Electromagnetic-Based Wireless Nano-Sensors Network: Architectures and Applications

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Abstract —Recent advances in nano-materials and nanotechnology have paved the way for building integrated devices with a nanometric size, named nano-nodes. These nano-nodes are composed of nano-processor, nano-memory, nano-batteries, nano-transceiver, nano-antenna and nano-sensors, which operate at nano-scale level. They are able to perform simple tasks, such as sensing, computing and actuation. The interconnection between microdevices and nanonodes/nanosensors has enabled the development of a new network standard, called Wireless Nano-Sensors Network (WNSN). This paper provides an in-depth review of WNSN, its architectures, application areas, and challenges, which need to be addressed, while identifying opportunities for their implementation in various application domains.

Index Terms —Nanotechnology, nanosensors, wireless nan-sensors network, protocols and applications

I. Introduction

Recent advances in nanomaterials and nanotechnology have enabled the development of tiny nanoscale devices, named nanonodes or nanomachines. Composed of a nano-battery, a memory, an antenna and an actuation unit, the nanomachines are fully autonomous nano-nodes able to execute simple operations while communicating at short distances [1]. Wireless nano-nodes, which are able to detect and interact with their environment, will bring radical changes to everyday life applications [2]. However, due to their tiny size, energy and physical (e.g. computation, storage) capacities are extremely limited. As a result, interesting applications, using wireless nano-sensors communications network (WNSN), may require thousands of cooperating nanonodes [3]. For instance, nanoscale devices, which operate at the nanoscale level, could provide very important technological solutions in various fields, including biology, military, agriculture, smart cities, environmental and food safety [4]-[6]. For example, nanosensors could detect chemical compounds at atomic level or the existence of toxic substances in the air/water [7].

WNSN networks will increase the efficiency of nano-devices by allowing them to perform simple sensing and computation operations. Data sensed at nano-scale level could be submitted and shared with other nodes, via hop-by-hop routing and dissemination protocols (e.g., flooding). Alike traditional networks, nano-routers play an important role, by routing and communicating data from source nodes to the nano-interface device, which acts as a bridge between the nano world and the micro world. The interconnection between these nanonodes can be achieved by one of the following communication mechanisms: electromagnetic, acoustic, nanomechanical and molecular communication [8] [4]. In this paper, we focus on the nano-electromagnetic communication. It is based on the transmission and reception of radio frequency electromagnetic waves in the Terahertz band using nanomaterial-based antennas, in particular graphene-based antennas, and nano transceivers [4].

The remainder of this paper is structured as follows. We first present, in Section 2, a general overview of the architecture of nanodevices as basic elements of WNSNs, then we describe a typical architecture model for an EM-based WNSN in Section 3. Opportunities, which can be realized for WNSN applications, are highlighted in Section 4. In Section 5, we describe the main challenges of implementing WNSN applications, in particular those related to the deployment, data analysis, routing technology and coexistence with other categories of networks. Conclusions and perspectives are given in Section 6.

II. Nano-Machine Architecture

Recent progress in nanomaterial technology allows building novel miniaturized nanomachines. Basically, these nanomaterials can be arranged into three categories: metal nanoparticles, quantum dots and carbon nanomaterials. Various types of metal nanoparticles have been extensively used in a number of nanosensor applications, such as magnetic iron, copper, gold, zinc, and silver [9]. The high ability of these nano particles, to easily operating with the targeting analyte (e.g., pathogens, antibodies, DNA), has been exploited for use in highly selective nanosensors [10].

Quantum Dots are nanoscale elements made out of semiconductors materials. They are known for their nanoscale size (1-10 nm) and have unique optical properties from traditional fluorescent dyes. They have very efficient wide excitation ranges and narrow and

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adjustable emissions depending on the size [11]. The high sensitivity of fluorescent emission offered by these Quantum Dots can be utilized to fabricate performant selective nanosensors [12]. Recently, a novel Graphene quantum dots based nanosensor for recognition of Metronidazole in biological samples was introduced for a none-fluorescent pharmaceutical compound detection [13]. Carbon nanotubes (CNTs) and graphene are frequently utilized for building nanosensors because of their large surface area, great electrical conductivity, and high thermal conductivity [14]. They have used to ameliorate the accuracy of an electrochemical sensing unit by extending the sensitivity of glassy carbon electrodes [15].

The design of miniaturized nanosensors, as stated above, will benefit from the extremely advances in nanotechnology and nanomaterials, and has been exploited for use in highly selective nanosensors, which are able to examining previously inaccessible areas, such as disease diagnosis and treatment. According to [4], a generic nanosensor node includes an energy source module, a communication asset, a processing remote node with nano memory, and a module for sensing and actuation (Fig. 1).

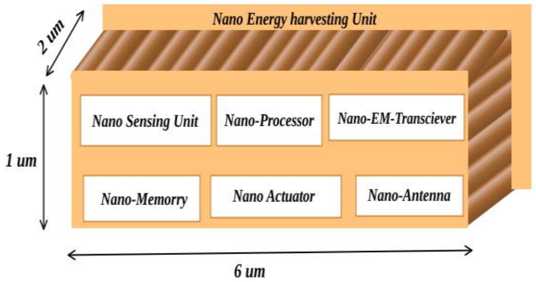

Fig. 1. Nanosensor architecture [4].

The sensing unit is able to detect an optical, biological or mechanical event, with high sensitivity and selectivity, and converting the response to an output electrical signal. Generally, these units are developed using nanomaterial, such as graphene GNR and nano tube carbon NTC [4]. It is a sensing entity, which can detect new collections of events at the nanoscale level, such as properties of nanomaterials, the concentration of certain chemical elements and the presence of bio-elements (e.g., virus or bacteria). These nanosensors can be classified into three types which will be detailed later in this section.

The discovery of new nanomaterials has greatly accelerated the development of nano energy harvesting systems at nanoscale with high power density, good time to live and charge/discharge periods [16]. However, the nano-sensor can be distributed in inaccessible areas where it is not possible to recharge. Therefore, self-power approaches and techniques have been introduced. Autonomous power systems can convert one form of energy (i.e., mechanical, thermical, vibratory or hydraulic energies) into electrical energy. This conversion is achieved by the nano-piezoelectric effect of zinc oxide (Zno), which consists of converting a nanoscale mechanical energy into electricity [17]. The authors in [18], presented a thermo-electric energy harvesting method, which consists of converting the heat flow into electricity using the temperature gradient between two dissimilar electrical conductors.

Similarly, nano-transistors based on graphene provides ballistic electron transport that allows for the development of faster switching devices [19], [20]. Recently, the Berkeley National Laboratory at Stanford University in California developed the smallest transistor. It is a molybdenum disulfide ($MoS2$) Nano transistor with a 1-nm physical gate [21]. However, the nanoscale size of the nanosensors limits the total number of transistors in a nano processor and the complexity of operations.

The storage unit is in charge for storing the aggregated data coming from the sensing element. Because of the restrictions in size of nanomachines storing, data at nanoscale is one of the issues that still under research and development. Recently, research has been announced that it is possible to store data directly in the smallest possible component. Atomic memories have now been introduced using carbon nanotubes. Researchers have integrated more than one million random access memory (RRAM) cells, making it the most complex nanoelectronics system ever created with emerging nanotechnologies [22]. Researchers have also introduced a method to magnetize sections of nanowires. By producing a current, they can move the magnetic sections along the wire, which enables data to be read by a fixed nanosensor [23].

The nano-antenna entity is responsible for enabling the communication between nano-devices. The recent advances in nanomaterials, such as CNTs and GNRs, have paved the way to build a Graphene based nano-antennas and carbon nanotube antennas for communication among nanosensor devices [24] [25]. The reduced size nano-antenna can achieve the nano-device size requirements and can radiate in the high operating frequency in the terahertz band. A graphene nano-antenna with 1 μm long can emit electromagnetic waves within the product range 1 -10 terahertz band [4] [26].

Nano-transceivers are nanodevices able to convert a recognition nanoscale event into a measurable physical phenomenon, such as a change in electrical resistance. In [27], authors demonstrate a plasmonic nano-transmitter-receiver that allows the electrical excitation of surface plasmon polariton (SPP) waves. These later can radiate by a nano-antenna at Thz band frequencies. A graphene-based plasmonic nanotransceiver for wire- less communication in the Terahertz Band was presented recently in [28]. The proposed system is composed by a signal generator, which generates an electric signal that needs to be transmitted, and a plasmonic transmitter, which converts the signal into a modulated SPP wave. The SPP wave is then radiated by a nano-antenna at Thz band frequencies.

The primary role of nano actuator units is to enable the nano-sensor to interact with surrounding events. This entity receives control input signal (generally in the electrical form) and generates a change in the physical nano-system by producing a physical feedback, such as force, motion, heat. According to [4], there are three types of actuators: physical, biological and chemical. The piezoelectric nano-actuator is proposed as one of the novel actuators, which are able to achieve nanoscale positioning resolution. This type of actuators will provide smart and exact actions and processes in nano-dimension [29].

It’s worth noting that, as described above, nanosensors are designed to respond to an actual chemical, optical, or biological event and converts it into electrical signal. Based on the sensing event, as depicted in Fig. 2, nanosensors can be classified into three main categories [4] [30]. Mechanical nanosensors are type of nano-sensors that can measure the quantities, such as mass, pressure, force or displacement. For example, Graphene embedded nano-composites are utilized to monitor strain [31]. Multi-walled carbon nano tubes are used to supervise strain in the bridge decks. The nanosensors might be embedded in highways or coated on bridges for monitoring the processes that subscribe to deterioration and cracking, and alert the appropriate authorities long before the damage is detectable by human inspectors [32]. Unlike mechanical nanosensors, optical nanosensors operate by using optical features of nanomaterials. They can be applied in various domains, such as the chemical industry, medicine, environmental security, and human protection [33]. Recently, a method has been proposed for early cancer detection using nano-optical devices [34].

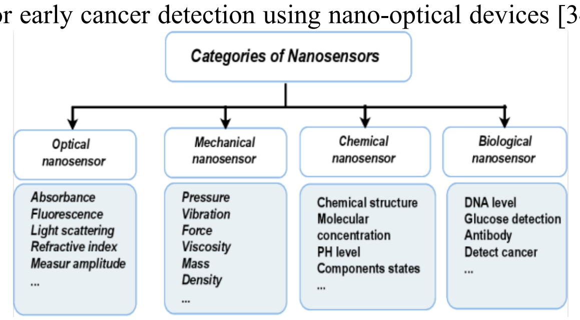

Fig. 2. Nanosensor classification according to the sensing event.

Chemical nanosensors are built mainly to measure quantities, such as the concentration of a certain gas, the clear presence of specific molecules or perhaps a certain molecular composition [35]. Their working mechanism is based on changes in the CNT or GNR electrical properties, when several types of molecules are absorbed along with them. Biological nanosensors are analytical device integrating a bio-recognition sensing element associated with an electronic component to extract a measurable signal and detects from a target compound. The recognition phenomena generate a biological signal, which is converted into a measurable quantity by the transuding unit. The output signal can be displayed in the form of optical (luminescence, fluorescence, surface plasmon resonance) or electrical (capacitance, impedance, voltammetry) or magnetical (Magnetic field, flux, permeability) or any other format, and transmits information about the presence of various biological substances in the environment [36], [37].

III. WNSN ARCHITECTURE

As mentioned in the previous section, a single nanosensor is characterized by limited sensing range, which is reserved to its close surroundings nodes. Therefore, WNSN nodes need to expand their coverage areas. WNSN consists of a certain number of interconnected nanosensors, diffused to cover larger zones and to perform sensing and data collection from its environment, and send it to a making decision unit via micro-interface conventional micro-device, which can act as an intermediate device between the WNSN and micro world [38]. As presented in [4], a generic WNSN should be composed by a collection of nanosensors (with fixed position or could be mobile according to the targeted application). These nanosensors can be diffused into a target area for capturing different events from one specific area. Fig. 3 illustrates the hierarchical structure that enables WNSN to interact with microGetway. The network architecture of WNSNs is constituted by the following components: nano-nodes, nano-routers, and a nano-interface.

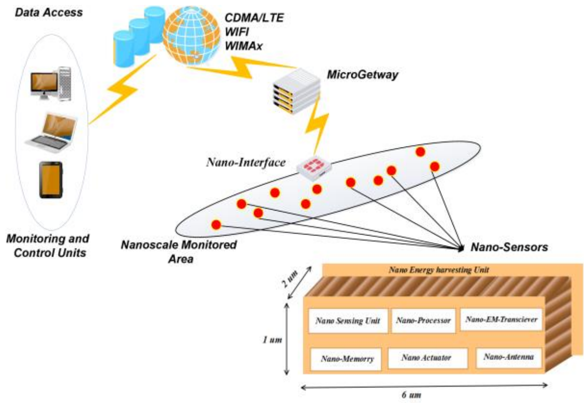

Fig. 3. WNSN interfacing to a micro gateway.

Nano-nodes are selective nanosensors, which are able to examine inaccessible areas by performing a simple detection of nano component. Their constrained energy and communication capacities make them able to communicate only over much reduced ranges. Nano-routers are greater than nano-nodes in size and have larger computational resources than nanonodes. They aggregate the data originating from nano-sensor nodes and can issue the straightforward command to regulate the behavior of nanonodes. Nano-micro interface aggregates the information coming from nano-routers and forward them to a microscale device or vice versa. They are assumed to be hybrid devices, which can act as gateway between the nano and the micro scale world. They should be able to convert WNSN messages to a traditional network system (i.e., WiFi, cellular networks...)

and vice-versa. The micro gateway requires dual transceivers, one to communicate with WNSN in the THz band, while the other one is dedicated to communicate with micro conventional network system.

The special achieved advances in the field of nanomaterials have paved the way to the communication between nanodevices. However, the development of a particular microgateways device, which can connect the nanoscale world to the microscale world, and the management interface over standard networks, is still constantly an open research issue. Therefore, the typical architecture of WNSN can change according to the targeted applications.

IV. Applications Areas of WNSN

Nanosensor capabilities to sense nanoscale events together with the development of WNSN protocols will enable the development of new applications. Various intelligent and smart applications in different areas are envisioned for being developed. For instance, we can site healthcare, agriculture, food safety and environmental and certain cross-domain scenarios. This section introduces some of these applications and scenarios.

A. Healthcare

A number of nanomachines could be deployed inside the human body in order to detect the presence of different biological elements in such environments. The network formed by this heterogeneous set of wireless body nano-sensor nodes is termed a wireless body-area network (WBAN) [39]. Fig. 4 depicts the architecture for the WNSN in healthcare applications, namely, intrabody nanonetworks for remote healthcare. Each WBAN is basically a composition of several wireless nano-sensor nodes and an individual nano-interface. The nano-interface is primarily responsible for the acquisition of the sensed data from all nano-sensor nodes and first-level aggregation of the data before transmitting it for further analysis and processing to the data center.

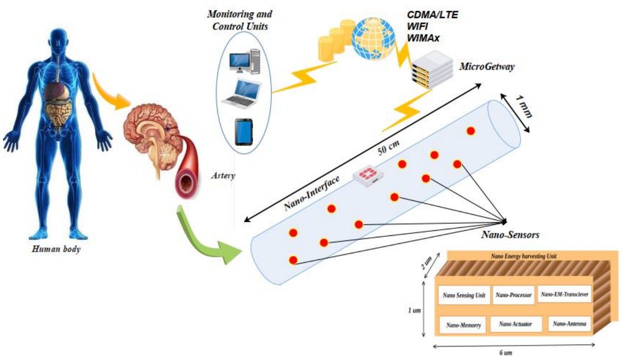

Fig. 4. The WBAN-based medical care in a hospital environment.

The main goals of WNSN healthcare applications are to analyze, monitor, and prevent healthy bad circumstances as well as the presence of viruses on the grains, cell, or the variations at DNA level [40]. Nano-sensors can be installed in the patient's environment to monitor her regular activities and alert emergency units to irregular changes in her attitude [41], [42]. WNSN health applications can also detect the clear presence of certain molecules, chemicals or infections and send notifications to a control agent [43]. In addition to the above-mentioned applications, WNSN also promote other medical applications, such as real-time medical imaging and video streaming, emotion detection and the obvious presence of harmful in biological cells.

B. Food Safety and Food Packaging

WNSN enables the application of nanosensors in the food packaging in order to monitor their quality in the course of the various phases of the logistics process, and to guarantee high quality of the product to consumers [44], [45]. The intelligent packaging is a category of container that provides particular functionality beyond the physical barrier between the food product and the environment [46]. Through smart packaging, WNSN can help to provide authentication, traceability and product location. The integration of a nanosensor into a food container will allow for exponential growth in the field of food security in the coming future. [47]. Another application of the WNSN network in food safety is to exploit nanosensors to detect molecules, gases and oxygen by installing different nanosensors inside the physical product to detect toxins, it enables giving a definite and visible sign if the food is fresh or not [48]. An intelligent product is a physical product that has the ability to communicate its condition information to a provider's agent, the nanosensors collect the information from the product environment, and sent them to the decision-making agent. The connection between the physical product and the decision-making agent is made using a nanointerface and a microgetway. Due to the WNSN, the smart product will provide great improvement in the food industry sector. The connected nanosensors, in the form of tiny chips that are undetectable by the human eye, are embedded in foods or containers, allowing food to be monitored at all stages: production, distribution and consumption [49].

C. Environment

The WNSN network will allow the use of nanosensors in the environmental safety, through the installation of nanosensors in high density public locations, such as hospitals, airports, and restaurants, to trace the circulation of viral viruses and improve the interpretation how various types of people are affected. Wireless nanosensor networks could also be utilized to supervise the environment, including pollution and greenhouse gas emissions. Similarly, the water quality sector would benefit from the use of nanosensors to detect bacteria, diseases and other harmful infectious agents [50]. An electrochemical nanosensor with nanointerfaces provides a biocompatible real-time monitoring system, these nanosensors are the major players in detecting environmental contaminants (especially metal ions, pesticides, and pathogens) in water [51]. Sensing and detecting different contaminants in water at nanoscale under laboratory and field conditions will offer assistance in developing modern nanotechnologies systems that will have better detection and sensing ability [52]. In Fig. 5, we introduce the architecture for the WNSN used to monitor water quality. The Smart Water nanosensors installed in the river measure different air and water quality parameters. Different nanonodes distributed in the same zone send data to an Internet Gateway. Nanointerface is used to collect the data from the nanosensor nodes and transmit them to pollution control authority. In this situation, the decision-making agent can access these data in real time to know the state of the water and correct accordingly the anomalies. This real-time monitoring will help to provide critical data for agronomic intelligence processes, such as optimal planting timing, but also for water level monitoring [53].

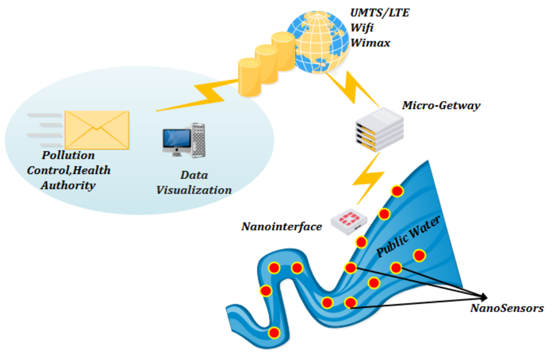

Fig. 5. Water quality monitoring architecture.

D. Agriculture

A requirement for detecting many conditions that a farmer desire to monitor (e.g., detection of plant viruses or the degree of soil nutrients), has tempted to use wireless nanosensors with nanoscale sensitivity to be especially crucial in realizing the vision of intelligent plants [54], [55]. A monitoring system that takes less time and can produce results in a few hours, that is simple, portable and accurate, allows the farmer to have all the information about the environmental conditions of the plants using a simple portable device. If an autonomous nano-sensor connected to an Internet system for real-time monitoring can be distributed around the plants to monitor soil conditions and detection of plant viruses, that would be an excellent solution to increase food production, with equivalent or even higher nutritional value, quality and safety [56]. For example, nano encapsulated atrazine allows the utilization of lower doses of herbicide without any loss of efficiency [57].

The combination of biotechnology and nanosensors will allow building a device of increased sensitivity, allowing real-time responses to attenuation in leaves due to the effect of thickness, and presence of water contents in leaves [58]. WNSN technology is on the verge of generating the tools for establishing real-time plant monitoring system, composed of chemical nanosensor merged with plants, nano-scale interface device and network micro gateways, as depicted in Fig. 6. Chemical nanosensor nodes are miniaturized machines that interact with the environment to collect a collection of chemical compounds disseminated by plants. Nano-interfaces are considered as control units that manage clusters of nanosensors, for example, conducting data fusion and planning. Finally, micro-gateways are interfaces that stimulate the applications of wireless network distribution networks by interconnecting data collected from the nano-network to the external network, then to the decision officer of the analytical laboratory [59].

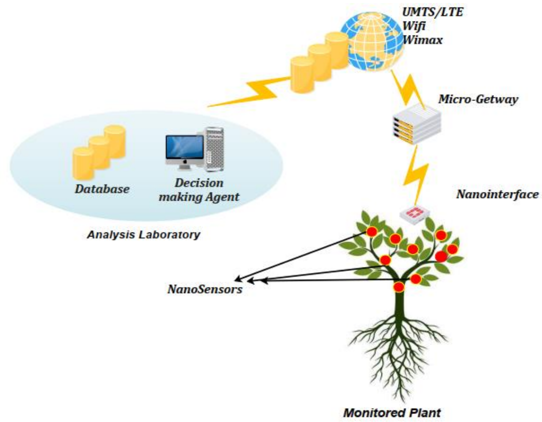

Fig. 6. The architecture of a plant monitoring nanosensor network.

E. Civil Engineering

By significantly improving the performance of sensor units and data collection systems and reducing their size, developments in nanotechnology can also benefit construction engineering and the built environment by enabling the practical deployment of structural condition monitoring systems for large civil engineering systems. Since nanosensors can be minimized and integrated into a composite material, this material can provide information on its performance and environmental conditions by monitoring structural loads, temperatures, humidity, heat gain or loss, and air conditioning loss, can be used for the construction of smart buildings [60]. Minimized-size nanosensors could be integrated into highways or coated on bridges for monitoring the processes that contribute to degradation and cracking, and alert the making decisions authorities a long time before the damage systems is detectable by human inspectors [61].

Wireless nanosensors embedded into roads and structures would allow engineers to monitor deterioration and cracking without any additional costs of physical intervention. Similarly, mechanical nanosensors in bridges have been emerging as a key device for such label-free and real-time vibration and loads measurements, allowing researchers to assess weaknesses and correct them long before they become apparent to inspectors [62], [63]. Road sensor networks could gather and provide data to transport operators to better control congestion and incidents and detect rapidly changing weather conditions.

F. Accident Avoidance

A nano-sensor can be utilized to detect the drowsiness of a driver and transfer the information to the decision maker agent. WNSN networks increase the monitoring range compared to conventional sensors [64], [65]. By distributing the nanosensors into the drive's body, we could detect drowsiness and transfer the information to the central control unit. Further progress can be made by deploying and networking nano sensors between the driver's body and the vehicle's engine unit to facilitate a safely stopping of the vehicle when drivers are not appropriate for driving [66]. The real-time driver-alertness monitoring system is an aimed model, which can be achieved by using the nanosensors wireless technology. A real-time monitoring system can be built to evaluate the driver's situation while driving using a network of wireless nano sensors [67]. This monitoring system can be implemented in a flexible nano headband, which can be designed to get an operational edition of the proposed real-time monitoring system.

G. Wild Life Monitoring

The WNSN network can be extremely useful for monitoring the health and condition of wildlife. The nanoscale dimensions of the nanosensors should be in the nanometer range and will not disrupt the life of the animals or birds monitored. Wireless sensors are currently used to monitor wildlife and birds [68], [69]. One of the major issues of the conventional sensors used for the wildlife monitoring is their large size, when they are fixed directly on the physical body of wild animals, these living organisms feel uncomfortable, therefore they will try break free and the system would be damaged. Then it must be changed. The problem is that detecting the location of this animal took a lot of time and work. Nanosensors will help in detecting explosions and affections by installing them along some insects such as bees [70]. The nanosensors can be installed on the insects delivered into surrounding environment, once the target substance elements have been found, the nanosensor sends data information to the nano-interface.

V. WNSN Challenges

The WNSN can be applied to improve many of our real-life applications. In order to achieve this potential, many requirements must be incorporated into the design of protocols. In this section, we examine the different requirements and challenges related to the WNSN applications deployment and management.

A. Data Collection and Processing

The detection, recognition and quantification of special chemical and biological ingredients are essential requirements for the development of nanosensors. In addition, it is planned that these various collected data will be integrated into a platform offering different services to the end user (messaging, file transfer, terminal emulation, monitoring,...). These services are standardized and accessible through standard interfaces. The application design for WNSN services needs to satisfy real-time requirements, in the other hand, the exceptionally short transmitting range of nanodevices will produce an arbitrary delay, which must be taken into account in WNSN implementation. In addition, the heterogeneous nature of nanomachines due to their use in different application scenarios will lead to different representations and forms of data [71]-[74]. Therefore, data fusion should be optimal and tolerant of delays for applications requiring the insertion of diverse data sources and requiring periodic monitoring by a decision-making unit.

Data aggregation and merging are not always practical for WNSN applications, due to real-time requirements, and many of these applications depend on fine temporal domain variations lost during the data aggregation process. In the other hand, data collection procedure presents different data-quality challenges in wireless nanosensors network. Nanosensor can be put erroneously on the body, or, in the event that at first is located at the correct area, could along these times slip or become detached. A nanodevice might intentionally corrupt data quality to preserve battery life. These issues call for new research in data detection quality. Finally, we require measurements to characterize the distortions and uncertainties related with collecting the data and the resulting mistake because the agent decisions are based on that data quality. The specification of such measurements is an open research question.

B. The Addressing Process

The nanoscale level and the large number of nanodevices in WNSN make it impractical to have individual network addresses for each nanodevice. On the other hand, the cluster-based addressing can be utilized instead of nanonode-based addressing. This makes it conceivable to identify a group of nanonodes according to the task they execute or the phenomena they supervise. One solution proposed in [75], which consists of tanking in specific scenarios where is not necessary to have information from a specific nanomachine, but, for example, from a type of nanomachine. In particular, different type of components may have different addresses, but identical nanomachines can have the same one [71]. The authors in [76] propose an 3D geographic-based addressing to assign several neighboring nodes located in one zone by the same address, in this case one address refers to a territory, noted zone. The fact that all nanonodes in one specific zone share the same geo-address guarantees a degree of natural nanonode tipping. Another challenge that is not debated in the design of protocol stack for WNSN, is the flow control mechanism and collision detection, particularly in a dense nanomachines arrangement methodology. Despite the fact that a few methods from electromagnetic communication may be adjusted for the Terahertz band, it isn't however clear how congestion will be addressed.

C. Routing Technology

Due to the restrictions of nanonodes (low processing capacity, small memory unit) and high density of WNSN nodes, the communication remains more challenging. The routing protocol is the method of selecting communication ways in a network and it a critical requirement for information transmission under given energy and complexity constraints. Basically, due to the restricted processing capability and energy storage of nanonodes, flood-based approaches are encouraged due to their simplicity, in which each nanonode rebroadcasts the packet received for the first time. Although flood-based protocols can accomplish high robustness, the high density of nanonodes leads to serious redundancy and conflicts, consequently increasing energy consumption. As a solution to this problem, threshold-based routing schemes have been suggested to prevent certain nanonodes from the excessive rebroadcasting by using a certain threshold (e.g. distance, redundant message counts, or broadcast probability) [77], [78]. All these algorithms, schemes attempt to ameliorate the performance of flooding schemes.

Based on the routing path, existing studies with data forwarding techniques can be classified mainly in two types of protocols: Multi-path protocols and single-path protocols. In a single-path routing approach, any nanonode received a message will retransmit the message to a particular next-hop nanonode. This type of routing algorithms can essentially reduce energy consumption, but if a nanonode is located on the wrong path, it'll result in packet loss. Nanonodes have constrained memory ability and cannot store neighbors' data. Therefore, when a nanonode gets or creates one packet, it has to select one of the neighboring nodes for forwarding by negotiation with them, which can increase the transmission delay. The Multi-path protocols are flood-based, when a nanonode receives or generates a message it exclusively has to choose whether to rebroadcast the message or not. Multi-path protocols ordinarily require lightweight computing resources, but will increase energy consumption.

TABLE I: COMPARISON OF WNSNS ROUTING PROTOCOLS

Protocols	RADAR	CORONA	DEROUS	SLR	MHTD	EEMR	ECR	TTLF	RDDA	PBDA
References	[79]	[80]	[81]	[76]	[82]	[83]	[84]	[85]	[86]	[87]
Deployment	2D	2D	2D	3D	2D	2D	3D	2D	2D	2D
Topology	Flat	Tree	Flat	Flat	Tree	Tree	Tree	Flat	Tree	Tree
Routing Path	Multi	Multi	Multi	Multi	Single	Single	Single	Single	Single	Single
Computing	Low	Low	Medium	Medium	High	High	Medium	Low	High	High
Mobility	static	static	static	static	static	static	static	static	static	static
Energy-aware	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Storage	Low	Low	Medium	High	High	High	Low	Low	Low	Medium
Position awareness	No	Hop counts to anchor nodes	Hop counts to radius	Hop counts to coordinate node	Distance to nano controller	Distance to nano controller	Layer	No	Hop counts to center node	Hop Counts to ClusterHead

In Table I, we have compared each protocol according to several factors, including the deployment space, the network topology, routing path, computing capacity, nanonode mobility, position awareness, energy-aware and storage requirements. The conception and implementation of routing protocols are considered imperative in WNSN. This is because of nanonetworks' nanodevices are usually constrained in their processing capacity, communication range and energy capacity. In any case, several design perspectives should be taken in to consideration. In fact, energy is the foremost critical and restricting factor in any areas of monitoring applications by using WNSN. In that sense, routing protocols, which optimize the energy consumption, while satisfying diverse constraints, are expected to have an incredible impact on the WNSN paradigm.

D. Channel and Physical Models

At the PHY/MAC layer, WNSN applications require the investigation of the characteristics of the communication inside the Terahertz band, specially the path-loss, noise-loss, bandwidth and channel capacity. The transmission channel capacity is depending on the nature of the obstacles located between the nano-sender and the nano-receiver. Since the transmitting range of nanonodes is exceptionally restricted, dense arrangement of nanomachines are required, combined with multi-hop communication path. This makes the choice of channel coding a complicated operation [88]. The attainable bandwidth depends mainly on the molecular characteristics existed in the channel, this make the channel models for electromagnetic radio frequency propagation challenging to model. This enabled more research to provide other communication techniques (e.g., ultrasonic communication) in order to perform the internetworking of nanomachines [89]. In [90], authors presented and evaluated a recent MAC layer protocol based on the joint selection by the transmitter and the receiver of the communication parameters and the channel coding scheme that minimizes the interference. The proposed scheme, called PHLAME, maximizes the probability of successfully decoding of received information. On other hand, Rikhtegar et al. developed a recent MAC layer protocol called Energy Efficient Wireless Nano Sensor Network MAC layer protocol (EEWNSN-MAC). The aim of the proposed scheme is to optimize the power consumption in wireless nanonetworks by taking the advantages of the clustering strategy and TDMA planning scheme to reduce the mobility impacts and transmission collisions [91]. Similarly, another mechanism was presented in [92]. The presented energy and spectrum-aware MAC protocol take advantage of hierarchical architecture of WNSN, so that all nano sensors can directly communicate with nano-routers through single-hop. Recently, Juan Xu et al. presented a load-aware dynamic TDMA (LAD-TDMA) protocol. This protocol is built on a novel pulsed-based communication scheme, called TS-OOK, and avoids symbol collisions to achieve high energy efficiency [93].

VI. Conclusion and Perspective

Wireless nano sensors have transformed classical approaches for solving a vast array of problems, especially in the healthcare, smart environment, agriculture, and food safety domains. Their flexibility and their broad range of applications are generating more and more interest from the research community and they have the potential of triggering the next revolution in information nanotechnology. In this paper, we focus on wireless nanosensors network paradigms. The architecture, applications fields and challenges are summarized and elaborated. We review and present the hierarchical architecture and applications areas of WNSNs, and challenges including routing algorithms and data analysis. WNSNs will serve as a more intelligent and nanoscale monitoring model to promote the development of IoNT. This is a valuable area of research that will influence future academics and industry researches. However, the special characteristics of nanoscale machines need to be unified for the design of WNSN architectures, and the challenges of WNSN paradigms need to be focused on the design of efficient data dissemination algorithms and the integration of WNSN with current internet of things microsystems and networks.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

This work is done by Ayoub Oukhatar and Dr. Mohamed Bakhouya and Dr. Driss El Ouadghiri as follows: The first author conducted the research and wrote the paper under the second author supervision. The third author provided guidance. All authors have read and agreed to the published version of the manuscript.

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