Radio Context Awareness and Applications

Luca Reggiani, Jocelyn Fiorina, Sinan Gezici, Simone Morosi, Montse Najar

Abstract

Context regards “any information that can be used to characterize the situation of an entity, where an entity can be a person, place or physical object”. Radio context awareness is defined as the ability of detecting and estimating a system state or parameter, either global or concerning one of its components, in a radio system for enhancing performance at the physical, network or application layers. In this paper we review the fundamentals of context awareness and the recent advances in the main radio techniques that increase the context awareness and smartness, posing challenges and renewed opportunities to added value applications in the context of next generation wireless networks.

Index Terms

Wireless Sensor Networks, Detection, Positioning, Radio Identification, Context Awareness

I. Introduction

MODERN wireless systems are required to manage radio resources in an effective and flexible manner in order to maximize the network capacity. Moreover they are increasing their complexity and pervasiveness in the real world at several scales, giving rise to heterogeneous, more decentralized and sophisticated systems. In this context, next generation radio systems are required to achieve high capacity, high reliability, flexibility, adaptivity and full support to innovative applications and services that make use of the awareness of both the context and the surrounding environment. Therefore, collaboration, awareness, smartness, and adaptivity are the keywords of a trend that involves all the radio technologies, from Wireless Personal Area Networks (WPAN) to Wireless Metropolitan Area Networks / Wide Area Networks (WMAN / WAN) and Wireless Regional Area Networks (WRAN) as depicted in Fig. 1. Wireless sensor networks (WSN), whose radio technologies belong mainly to WPAN, play a fundamental role in the field of radio context awareness: these sensing networks are usually composed of a large number of low-power, low-cost and long-life nodes equipped with sensing, computation and wireless communication capabilities and they can produce, with several degrees of performance and complexity, the features and the related applications that will be discussed in this paper.

As stated efficaciously in [1], context regards “any information that can be used to characterize the situation of an entity, where an entity is a person, place or object that is considered relevant to the interaction between a user and an application, including the user and applications themselves”. Therefore radio context awareness concerns the ability of detecting and estimating a system state or parameter, or global or concerning one of its components, in order to enhance communication performance from the physical to the network layers or in order to provide the necessary context information for advanced services and applications. Channel state information, energy consumption, positioning and environment mapping, mutual interference among active devices, and spectrum usage, are examples of system state information that can enhance either the efficiency of the communication network itself or the effectiveness of the applications which can be built on this context knowledge [2]–[10]. Nowadays it is clear that radio context-aware techniques can give a further strong impulse to new applications and enhance communication performance operating on several aspects of the system.

This trend is enforced also by the ongoing Internet of Things (IoT) development, in which a pervasive connection of the environment will facilitate sensing, communication and interaction capabilities never observed until now. IoT and Internet will provide a potentially dramatic increase of earth awareness and in the future communication platforms, characterized by relevant and increasing levels of spread awareness, the radio technologies will play a crucial and irreplaceable role either for their mobile and flexible communication capability or for the information that can be extracted from the surrounding environment [11], [12]. Thanks to the properties of electromagnetic propagation, a radio transceiver is not only a communication device anymore but a sensor itself of the surrounding context and environment. Therefore, wireless communications is one of the key enabling technologies of this new paradigm. Examples of potential application fields cut across all the most promising next generation systems and infrastructures, as (i) eHealth (electronic health systems), (ii) smart vehicles and intelligent transportation infrastructures, (iii) smart buildings and homes, (iv) smart energy grids, (v) environment monitoring and control, (vi) context aware mobile services.

L. Reggiani is with Dipartimento di Elettronica, Informazione e Bioingegneria, Politecnico di Milano, Milano, 20133 Italy, email: reggiani@elet.polimi.it.

J. Fiorina is with Departement de Telecommunications, SUPELEC, 91192 Paris, France, email: jocelyn.fiorina@supelec.fr.

S. Gezici is with Department of Electrical and Electronics Engineering, Bilkent University, 06800 Ankara, Turkey, email: gezici@ee.bilkent.edu.tr.

S. Morosi is with Dipartimento di Ingegneria Elettronica, Universita’ di Firenze, 50139 Firenze, Italy, email: simone.morosi@unifi.it.

M. Najar is with Departament de Teoria del Senyal i Comunicacions, Universitat Politcnica de Catalunya, 08034 Barcelona, Spain, email: montse.najar@upc.edu.

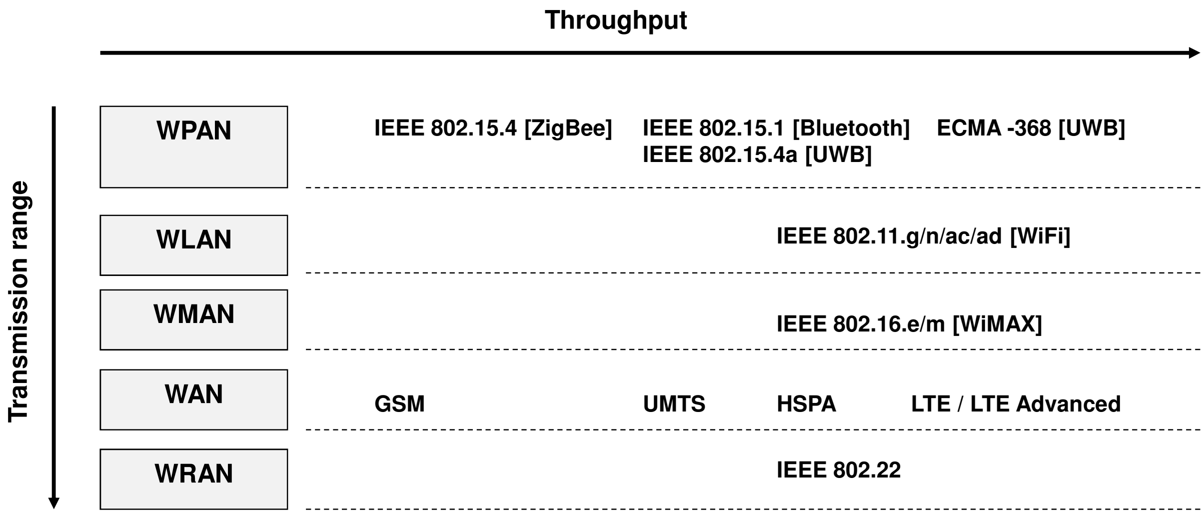

Fig. 1. Current scenario of radio technologies and standards.

In this review paper we particularly take an interest in those techniques which, via radio transmission, provide information that can enhance *context aware applications*. Sect. II describes the main concepts and the radio context awareness model we use for categorizing the contributions in this field. In particular we divide the contributions of radio awareness that are used to enhance system performance from those that can be used in the application layer for specific services and functions. The next sections are dedicated to the three main sectors that have been active in the recent years in this area and that can provide a further contribution and development in the near future: Sect. III presents a survey of identification of persons or objects through wireless technologies, Sect. IV to the vast area of radio detection and Sect. V to radio localization. All these sections are the expression of the main contributions to context awareness that arise from the radio physical layer of modern and future communication systems.

II. The radio context awareness model

Awareness is the prerequisite for any cognitive activity and therefore to what we commonly call intelligence. In [13], Mitola classified the cognition tasks in terms of nine levels of capability in a radio network; the process from a standard to an intelligent radio includes the following fundamental steps, characterized by an increasing level of cognition ability.

- Context or environment awareness with minimum user involvement.
- Capability of learning and planning according to an objective.
- Capability of adapting autonomously, modifying plans and protocols.

Since Mitola's work [13], [14], the concept of cognitive radio has opened a wide research activity, with the objective of improving spectrum efficiency and design flexibility of radio systems. In particular, the spectrum usage in terms of opportunistic and efficient exploitation of available, free radio channels has been the main research subject in this field and spectrum sensing has become the fundamental, enabling function for the physical layer of cognitive radio systems [2]. Many times it's been observed how the evolution of the congestion of the licensed spectrum has not avoided its under-exploitation, leading to the necessity of new spectrum sharing systems [15]. S. Haykin, in [16] formulated the following definition of cognitive radio in a radio network: Cognitive radio is an intelligent wireless communication system that is *aware of its surrounding environment* (i.e., outside world), and uses the methodology of understanding-by-building to *learn* from the environment and *adapt* its internal states to statistical variations in the incoming Radio Frequency (RF) stimuli by making corresponding changes in certain operating parameters (e.g., transmit-power, carrier frequency, modulation and coding schemes) in real-time, with two primary *objectives* in mind: (i) highly reliable communications whenever and wherever needed, (ii) efficient utilization of the radio spectrum. Again, it is clear that *to be aware*, *to learn* and *to adapt according to some objectives* are the key steps of the cognition cycle.

Several other definitions are present in the literature and in documents by standardization institution and an exhaustive discussion on these definitions can be found in [17].

In the vast spectrum of methodologies and applications that have occupied the radio context awareness area, herein we are considering those techniques that are more strictly related to the possibility of creating *intelligent context aware applications* rather than improving directly communication efficiency, namely to those properties of wireless transmission and propagation that can provide some crucial capabilities to the context aware systems. In Fig. 2 we classify the main functions that can arise from radio transmission for context awareness according to their main usage: (i) for the application and service layer or (ii) for the efficiency of the wireless transmission itself in terms of capacity, coverage and/or opportunistic exploitation of

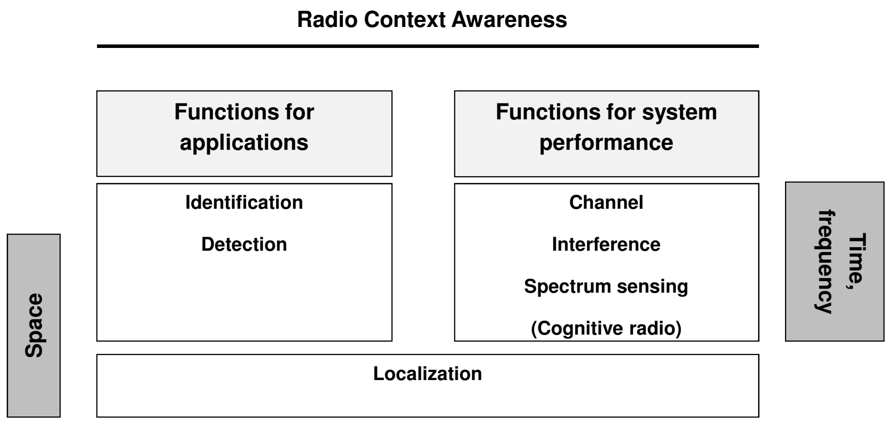

Fig. 2. Radio context awareness: impact on applications or on communication efficiency.

the radio resources. We observe that this division is related to the exploitation of the three fundamental physical domains, i.e. time, frequency and space. Increasing awareness in the time and frequency domains of the environment opens new potential abilities of increasing the transmission efficiency since this is related to the enhanced knowledge of the *signals* (and possibly of *interference*) in the surrounding environment. On the other hand, all is related to an enhanced knowledge of the space around the transmitters can have either some advantages on the transmission efficiency or, more importantly, numerous applications and services for users, machines and systems that are present and work in that surrounding environment. Therefore, the relation between electromagnetic propagation and space and the possibility of deriving space properties (in terms of existence or detection and identification, position, velocity) of users and/or objects is the main contribution that radio transmission physical layer can provide to the application layer of context aware systems.

It is worth to observe that this formulation of radio context awareness can be integrated also in the more recent evolutions of cognitive radio, in particular cognitive networks, where the environment cognition is extended from the physical and data link layers to the network and application ones. According to this research line, the wireless environment is enriched by other cognitive layers, firstly the network and user environments forming a sophisticated and cross-layer so-called multi-domain environment [18], [19].

Obviously, radio context awareness has also some costs and drawbacks, mainly regarding the increased complexity (in the device architecture and/or in the algorithms computational load), traffic (between the nodes in a WSN) and energy consumption. These challenging issues and drawbacks depend on the algorithmic solution chosen for achieving the context awareness measures. We can classify the algorithmic approaches according to their cooperative nature and to the distribution of the computational load. Firstly, in a cooperative approach, a network of sensors perform the observation and the measurement regarding the context parameter. Several motivations support the adoption of cooperative approaches w.r.t. non cooperative ones: large networks with large numbers of nodes may have a great potential advantage from an extended number of measures and, in numerous situations, ad-hoc wireless networks necessarily adopt cooperation for achieving the requested context measure. The main drawback of a cooperative approach, especially in a WSN, is the energy consumption since more nodes are required to join the overall process; therefore a compromise has to be achieved between the performance gain and the energy consumption. Secondly, algorithm can be operated in a centralized or distributed manner. In a centralized approach all the nodes transmit the estimated measures to a single node, chosen according to the network topology or its technology and characterized by a large computational capability. Conversely, in a distributed approach the algorithm is performed by a subset or by all the nodes and the result is computed locally. The main advantage in a distributed approach is given by the reduction of the necessity of transmitting data to the unique central processor; in fact, in a distributed approach, nodes send measured data mainly to their neighbors and the final location is usually derived by successive refinements performed in an iterative way. So centralized and distributed approaches have an impact on the network traffic, on the computational load, on the final performance, on the estimate latency and on the energy costs. The main trade-off to be analyzed is usually between the network traffic and the computational load in the network nodes. Also in this case, the energy consumption plays an important role since transmission is usually more expensive than data processing and computing and hence reductions of data traffic can guarantee important advantages.

The next sections, dedicated to the areas of radio identification, detection and positioning respectively, present a brief review of the radio technologies that realize these functions, of the main practical applications and then a survey of the recent advances published in the literature.

III. Radio Identification

Radio identification relies on the possibility of exchanging automatically information about the identity of a person/object by means of radio transmission of short packets. Radio identification can occur by using active or passive systems, referred as

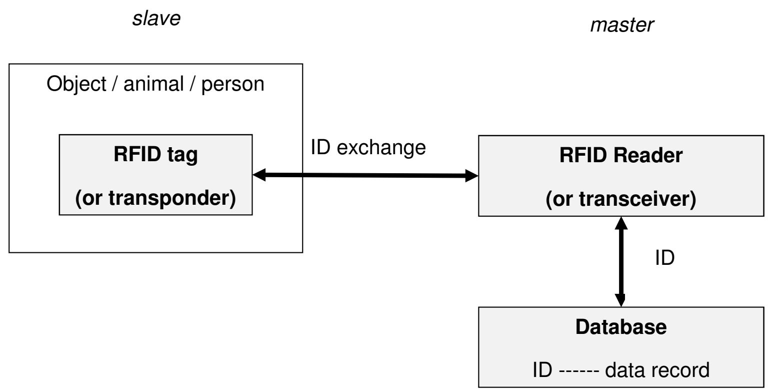

Fig. 3. The basic architecture of an RFID system.

RFID systems: the former use a power source for emitting a radio frequency signal while the latter can be read by means of electromagnetic induction at short ranges. RFID systems provide automatic identification and consist of small devices, called transponders or tags, which can be read or written by transceivers, called readers. Moreover the system is usually completed by a database, which contains the data records linked to the identification messages sent by the tags (Fig. 3). RFID systems can be used for identifying objects and persons in order to manage inventory and tracking in a huge variety of applications and fields, such as:

- tracking of persons and animals.
- Logistics and tracking of objects (inventory, supply chains management, baggage control in airports, warehouses, commercial centers, industries, hospitals, waste control, containers).
- Authenticity control of goods (luxury goods, prescribed drugs).
- Access control (building access, car access).
- Toll contactless payments, ticketing (subway, public transport systems, museums, stadium).

The physical functioning principle is based on the passive or active interaction between tags and readers, which realizes a centralized master-slave architecture. The tag contains electronically stored identification information which can be read at several distances (ranges from few centimeters to several meters away), not necessarily in line of sight wireless conditions. Also the radio frequency bands are different and they are related to several power and performance parameters; Table I reports the existing main standards with the corresponding operating frequencies.

While active tags operate by transmitting and receiving short packets with standard digital modulation formats, passive tags rely on a different physical mechanism for exchanging information with the transceiver. In this latter case, the tag transponder receives its power from the reader by magnetic induction: the transceiver sends an electromagnetic signal to the tag, the tag dipole antenna charges a capacitor and then the capacitor releases the accumulated energy to the tag's coil. Finally the coil transmit a signal containing the encoded information that will be read by the transceiver. For a more detailed review of the RFID technology and applications, the reader can refer to [20]–[26].

In the context of radio identification, near field communication (NFC) is a set of standards for the confluence between RFID and cellular telephony, particularly smartphones and similar devices [27], [28]. Radio communication is activated by close proximity (usually less than 10 cm) or contact between two mobile devices and the most promising applications include contactless, fast payments and social networking. NFC is an open platform technology present in ISO/IEC 18092, ISO/IEC 21481 and ECMA-340, ECMA-352 standards (see Table I): these standards specify the modulation, coding, frame format and the initialization and transport protocols.

Next Sect. III-A summarizes the most recent results in this field through a selection of papers published in the last 3 years.

A. Recent advances in radio identification

We have organized the selected publications into the following main research and development fields.

1) **Antenna design**. The largest number of recent articles is dedicated to the design of the two fundamental elements of an RFID system, i.e. the antennas at the reader and the tag [29]–[31]. The reader antenna should generate a strong magnetic field while tag antennas, usually subject to size and shape constraints, should also be robust against angular position and orientation. In [32], the authors present a narrow-band, small antenna, which is implemented by spraying it with conductive paint on a car chassis.
2) **Tags on metallic surfaces**. It is well known that RFID tags suffer from large performance degradation when attached to conductive surfaces. In [33], [34], the authors present two antenna designs that are suitable for installation on metallic objects.

3) **Technology**. In this context, [35] presents the design and fabrication of RFID tag antennas operating in the low microwave frequency range (3.5 GHz) on paper substrate and with an inkjet printing process; this technology assures very easy reproducibility, mechanical flexibility and ultra-low costs.
4) **Security**. Security is another current research subject since most existing RFID tags can be cloned or tracked. In [36] the authors implement and study RF fingerprinting for authenticating individual RFID tags at the physical layer; RF fingerprinting works associating an RF waveform with its unique source and, in an RFID tag, this requires finding these unique variations in its RF signature. In [36] the authors use combined techniques as dynamic wavelet fingerprint, wavelet packet decomposition and higher order statistics, obtaining high levels of authentication accuracy.
5) **Applications**. A considerable number of articles are dedicated to RFID applications or design of RFID devices and systems for specific uses. We mention two fields that are really promising, robotic navigation and healthcare systems. In [37], the authors design specific RFID tags and devices for mobile robot navigation and localization, facing the typical problems that limit standard RFID technologies in this application, i.e. size, weight, power consumption of transponders, effect of multipath, dependence of RFID performance on the support surface. Therefore, ad-hoc readers and tags are designed and implemented with a particular care to antennas design, optimized in terms of technology cost, radiation pattern, polarization, gain and frequency requirements. This study confirms that RFID technology, being characterized by low cost and largely available technological solutions, offers the opportunity and flexibility of customizing specific solutions. In [38], the RFID application to healthcare is considered by means of the design, implementation, and testing of a system for automatic patient identification, real-time location and tracking of medical assets and equipments, reliable drug inventory in an oncology hospital in Cyprus.

B. Research challenges and opportunities

The main research and technical challenges of radio identification regards range and reliability performance in presence of harsh environments, especially characterized by metallic surfaces and/or multiple sources. Antenna design and technologies for miniaturization of these devices are part of a process that will bring, in the future, to be embedded invisibly in many objects since their production; these aspects are clearly related to the huge number of objects that will be connected to Internet in the future (IoT). Of course energy harvesting and management techniques will continue to be a fundamental research and development subject for autonomous, passive or active, devices. Finally security for preventing unauthorized access and misuse in this kind of simple and inexpensive networks will surely require a further research effort in the next future.

IV. Radio Detection

A radio device can be designed for sensing variations in the received signal or, more significantly, in the channel impulse response. These fluctuations in the received signal are originated by variation of the radio wave propagation when additional

ISO/IEC 18000	RFID for Item Management	Part 1 Generic Parameters for the Air Interface for Globally Accepted Frequencies Part 2 Parameters for Air Interface Comm. below 135 kHz Part 3 Parameters for Air Interface Comm. at 13.56 MHz Part 4 Parameters for Air Interface Comm. at 2.45 GHz Part 6 Parameters for Air Interface Comm. at 860 to 960 MHz Part 7 Parameters for Air Interface Comm. at 433 MHz
ISO/IEC 14443	Identification cards Contactless integrated circuit(s) cards Proximity cards	Part 1: Physical characteristics Part 2: Radio frequency power and signal interface Part 3: Initialization and anticollision Part 4: Transmission protocol
ISO/IEC 15693	Identification cards Contactless integrated circuit(s) cards Vicinity cards	Part 1: Physical characteristics Part 2: Air interface and initialization Part 3: Anticollision and transmission protocol
EPCglobal	Industry-driven standards for the Electronic Product Code (EPC) for RFID	Class 0 900 MHz RF Identification Tag Specification Class 1 13.56 MHz ISM Band RF Id. Tag Interface Spec. Class 1 860-930 MHz RF Id. Tag and Logical Comm. Interf. Spec.
IEEE Std 802.15.4f-2012 Amendment to IEEE Std 802.15.4-2011	Active RFID System Physical Layer	433.05-434.79 MHz 2400-2483 MHz 6289.6-9185.6 MHz (UWB)
ISO/IEC 18092	Near Field Communication Interface and Protocol (NFCIP-1)	13.56 MHz
ISO/IEC 21481	Near Field Communication Interface and Protocol -2 (NFCIP-2)	13.56 MHz
ECMA-340	Near Field Communication Interface and Protocol (NFCIP-1)	13.56 MHz
ECMA-352	Near Field Communication Interface and Protocol -2 (NFCIP-2)	13.56 MHz

TABLE I
MAIN RFID AND NFC STANDARDS AND OPERATING FREQUENCIES.

passive objects and/or persons are introduced in a given environment. If radio localization (Sect. V) is generally associated to location estimation of active transceivers, radio detection is associated to the detection of activities or subjects that do not participate in the radio transmission. Therefore, radio detection relies on the ability of sensing variations in the received radio signal generated by variations of the surrounding environment, responsible for specific scattering and reflection pattern of the electromagnetic waves. In this field the technologies are usually based on the following parameters that can be derived from the received signal, with increasing levels of complexity:

- Channel impulse response.
- Channel delay and Doppler offset.
- Received signal strength indicator (RSSI).

These parameters are usually estimated between two or more active, usually but not necessarily stationary devices that monitor the environment. These devices, which can be also co-located as in the classical radar case, exchange radio signals in order to monitor the parameter variations. The channel impulse response is the most general approach for detecting modifications in the environment caused by the introduction of new elements in the environment or modifications of the existing ones; the underlying physical mechanism is simply the superimposition or modification of the multiple paths of the electromagnetic waves. Channel delay and Doppler frequency offset are usually exploited by radar applications, in which mobile objects are detected and possibly tracked by processing the reflected signals. On the other hand, variations in the RSSI are typically used for detecting intrusion or presence of new objects or persons in a given environment. Here we are interested to the application of radio detection in indoor environments since this is the most challenging and innovative case, from an application point of view. Therefore, the main technologies involved in indoor applications are the WLAN and WPAN ones, namely the standards IEEE 802.11 (e.g. WiFi) and IEEE 802.15 (e.g. Bluetooth and ZigBee).

If outdoor radar system is the main technology in the field of radio detection and tracking, the more recent indoor radar technology is acquiring increasing significance for its many applications. In the recent years, Ultra Wideband (UWB) technology has been extensively studied in this field for its interesting properties in terms of time and consequently channel response resolution. UWB impulse radio (UWB-IR) makes use of ultra-short duration pulses which yield ultra wide bandwidth signals characterized by extremely low power spectral densities. These signals can be used as an overlay technology for short-range wireless communications and they potentially combine immunity to multipath fading, low probability of intercept (LPI), low power consumption, and high time resolution. According to the IEEE 802.15.4a standardization (Fig. 1), the mandatory signal 3-dB bandwidth is 494 MHz and the UWB-IR transmission is centered around carriers between 3 and 5 GHz, and between 6 and 10 GHz.

In the last years, great interest has attracted also the through-the-wall radar imaging (TWRI) technology, which exploits the penetration of wide-band signals through obstacles for detecting and discriminating persons and objects separated by walls w.r.t. the transceivers. This technology clearly suffers from significant wall attenuation, increased multipath and scattering effects, larger false alarms probabilities w.r.t. standard indoor radar. These impairments are usually mitigated by increasing the number of sensors, usually organized in arrays for exploiting beamforming techniques and optimizing their positions outside the area to be scanned; nevertheless the physical parameters used for detection are usually Doppler signatures and signal variations as well.

The main applications of radio detection are summarized in the following fields.

- Intrusion detection of persons or animals.
- In the electronic health (eHealth) context, some technologies can be used for detecting abnormal status of some patients parameters, e.g. breathing.
- Motion detection of objects or persons.

A. Recent advances in radio detection

This section is dedicated to a survey of the main advances in this field through some selected publications of the last 3 years, situated in the following fields.

1) **Activities or intrusion detection.** In [39] we find an example of activities detection from the analysis of modifications in the RF channels. The authors classify activities of non cooperating (i.e. non transmitting) subjects, as walking, lying, crawling or standing persons and they detect them achieving a localization accuracy within 1 meter. References [40], [41] present examples of human and intrusion detection systems based on monitoring the RSSI variations in indoor environments, with a remark on alternative applications, such as energy savings in residential environments. Finally [42] shows the implementation of an RF sensor for shoe-based navigation that can measure its position w.r.t. the surface with a precision better than 1.3 mm, so detecting a person motion as slow as 191 $\mu m/s$, representing a considerable improvement w.r.t. standard inertial sensors.
2) **Vital signs detection.** Detection of signs related to breathing and heart frequency by means of RF signals is attracting a considerable interest in the healthcare field, especially for the non invasive nature of these systems. Automatic healthcare monitoring systems might be really effective especially for ageing population and very early symptom detection in heart attacks or some chronic diseases. Sensors presented in [43], [44] are based on the properties of UWB-IR technology

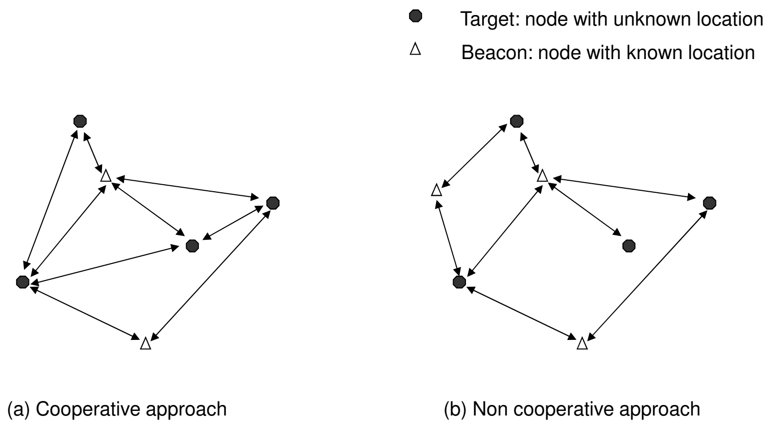

Fig. 4. The localization scenario and the organization of reference and target nodes.

(large bandwidth and high time resolution) while [45], [46] are based on a wearable Doppler radar at 2.45 GHz and an environment activity detection system at 5.8 GHz respectively.

3) **Indoor radar.** In [47], it is proposed a navigation system based on UWB, which permits mobile robot navigation in indoor environments in a more accurate way w.r.t. existing sensors technologies, as odometers and sonars. This confirms the advantages in terms of obstacle detection of UWB signals, thanks to their high time and space resolution. Then [48] presents an UWB radar system, able to integrate camera-based surveillance systems, which exploits a low number of antennas (five) for estimating the target motion, rotation and shape with an accuracy level significantly greater than conventional schemes based on antenna arrays at the same transmission frequencies.
4) **Through the wall imaging.** The system proposed in [49] improves the robustness to the mentioned TWRI impairments (Sect. IV) by means of a sophisticated target classification; the image is divided into segmented objects which are classified according to features like material, shape, etc. The peculiarity of this target classification is that measured features, statistical and geometrical, are resolution and position independent and this property enforces robustness and performance of the high resolution TWRI based on antenna arrays. On the other hand, [50] is focused on an adaptive detection scheme, which does not rely on image statistics a priori knowledge but it updates and adapts its parameters during the iterative detection process.

B. Research challenges and opportunities

The main research and technical challenges of radio detection regards the achievement of satisfactory performance in presence of difficult propagation environments, in particular NLoS and/or with multiple, potentially interfering targets. In the typical propagation conditions of indoor radar and TWRI implementations, also clutter phenomena complicate management of false alarm events. Finally the possibility of enhancing information acquired during detection of passive objects (e.g. regarding the shape and rotation) is a challenging and interesting opportunity especially in presence of sensor systems with limited complexity.

V. Localization

Wireless localization has been a topic of great and increasing interest in the last years since it opens a wide spectrum of advanced applications with a crucial role in the near-future wireless markets. In all the wireless systems of different scale (Fig. 1), from short range WPAN to large range cellular mobile systems (WAN - 2G, 3G, 4G), the localization of fixed/moving devices (or targets) is obtained by exchanging radio signals among reference base stations placed in known positions (called beacons or anchors) and the targets in unknown positions.

Localization can be exploited in a large spectrum of applications and fields, such as manufacturing, transport, vehicular ad-hoc networks, medicine, agriculture, tourism, just to mention a few. The main applications of the localization capability of properly designed radio systems can be categorized as follows.

- Location-aware services.
- Emergency situations.
- Security.
- Environmental monitoring.
- Positioning and tracking of objects, persons and animals.

The target coordinates are computed by using a preliminary estimation of some physical parameters that can be derived from the received signals. The typical parameters for localization are in the following list.

- Time of arrival (TOA) and time difference of arrival (TDOA).
- Angle of arrival (AOA) or direction of arrival (DOA).
- Received signal strength (RSSI).

The RSS measures are relatively inexpensive and simple to be carried out while the high-resolution TOA-based measures (especially in ultra wideband systems) can require relevant resources in terms of sampling rate and computational complexity. The estimate precision of these parameters depends mainly on the signal-to-noise ratio. In addition times of arrival are influenced by the signal bandwidth (time resolution is inversely proportional to the bandwidth), non-line of sight (NLoS) channel conditions (which introduce an offset on the propagation times), multipath. Angles of arrival can be estimated by using arrays of sensors or devices and hence they are primarily influenced also by the number of array elements while RSSI is greatly affected by large scale shadowing and small scale fading effects, which affect the relation with the real propagation distance.

These parameters are then combined by means of different estimation approaches, which mainly apply the classical estimation methods and exploit geometric multi-lateration/angulation constraints. These algorithms achieve, usually in a sub-optimal and iterative way, the minimization of a cost function related to the target coordinate errors. Therefore, the relations between these parameters and the target coordinates are given either by analytical models or by field measurements, commonly referred as fingerprinting techniques or digital maps. A great research effort has been spent also in the integration among different measure parameters through the use of data fusion and hybrid localization algorithms. Among the design and development challenging aspects of these systems, we mention the necessity of low cost systems, energy-efficiency algorithms, robustness to hardware impairments, time-variant multi-path and fading propagation conditions, NLoS channels and interference. Fig. 4 illustrates a typical scenario in which some target nodes should be located in presence or not of fixed beacons. It is clear that, in absence of fixed beacons with known positions, only the relative locations of the existing targets will be computed (Fig. 4 (a)) while the presence of a sufficient number of beacons with known positions allows the determination of the targets absolute coordinates (Fig. 4 (b)). It is also important to remark that the localization performance is determined either by the number of nodes that are involved in the localization process or their locations. Fig. 4 and Table II report the main concepts that characterize the approaches for determining the location estimates, according to different modes for involving the network nodes in the process. Firstly, the principle of cooperative localization opens one of the fundamental design choices in this context: in a cooperative approach, also nodes with unknown positions, or targets, cooperate to the positioning algorithm, i.e. by allowing nodes in unknown locations to exchange measurements on a peer-peer basis. In a non cooperative approach, the targets exchange measurements only with the beacons (Fig. 4). In addition to the motivations expressed in Sect. II, cooperative localization can take advantage from the integration of nodes with different technological platforms (e.g. cellular and WLAN systems, or GNSS - Global Navigation Satellite System with WPAN solutions). Also centralized and distributed implementations require careful design compromises in trms of traffic, computational load and energy budget, as already observed in Sect. II.

Finally, many localization approaches are based on standard estimation techniques: non Bayesian approaches, as Maximum Likelihood Estimation (MLE), classical gradient-descent methods Least Squares (LS) and Weighted LS (WLS) and Bayesian approaches, as Maximum a Posteriori (MAP), Minimum Mean Squared Error (MMSE) or exploiting particle filters. Other methods for minimizing the cost functions are based on genetic algorithms, applied mainly to centralized solutions.

Of course the localization concept is completed by the tracking, that includes the ability to treat the correlation between consecutive target positions inside a trajectory. A detailed review of the localization algorithms can be found in [51]–[60].

A. Recent advances in radio localization

This section is dedicated to a brief survey of the main advances in this field published in the last 3 years. The selected publications, which provide also a view on the most promising current research areas, are situated in the following fields.

1) **Performance limits.** Considerable effort has been spent for investigating the theoretical performance bounds of localization algorithms; this problem is complicated since localization accuracy depends either on the link transmission quality either on the network topology. References [61], [62] present fundamental limits of localization performance, in terms of squared position error bound (SPEB), in wideband wireless networks and multipath environments. Reference [61] is dedicated to the general theoretical framework, which is based on the notion of equivalent Fisher information and developed on the received signal waveforms instead of signal metrics, such as time-of-arrival and received signal strength. Reference [62] investigates the limits of cooperative location-aware networks, providing a geometrical interpretation of equivalent Fisher information for cooperative networks (with presence of beacons and targets) and deriving performance

Targets role in the algorithm	Cooperative	Non cooperative
Computational load	Centralized	Distributed
Beacons presence	Network with fixed reference points	Ad hoc network
Estimation algorithms	Bayesian	Non Bayesian

TABLE II
DIFFERENT APPROACHES IN THE LOCALIZATION ALGORITHMS

limits with their scaling properties. Then [63] exploits an interesting concept: the localization of a mobile device is modeled in the framework of Shannon capacity communication bounds, modeling the location as a transmitted message encoded by propagation conditions. This approach allows the determination of an information theoretic bound in urban environments, which provides conditions for achieving arbitrary small probability of the localization error. The work [64] investigates of performance limits for RSSI based localization analyzing the corresponding Fisher information and the Cramr Rao bounds (CRB). Finally [65] presents an iterative maximum likelihood solution to sensor localization in presence of nonlinear propagation of localization error in the sensor network, as in Radio Interferometric Positioning Systems (where radio frequency interference is used for obtaining sum of distance differences between the locations of four devices). The proposed method is optimal since it achieves the CRB.

2) **Hybrid systems.** Hybrid systems rely on the combination or fusion of measures from different techniques for achieving or improving localization. In [66], the authors propose a distributed, cooperative positioning algorithm that exploits positioning measures from satellites and terrestrial wireless systems and works by an iterative message passing algorithm; an interesting contribution of the paper is the construction of a factor graph suitable for the application of the sum-product algorithm to hybrid positioning. The work presented in [67] faces a relevant issue that is often neglected in many articles on localization: the authors present a framework for hybrid fusion based on the determination and dynamic updating of the likelihood functions that represent the relation between measurements and distances. This operation allows the use of an adaptive estimation procedure based on particle filters, which is able to address the nonlinear and non Gaussian nature of the localization problem, producing performance results very close to the CRBs. The recent [68] is devoted to a concrete example of hybrid measurement fusion for improving localization performance: the algorithm uses pyroelectric infrared (a pyroelectric infrared sensor detects motion and human or animal presence through sensing infrared radiation that depends on the target temperature) and radio RSSI measures and has shown interesting experimental results also in presence of multiple targets. Finally [69] presents an idea for improving the accuracy of localization, also in presence of hybrid data sources, by using Kalman filtering for pre-processing noisy distance measurements gathered in difficult environments and then a cooperative spring relaxation for refining the nodes initial coarse position estimates.
3) **Heterogeneous systems.** In this field the hybrid fusion of different measures is achieved by integrating measures from different radio technologies or systems. The presence of multiple, heterogeneous wireless infrastructures and the increasing demand of localization services, either outdoor or indoor, open new opportunities for the integration of these systems. In [70], the author presents a cooperative approach that is able to combine RSSI measures from different technologies according to different weights representing the information contribution of each measure. This algorithm is tested with real measurements from GSM, DVB, FM and WLAN systems in outdoor and indoor environments. In [71], the fusion approach is extended to a GSM multiple provider scenario, showing that a cross-provider positioning algorithm (e.g. by means of a dual SIM phone) provides a significant accuracy improvement.
4) **Fingerprinting.** Fingerprinting techniques determine a device position by comparing its RSSI measures with stored RSSI maps and they are widespread especially in WiFi systems, where the RSSI measure is the only available. The work in [72] is dedicated to the critical design of an effective RSSI-location mapping function, which is derived by improving the diffused projection techniques known as principal component analysis (PCA) and multiple discriminant analysis (MDA) by means of a dynamic hybrid projection approach. Then [73] shows how the expensive map construction phase can be conducted by a collaborative system in which anonymous mobile smartphone users automatically collect and send data regarding an indoor area to a server that progressively creates a fingerprinting map with a satisfactory accuracy level. Finally [74] presents the application of a particle filter approach with a likelihood estimation mechanism to real data obtained from a WiMAX network in the city of Brussels (Belgium).
5) **RSSI.** The RSSI measures are typically less expensive and less precise w.r.t. the others and they are often obtained with some simplified assumptions on the noise and channel environment. In [75] the authors propose some novel and more rigorous probabilistic models for RSSI accounting for background noise and their corresponding maximum likelihood estimators. Then it is worth mentioning that in [76] an improved linear least squares estimator for RSSI-based positioning is shown to achieve the CRB at medium-high SNRs.
6) **Multitarget localization.** Localization and tracking of multiple target is another challenging issue because of the limits imposed by spatial resolution. The recent paper [77] proposes a novel technique for multitarget simultaneous localization and mapping (MSLAM) based on the parallel between a partition particle filter and a truncated unscented Kalman filter; the algorithms performs better than previous SLAM approaches in multitarget scenarios.
7) **Optical localization.** An interesting localization technology, usually referred as optical wireless indoor localization, is based on light emitting diodes (LEDs) and it works on the same principles of the microwave versions [78], [79]: the phase differences are translated into time differences of arrival (TDOA) and it is interesting to remark that the modulation bandwidth of white LEDs used for indoor lighting is compatible with typical localization indoor applications.
8) **RFID localization.** Of course also RFID technology can be used or integrated in localization applications. In [80], the proposed algorithm, whose inputs are backscattered signal RSSIs from RFID tags and a tagpath position database, uses Kalman filters for tracking the reader position and incorporates an angle-dependent path loss factor for improving the final performance. In [81], performance of an RSSI human tracking system based on RFID badges is greatly improved

by incorporating the impact of the human body on the badge antenna gain and directivity; to this purpose a model of the directionality of a transmitter badge worn by a person is developed and included in the tracking process. Finally [82] is focused on another application field of great interest: the presented method enables self-recognition of a moving vehicle position in harsh environments (e.g. industries and storage warehouses) with two RFID readers that return RSSI measures by the mounted RFID tag.

9) **Context awareness.** The work in [83] regards the relation between performance of a communication and/or localization system and its operational environment. The authors propose a context-driven hierarchical classification scheme for classifying the Global Positioning System localization accuracy according to different environment conditions; in fact this aspect has a considerable impact on performance and the ability to classify the measurement conditions would allow the target to use the localization estimates with an improved awareness in its decision strategy.

B. Research challenges and opportunities

Among the research challenges and opportunities in this field, indoor and multitarget localization represents a promising field, especially if we consider real and diffused applications in public spaces where the available networks and devices are currently not specifically design for this task (WiFi networks and smartphones). Also the difficult propagation conditions are still an open research issue for this application, especially when exploiting systems with limited complexity. Finally energy optimization in localization and tracking systems, i.e. the optimal power allocation among the cooperating devices, is another challenging issue, relevant for applications in WSNs with battery powered sensors.

VI. Conclusions

In this paper, we have reviewed the main radio techniques suitable for application in the field of context awareness, highlighting the main technologies, the standards and the basic mechanisms at the physical layers. In the three main fields, radio identification, detection, and localization, we have reviewed the recent advances published in the last three years, hence remarking the challenges, the opportunities and the next research and development steps in the future wireless networks for context aware systems.

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