

Opportunities to implement Software Defined Radio in network sensors

Oportunidades para la implementación de radio definida por software en redes de sensores

Oportunidades para a implementação de rádio definida por software em redes de sensores

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Abstract

This paper reviews the concepts and characteristics of Software Defined Radio (SDR), focusing on the problematics of the wireless sensor networks in their fields of application; this with the purpose of finding opportunities to implement SDR functionalities to solve the requirements within the environment of a wireless sensor network.

Key words: Software Defined Radio; Wireless Sensor Network.

Resumen

En este artículo se revisan los conceptos y las características de la radio definida por software. Se presenta una revisión de las problemáticas de las redes de sensores en cada uno de los campos de aplicación desde la perspectiva de la integración con SDR, para finalmente hacer un análisis de oportunidades y desafíos como estrategia de solución a algunas de las problemáticas más importantes en redes de sensores.

Palabras clave: Radio Definida por Software; Redes de sensores.

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Resumo

Neste artigo revisam-se os conceitos e as características da rádio definida por software. Apresenta-se uma revisão das problemáticas das redes de sensores em cada um dos campos de aplicação desde a perspectiva da integração com SDR, para finalmente fazer uma análise de oportunidades e desafios como estratégia de solução a algumas das problemáticas mais importantes em redes de sensores.

Palavras chave: Rádio Definida por Software; Redes de sensores.

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I. INTRODUCTION

Wireless communications have dynamically grown and evolved in recent years, offering new connectivity services to users, who demand a faster information transfer and improved mobile services. New scenarios appear where heterogeneous networks and a dynamic access to the spectrum become more important to the industry, the academia, and the regulators [1, 2]. On the other hand, semiconductor manufacturers and workgroups, such as WiFi Alliance, ZigBee Alliance, and Bluetooth Alliance, are making an effort to both improve the functionalities of electronic devices and create standards that allow the mass use of technologies such as Wireless Sensor Networks (WSNs) in IP connectivity schemes, developing the paradigm known as “Internet of Things” (IoT) [3]. Recently, WSN solutions have been developed in the fields of industrial and building automation, process control, agricultural monitoring, medical assistance, public transportation, and emergency care systems, among others, demonstrating that the WSN increasingly integrates into everyday activities, improving various tasks [4, 5]. In this context, the concept of Software Defined Radio (SDR) is of great importance thanks to its adaptability, interoperability, and convergence, as well as its ability to implement dynamic access functionalities to the spectrum. Nowadays, those aspects have not been commercially implemented, due to the high costs and complexity of the equipment [6].

From this perspective, this review paper approaches the problems of the WSNs from the point of view of integration with SDR. First, the paper introduces

the concepts of SDR; then, it reviews the WSN application fields, and the problems that can be attacked from a SDR perspective; subsequently, it analyzes and discuss the current state of WSN and the opportunities for SDR; and finally, it compares the available development systems that allow implementing these functionalities.

II. SOFTWARE DEFINED RADIO

The term “Software Radio” was used in the early 1990’s by Joseph Mitola III to refer to a type of radio that was able to implement different communication standards from the same hardware. For this purpose, the signal modulation and encoding are performed by a software [6]. Software radio seeks to work the signal mostly in the digital domain to delegate some functions of the hardware to the software, using analog-to-digital (ADC) and digital to analog (DAC) converters. Figure 1 shows a functional block diagram of a device implementing SDR functionalities, in which three important sections are shown. The Radio Frequency (RF) section that receives and sends the signal to the medium is essentially composed of the antenna and radio frequency amplifiers; the Intermediate Frequency (IF) section is responsible for changing the domain to the signal, i.e., in the case of a receiver, the signal goes from the analogue to the digital domain, while the operating frequency is taken to an intermediate frequency by means of the Digital Down-Converter (DDC); finally, the baseband section is where the signal is processed to demodulate and decode, and thus extract the information [7, 8].

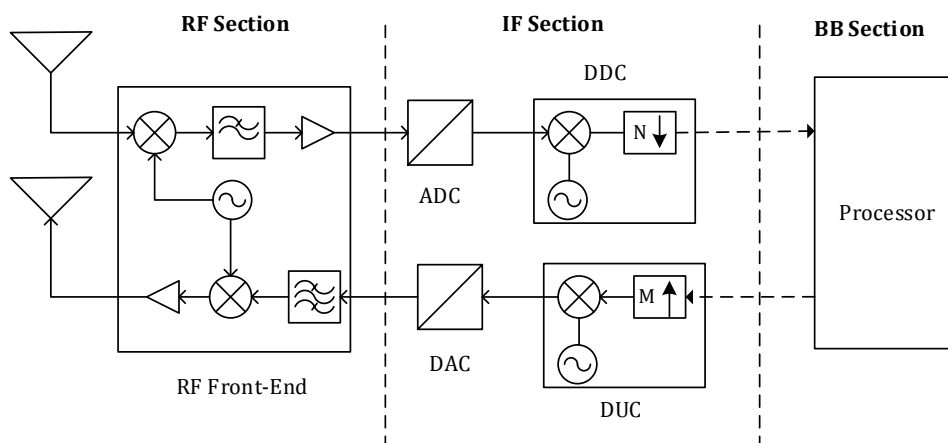


FIG. 1. Functional block diagram of an SDR. Adapted from [8, 9].

The ability to implement hardware functionalities in software through signal processing in the digital domain instead of the analogue creates a new scenario for telecommunications. First, it allows to operate different multi-band, multihoming, and multi-purpose standards in the same device without any hardware modification [10], and second, it provides scalability of communication systems by facilitating network updating and equipment functionalities from the physical layer to the application layer, thus achieving a better response to the market dynamics [10], which might change the scheme of a static network by an *ad hoc* network for mobility services [11]. In addition, it enables the implementation of the communication stack in a modular way for a specific application, responding to its particular needs in terms of operating frequency, modulation and coding form, number of nodes, or network topology to achieve a better performance. It also supports the use of dynamic spectrum access techniques to use the frequency bands of licensed users in idle time intervals, so that they do not interfere with the quality of the paid service [12, 13]; this paradigm is known as cognitive radio. Furthermore, it provides the necessary tools to maintain high levels of quality of service (QoS), from the frequency band adaptability, modulation, coding, transmission rate, or routing scheme [14] through the use of indicators such as PER (Packet Error Rate) or LQI (Link Quality Indicator). Finally, SDR is a technology that, due to its ability to update functionalities, allows the use of a device in different environments with different

characteristics, and in this sense, SDR equipment generates a lower environmental impact by having an obsolescence rate lower than traditional hardware.

III. WIRELESS SENSOR NETWORKS

Significant cost reductions in micro-controllers, increased information processing capacity, reduced energy consumption, and the emergence of free-bandwidth wireless technologies such as ZigBee, Bluetooth, and WiMAX have fostered the integration of WSN in industrial applications, and in the daily life of people. Nowadays, sensor networks can be found in a wide range of locations, such as manufacturing and production processes, agricultural farming systems, public transport systems, building surveillance systems, home automation and control systems, offices and industries, personal medical assistance services, crisis assistance systems, and natural disasters [4, 5, 15, 16].

Depending on the used standard, WSN implements point-to-point, multipoint, mesh, or star topologies (Fig. 2). However, in general, WSN presents a scheme containing multiple sensing nodes, and at least one central device in charge of managing the network (coordinator), which can act as Gateway to interconnect the network with other networks or interfaces with different standards. Figure 3 shows the general architecture of a sensing node. In practice, the sensing nodes can have actuators, and a graphical interface if required.

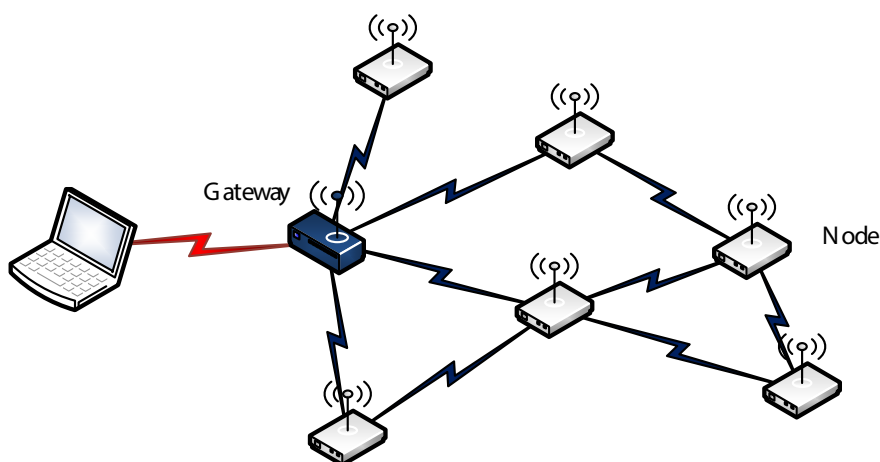


FIG. 2. Interconnect topologies in wireless sensor networks.

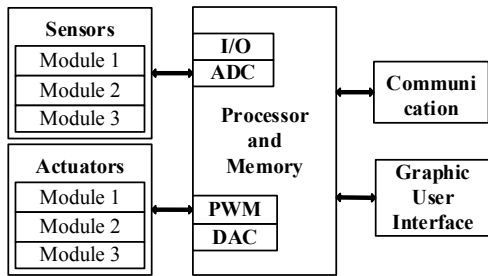


FIG. 3. General architecture of a sensing node.

A. Building automation

Applications related to the automation of spaces in homes, buildings, hospitals, hotels, and others have been highly commercially developed in recent years. Companies like Control4 offer services for personalization of spaces ranging from lighting control and multimedia content to air conditioning, the latter using HVAC (Heating, Ventilating and Air Conditioning) [17]. There are proposals oriented to security systems through the use of cameras, sensors, alarms, and identifiers that allow alerting in case of an anomalous situation [18]. Also, there may be tools to monitor and control the energy consumption of appliances [19]. For these purposes, technologies such as ZigBee, WiFi, Bluetooth, RFID (Radio Frequency Identification), UWB (Ultra-Wide Band), Home RF, Zwave, and GSM are implemented with a tendency toward remote administration from the Internet. In this sense, a Gateway or link element must be available between the personal network and a public access network [21, 22]. This type of environment is characterized by involving different communication standards within the same network, so that they can offer different services according to the characteristics of each technology, for example, to provide a better interaction between the system and the user through WEB interfaces, LCD screens, applications for mobile devices, or even GSM (Global System for Mobile Communications) connection for telephony services [23]. Internet connectivity is of great interest, so much so that different strategies like Web Services Description Language (WSDL) and SOAP (Simple Object Access Protocol) are implemented to make a virtual connection between the nodes and a web server, where the server identifies each device with an IP address [22]. Also, the easy integration and configuration of devices from the user's perspective, and the compatibility between teams of different companies have led to the

emergence of protocols such as OSGI (Open Service Gateway Initiative) [24].

In this context, a scenario exists with a lot of potential for sensor networks to offer and continue developing multiple services. However, some issues still remain unsolved in terms of installation ease and scalability, as well as incompatibility between devices, even though most of them are based on the 802.15.4 standard. Heterogeneous networks must be more flexible so that they can be upgraded to provide more services by including new wired and wireless technologies, such as compatibility with infrared communications, fiber optic services (FTTH), multimedia services in bands other than 2.4 GHz such as UWB, and better integration with Body Area Networks (WBSN). In this sense, SDR can offer viable solutions to cover these problems, for example, an approach to build a Gateway using an SDR device, which also integrates fiber optic technology, that solves the problem of interoperability by updating the network with the inclusion of new standards, and providing new tools to improve the quality of the multimedia services is proposed in [25].

B. Agriculture

Recently, the concept of precision agriculture has appeared, which, through sensor networks and environmental variable control systems, can increase productivity and crop quality [15]. Plantations in different regions of the world have used sensor networks to monitor parameters such as temperature, humidity, radiation intensity and photosensitive flow, among others, to keep records of productivity in relation to environmental conditions [26]. Also, these systems allow early identification of pests for early intervention and recovery of plants [27]. Automatic irrigation systems [28] and fertilizer distribution [29] have been developed according to the needs, so that water savings of 30 % to 60 % have been achieved. From variables such as humidity, CO₂, PH level, temperature, the appropriate levels of Nitrogen, Potassium and Phosphorus, and the amount of fertilizer to be supplied are determined [30, 31]. WSN allows identifying the factors that affect the quality of the harvest, a critical element in the production of wines, for example, as in [32], where the geographic characteristics of the terrain generated a variation of 35 % in the temperature within the vineyard, generating variations in the quality and profile of

the harvested grapes. In greenhouses, it is possible to implement automated temperature, humidity, and lighting control systems to ensure product quality standards [33], and in addition, these systems allow a more efficient use of resources, such as personnel, water supply, fertilizer and electrical energy, as described in [34], where two fuzzy controllers are implemented to achieve the desired internal temperature, with actuators in windows, artificial lights, water valves, and heaters.

There are many advantages of implementing WSN in agriculture, however, this is a field that is still under development, and has some important limitations, such as the energy consumption of the nodes, and the large dimension of the used networks in terms of number of nodes and coverage that hampers the design and maintenance of the network. Additionally, each case and application must undergo a particular development that must be validated in the field, in order to overcome potential problems of signal fading and degradation that the equipment may suffer due to the variable environmental conditions [26]. The monitoring and/or control systems seek to be remotely managed, so they must be connected to a network that facilitates interaction with the user, and that, for coverage issues, may be Internet or GSM; therefore, there must be a device that communicates between different standards. Also, new strategies should be reviewed to extend the life cycle of nodes, such as routing schemes, energy consumption, and transmission scheduling of periodic and non-constant information, which in that context might provide improvements. In this sense, SDR, as the central device of the network, could implement centralized routing techniques based on SDN (Software Defined Networking), reducing the energy consumption and the data traffic on the nodes [14].

C. Industrial automation

In the industrial field, WSNs support control and production processes that are not critical, and monitor environmental working conditions such as temperature, humidity, and the presence of someone in a specific area to alert any undesirable situations [35]. WSNs monitor the state of the machines to detect changes in their operation, and allow to perform a timely preventive maintenance, as presented in [36], where non-invasive vibrations were recorded in the motors, facilitating the detection of possible

parts failure that could be avoided by maintenance, and thus saving costs. WSNs also allow product tracking within a production chain, distribution, and even sales [37], by using passive UHF-RFID (Ultra High Frequency RFID) labels inside large rolls of paper, which improves storage and distribution in the entire process within the production chain. The used communication schemes generally work under wired TCP/IP schemes, however, wireless standards such as WirelessHART and ISA100.11, based on 802.15.4, have also been developed, being these more robust than ZigBee and 6LoWPAN [38].

In these environments, electromagnetic interference is experienced due to the presence of motors, welders and melting machines, and demanding conditions of temperature, humidity and vibrations that affect the quality of the signal. Therefore, the information being transmitted should not be sensitive to errors, delays, or to the Jitter effect [39]. For this reason, WSNs are not used as main elements in the monitoring of the production process synchronicity. On the other hand, aspects of quality of service and information security are of vital importance without fault tolerance, and in this sense, SDR provides the tools to provide a high level of QoS. Network maintenance schemes that do not generate discontinuities in production should be taken into account. Node architectures must be efficiently designed and implemented to meet these requirements, keeping in mind that there are limited resources in energy, memory, and processing [40]. From another point of view, the implementation of RFID technology within the entire production chain begins to be an interesting solution within the management of large inventories, allowing developing more efficient schemes in storage and distribution of the products, representing savings in personnel, time, and money.

D. Medical assistance systems

Since the development of consumer electronics, a number of devices known as wearable have recently appeared; these devices integrate heart rate, temperature, and accelerometer sensors to identify the type of activity performed by a person and their most important vital signs [41]. These systems have functionalities in the area of high-performance sports and remote monitoring of patients with physical or cognitive limitations, or of specific populations such as firefighters, blind people, infants [42], and

the elderly [43]. For these applications, the ANT+ standard has been developed, which is neither compatible with Bluetooth Smart nor 4.0, which are frequently used and characterized by having low power consumption and a low transmission rate (1 Mbps); both are available in smartphones, the first one only in some models [44].

Because these systems must be robust and the development of standards is still recent, they may be subject to modifications, as happened with the initial version of ANT+. However, this protocol is proprietary and the information is not open to the public. In this sense, it opens a door to many new applications in sports and medicine. New scenarios of convergence with other networks will appear in accordance with the dynamics of the market and the integration of these technologies with the user. In the meantime, the SDR perspective in this context is not entirely clear, but certainly, its integration and interoperability, updating and adaptability capabilities could be useful in hospitals, gyms, and/or sports centers in the near future.

E. Monitoring systems

A monitoring system consists of a transducer element that converts the physical variables into electrical signals that are sent by a serial interface to a microprocessor with storage and communication capacity to a central station. These systems allow monitoring environmental conditions at a lower cost than those based on specialized instruments. Seismic warning systems have been developed near volcanoes [45]. Microclimate characterization systems have also been developed in redwood trees [46] and in marine environments, where ultrasonic communication and an optic system for the transmission of underwater images are implemented [47], or through buoys where the ZigBee nodes are placed while the sensors are adequately submerged [48]. On the other hand, the use of monitoring systems in environments of smart grids is proposed. Decentralized systems of electric power generation need to record consumption and power generation levels, and transmit them in a timely manner to the energy plants, detecting faults and abnormalities in the service delivery [49]. Some network schemes have been proposed, taking into account domestic networks as a basis for the integration of energy

monitoring systems with users, and facilitating user interfaces already implemented [50].

Network schemes open the possibility of monitoring very diverse environments, many of them of difficult access and with somewhat unfavorable conditions for wireless communication. They seek an efficient use of energy consumption so that the investment made can be justified in the medium or long term. New communication interfaces such as ultrasound and optics have arisen, providing solutions for WSN, and at this point, SDR technology provides tools that allow the communication system to be adapted in the most efficient way to guarantee communication in each particular environment. In some cases, priority must be given to variables such as real-time transmission, transmission rate, or coverage. The SDR technology opens the possibility of adding new interfaces to the SDR devices by providing them adaptability in the electromagnetic domain, as proposed in [51], where the addition of an ultrasonic domain to the equipment is sought.

F. Tracking systems

The recent appearance of autonomous vehicles has brought a series of technical problems and regulations that are in the process of being solved. It is of great importance that these systems are constantly reporting their status and position to prevent accidents. In this sense, communication with other vehicles and with static control elements such as traffic signals is one of the aspects of greater attention, especially when it comes to avoiding accidents that involve human lives. The scenario of these communication systems is more complex than other environments; also, mobility aspects at speeds that can reach 120 km/h, as well as the large number of nodes within the same area make unfeasible the implementation of traditional standards like ZigBee or WiFi. For this reason, protocols such as CALM (Communications Access for Land Mobiles) and DSRC (Dedicated Short-Range Communications) have been developed to mitigate multi-path fading problems [52], and improve multi-hop and hop-by hop transmissions [53]. In this field, SDR technology is capable of providing *ad-hoc* services in point-to-point or multipoint networks, while providing different services in very different network topologies, for example, for buildings or traffic signals. Then, as a

flexible and heterogeneous platform, SDR could be considered for applications in mobility services.

IV. DISCUSSION AND ANALYSIS

Currently, WSN is very dynamic in different fields. Memory and processing capabilities have improved, and will continue to do so, allowing high-level programming libraries and languages to be integrated, making independent the hardware from the software. Open software tools such as “TinyOs” and “mbed” allow users to develop applications more easily in shorter times, prompting the emergence of new applications for the WSN. The tendency is toward creating heterogeneous WSNs that have connectivity to the Internet, strengthening the concept of “Internet of things”. Due to the diversification of applications, new standards have emerged to improve the performance of the WSN, particularly ANT+, Bluetooth 4.0, WirelessHART, CALM and DSRC. New application environments, and thus new standards that seek to reduce signal fading, interference and noise in the channel, critical event timing, delays and the Jitter effect problem, autonomy of the devices, security, and communication reliability will surely continue to emerge.

On the other hand, SDR development card costs have declined dramatically in recent years, making it affordable for academia and businesses. Devices such as RTL-SDR (\$20) have an interesting niche market, and their integration with devices such as Rabsberry Pi, for example, contributes to increase applications in different areas of the WSN. The need for a central device within the network to manage and provide different user interfaces allows the SDR devices to extend the functionalities of the network; for example, these devices have the capabilities to implement artificial intelligence schemes to provide learning features and automatic reconfiguration.

However, SDR should continue the process of cost reduction, as it has been doing to increase its deployment. It will also be necessary for these systems to integrate “On-the-air programming” tools, which allow device updates in real-time. It will also be important that these devices continue to improve in terms of processing capacity, so that more complex communication systems such as those with FHSS (Frequency Hopping Spread Spectrum) coding

can be implemented. Additionally, there are some regulatory challenges, when commercially using this kind of devices to protect the unauthorized use of software, also under the conditions of power and bandwidth according to the assigned frequency, these devices should not interfere with other equipment [10].

Some papers suggest the use of software-defined radio in applications of optimized heterogeneous networks, such as medical care, body networks, energy distribution networks, and communication systems for emergency care. This is according to the adaptability, convergence, interoperability, robustness, and scalability offered by the SDR. For example, libraries have been developed to use the physical and link layer OQPSK-PHY and CSS-PHY working in the 2.4 GHz band of the 802.15.4 standard for GNU radio [54, 55], and for Matlab [56, 57]. A BTS (Base Transceiver Station) of cellular telephony in the GSM bands of 800/900 MHz and 1800/1900 MHz has also been developed with the tool OpenBT [58]. Similarly, in [59], a new architecture for the nodes is proposed, integrating hardware that makes SDR integration possible. USRP1 development boards are used as the hub of a sensor network running on 802.15.4 and GMSK, and the ADC modules of the board are used to record the temperature level.

V. DEVELOPMENT TOOLS

Among GNU software tools, Radio Companion stands out; it is open source, integrates Python and C++, and has the Universal Hardware Driver (UHD) of a large number of devices capable of implementing SDR functionality; its development was originated in Linux operating systems, and is being extended to Windows environments. On the other hand, private application development tools like Matlab and LabView have less support and less compatibility with different hardware tools. Moreover, different equipment that have the general architecture of Figure 1 are available in the market. Table 1 presents a comparison of the most important characteristics, where aspects such as the bandwidth of the signal in baseband, transmission and/or reception features, ADC and DCA specifications, tuning frequency, and cost are described.

TABLE 1
COMPARISON OF FEATURES AND COSTS OF DEVELOPMENT CARDS

Board	USRP1	USRP B210	USRP B200	USRP N210	SDR-RTL RTL2832U	Hack RF one	Blade RF
BW/ MHz	16	56	56	50	3,2	20	28
Full duplex	Si	Si	Si	Si	Solo Rx	Half	Si
Interface	USB 2.0 HS	USB 3.0	USB 3.0	Gbit Ethernet	USB 2.0 HS	USB 2.0 HS	USB 3.0
V /Mbps	480	5000	5000	1000	480	480	5000
MIMO	2 RX - 2 TX	2 RX - 2 TX	1 RX - 1 TX	2 RX - 2 TX	1 Rx	1 Rx o 1 Tx	2 RX - 2 TX
ADC /Bit	12	12	12	14	8	8	12
DAC /Bit	14	12	12	16	~	8	16
ADC /Msps	64	61.4	61.4	100	3.2	20	40
DAC /Msps	128	61.4	61.4	400	~	20	38
F / GHz	0.4-4.4 @SBX	0.07 - 6	0.07 - 6	0.4-4.4 @SBX	0.024 - 1.776	0.03 - 6	0.3 - 3.8
FPGA	Altera Cyclone	Spartan 6 XC6SLX150	Spartan 6 XC6SLX75	Spartan 3A-DSP 3400	8051 +demod	CPLD	Altera Cyclone IV
Cost / USD	720,00	1120,00	690,00	1750,00	10,00	300,00	420,00

Table 1 lists different development tools with different characteristics and different costs, all of which are compatible with GNURadio, from which the signal processing blocks are generated for transmission and reception. Some of the cards have MIMO (Multiple Input Multiple Output) functionality to simultaneously receive and/or transmit multiple channels. Another important feature is the tuning frequency, which in some cases reaches up to 6 GHz. It is also important to mention that the shown signal bandwidth (BW) values refer to the use of a single channel, if more channels are used, this value will be reduced.

VI. CONCLUSIONS

In this work, we described how the inclusion of the SDR concept in wireless sensor networks can provide solutions to the heterogeneous networks concept in different application environments, some of them frequently used and others still in early stages of development. In each one of these environments, particular circumstances appear; therefore, depending on the application, different modifications

should be performed to assure different levels of coverage, transfer rates, bandwidth and storage of information, levels of security and communication reliability, energy dependency levels, as well as characteristics such as the mobility of the nodes or their number. In this context, traditional schemes for sensor networks such as ZigBee or WiFi have not been flexible enough to meet all needs, so new standards are beginning to emerge to provide more efficient solutions in each case. This aspect has created a scenario of heterogeneous networks with IPv6 compatibility, featuring a growing number of nodes, and in this sense, the characteristics of SDR can provide solutions to the designers of sensor networks. However, in order for this paradigm to compete with traditional developments, costs should be reduced and more accessible tools should be developed, while solving some normative limitations.

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