to the Internet.

FIGURE 6

Results found of the application of the technologies criteria



Sourcee: Authors' elaboration. 2018.

Concerning the hardware criterion, 16 of 26 publications emphasize the essential and, more common devices that should be used for the creation of an IoNT system and highlights the importance of nanotechnology as a fundamental basis for the discovery and development of the nano-devices of IoNT. The software criterion, only 3 of 26 of the publications mention the importance of incorporating a middleware, with the purpose of obtaining an administration of the systems, data analysis, and conservation of energy. But most publications do not even mention the need for software.

Regarding the architecture criterion, 18 of 26 documents analyzed show the importance of establishing an architecture, mainly highlighting which hardware devices are necessary for the establishment of a nano-sensor network.

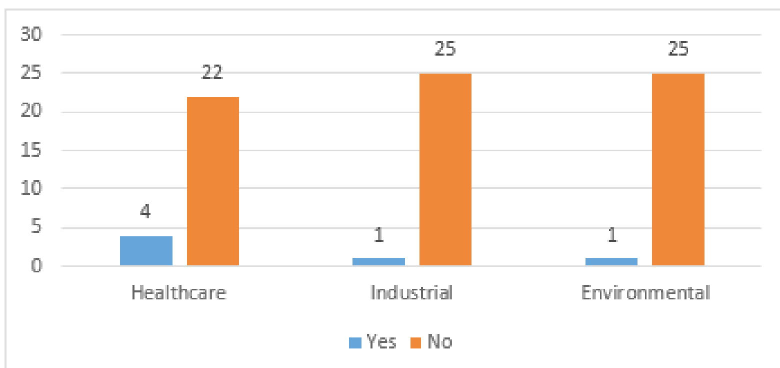
5.1.2. Applications IoNT

In the category of applications, the criteria to determine the trends of the work related to IoNT is highlighted, mainly highlighting the works developed under this criterion and which aim to provide a possible solution or improvement in that field. It is added that IoNT contains finer techniques for the collection of information in comparison with IoT, therefore, it allows IoNT to get involved in both new and existing applications.

Figure 7 contains the results of the application of criteria for the classification of applications in IoNT. Although there are multiple application areas that IoNT has in different fields, they do not determine the existence of works made and published in each one of them. On the contrary, it can be observed that among the publications studied there are only six works focused on the application of IoNT in a specific area.

FIGURE 7

Results found of the application of the criteria of the application



Sourcee: Authors' elaboration. 2018.

The healthcare criterion stipulates that 4 out of 26 of the publications (D-8, D-9, D-12, and D-13) focus on the biomedical field and represent the highest proportion of jobs applied in a specific area on the part of IoNT. It is necessary to emphasize that many of the publications studied refer to hardware or architectures focused on this criterion, but do not aim to provide or establish a solution in this field, rather than providing a vision or possibility for a future application.

The application criteria of industry and environment indicate only 1 of 26 of the publications studied, in the case of industry (D-16) focuses on dairy farming, consists of a work that is in process. They present IoNT with great possibilities and benefits for the monitoring of pastures, animal health, and reduction in the resistance of antibiotics.

The environmental area (D-11) presents a series of high-resolution models for plant monitoring by applying channel modeling, communication with the Terahertz band and nano-sensors through a Wireless Nano Sensor Network.

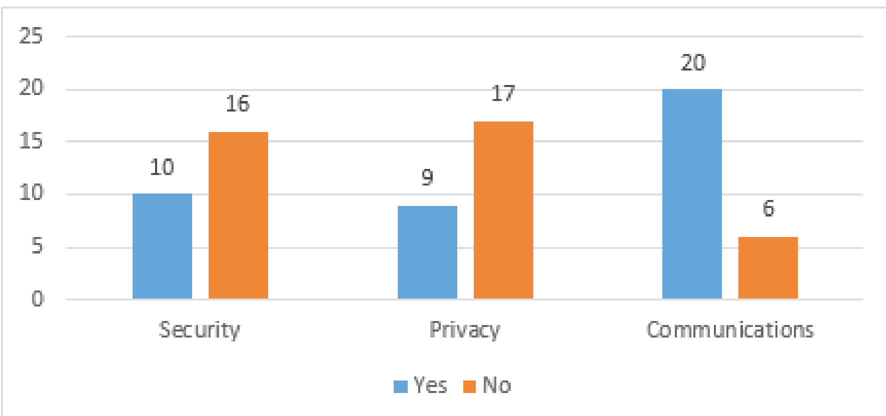
It is specified that the significant advances and applications of IoNT are focusing on medical health, highlighting among them the separation of IoNT in two application domains such as IoBNT and IoMNT.

5.1.3. Challenges IoNT

In this category, the application of the criteria seeks to determine in which critical aspects IoT systems face. If it consists of security, privacy or communication. Regarding the criteria of challenges, Figure 8 illustrates the results of the application in each of the publications studied, where the communication criterion stands out as the biggest IoNT challenge.

FIGURE 8

Results found of the application of the criteria of the challenge



Sourcee: Authors' elaboration. 2018.

The results obtained in the security criteria indicate that 10 out of 26 of the publications emphasize the importance of the protection of the IoNT systems. Particularly the security of the data that is collected through the nano-sensors, considering it necessary to comply with the aspects mentioned in Section 4, such as key management, intrusion detection, access control, etc.

For the privacy criterion, 9 of 26 of the studies studied show the importance of establishing new and better privacy mechanisms, remembering that in the application trends of the IoNT systems are located the care of human health. The most important thing about privacy in the biomedical field is that as soon as the data is collected from the human body, it must be protected against unauthorized access, as it is evident that these are private data. Based on this criterion, Section 4 presented the security objectives, which, if met, would ensure the privacy of the data, but it is necessary to establish mechanisms that can be trusted since most of the security techniques current systems cannot be implemented due to size and capacity.

The criterion of communication is the most relevant of the challenges, 20 of

26 publications mention the importance of establishing and consolidating communication mechanisms, mainly due to the problems they face today. Some of the communication problems are: addressing of nano-devices, routing of information, sharing of communication channels, detection of networks and reliability. In recent years, a high deal of research has emerged in the field of communication. However, communication techniques or methods have not yet been consolidated, fulfilling the communication problems mentioned in the previous section. Even more, integrating and solving security and privacy environments.

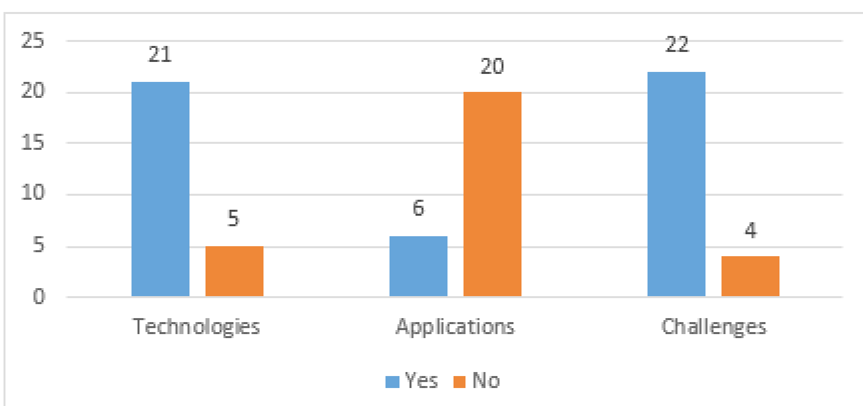
Furthermore, we must remember that communication in IoNT is faced in two domains; molecular communication and nano-electromagnetic communication. In both cases, the routing problems stand out. In the fact of molecular communication, they indicate that the information-carrying molecules move very slowly and may lose information. In nano-electromagnetic communication, the limited memory, the low computational power and the limitation of energy stand out.

5.1.4. Trends and challenges of IoNT

IoNT is a paradigm whose research is active and has increased year after year since 2010 where Akyildiz & Jornet make the first definition. Based on the analysis carried out, it can be seen in Figure 9 that 21 of 26 publications focus on exceeding the technologies and 22 of 26 indicate challenges they face to achieve the establishment of IoNT, recalling that the most significant problem centers on in aspects of communication.

It is reasonable that the investigations are focused on the technologies, and these present challenges because IoNT is a new paradigm and has not been fully established. The studies are focused on the possibilities and capabilities of nanotechnologies for the implementation of hardware and architectures as observed in Section 3.

FIGURE 9
Result obtained from the application of the criteria by category



Sourcee: Authors' elaboration. 2018.

Finally, only 6 of 26 of the publications are focused on an application to a specific field, with health care being the most involved.
It is understandable that so far there are few concrete works in IoNT because it is a paradigm that is maturing and still faces many challenges.

6. CONCLUSIONS

This paper offers a description of the current state of IoNT, analyzing the literature and identifying characteristics, trends, and possibilities, describing challenges that in one way or another are threats for the diffusion and establishment of IoNT. A list of bibliographical references was compiled which were classified into three main categories (Technologies, Applications, and Challenges) and a set of criteria.

IoNT presents capabilities and possibilities to improve many aspects of people's lives. Its main qualities are focused on monitoring and diagnostic services, which would help and enhance decision making and results in various fields of application. For example, it could allow progress in the establishment of telemedicine and eHealth.

It provides a great variety of nano-devices with diverse capacities independent of the type of architecture that is required, to obtain data of objects, people, animals, plants, etc. However, there is no homogeneity between the development of hardware and software. The hardware advances faster than the software, therefore, the deficiencies in the security and privacy of the data.

There are many challenges that IoNT faces, but nanotechnology provides diverse fields of study that advance with increasing force and increase the possibilities of solving current deficiencies. But, the current market directs research to particular situations that usually do not benefit most of the population.

The relevant issues regarding privacy, security and the architecture of nano-networks of IoNT do not apply under any standard of international standardization. A way forward would be to define standard interfaces where protocols and primitives are included to allow transmissions through nano-devices, interfaces that are also available with higher-magnitude systems, with the possibility of monitoring the networks.

Said the previous thing, creating new standards would allow establishing the communications between the nano-devices, obtaining that these normalizations can be implemented in diverse applications of IoNT.

Only time will tell how long it will last IoNT to establish itself thoroughly, but it's clear that it is a way to gather new technologies and that will transform products and services in the world.

In summary, the review of the literature provided some significant findings, where future research efforts can be focused. These include:

- The bibliography of IoNT is dominated by researches related to IoNT technologies. This is good because it provides the scientific community with new options and tools that could allow the development of implementations of systems based on IoNT.

- IoNT is not represented in management literature. This is a disadvantage because management has always been an essential activity for the reduction of risks, as well as to improve the use of existing technologies.
- The software coverage for the IoNT administration systems is scarce, practically nil.
- There is little evidence regarding international standards of hardware/network architectures for IoNT systems.
- The applications of the IoNT systems are mainly focused on aspects of health care. However, it is also necessary to focus the development of IoNT systems in other important areas such as the care of the environment through industry.
- Little work has been done on issues related to security and privacy for IoNT systems. Therefore, it is important to focus efforts on the coupling of the current security systems used in traditional networks in nanonetworks or to implement new ways to protect the privacy of users.
- The main challenges of IoNT are focused on communication aspects, mainly in routing, processing capacity, and energy issues. The studies follow the line of simplicity and low consumption, thereupon in a short time, the issues of capacity and energy consumption could be resolved.

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