Compressed Sensing Technologies and Challenges for Aerospace and Defense RF Source Localization

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***Abstract*— The paper presents an overview of technologies and challenges regarding the adoption of Compressed Sensing (CS) framework for ideation of novel instrumentation systems, that could be used for the next generation of radio frequency (RF) source localization and tracking. Established systems for accurate localization and fast tracking of non-cooperative RF emitters are costly and difficult to deploy. Nowadays, finding novel solutions of RF sensing system used for detecting, locating and tracking of mobile RF emitters represents a key challenge. Emerging application fields, where the potential of such novel RF sensing system may be used, like: (i) autonomous vehicles, (ii) domestic/military Unmanned Aerial Vehicles (UAVs), (iii) RF environment mapping, and (iv) land/marine rescue operation, are presented. Architecture of RF sensing system adopting CS, such as RF receivers using signal acquisition based on Analog-to-Information Converter (AIC), is presented and discussed. Depending upon target application, key beneficiary of these technologies could be the aerospace/defense industry sectors.**

***Keywords*—Compressed Sensing (CS), Radio Frequency (RF), Source Localization, Wideband Spectrum Sensing (WSS), Analog-to-Information Converter (AIC).**

I. Introduction

The needs of RF sensor systems, which are capable of precise RF source localization, became nowadays a desideratum [1]. Aerospace RF based communication systems need embedded technologies for fast [2]: (i) target recognition/discrimination, (ii) Wideband Spectrum Sensing (WSS), (iii) location tracking with real-time information processing, (iv) jamming suppression of multi-path signals, and (v) mobile deployment of RF sensor systems. Existing RF systems and technologies used for precise localization and tracking of non-cooperative RF emitters are costly and difficult to deploy. Moreover, particular applications rely on satellite communication which may not be always available and sometimes those communication are even susceptible to jamming.

In case of RF signals used in defense sector for radio communications, adopting novel solutions regarding RF source localization and tracking represents a desideratum [2],[3]. From the hardware point of view, such systems should be capable of: (i) short time for strategic deployment, (ii) low-cost, power consumption and size, (iv) sensor network integration, and (v) providing mobile wireless services. From the signal processing capabilities point of view, these systems should be able to: (i) RF mapping generation, (ii) automatic target localization and tracking, (iii) dynamic spectrum access, (iv) receive the directional power, and (v) work without relying on satellite communication (e.g. GPS) [4].

In this application field, the use of the CS framework to design RF sensors for localization and tracking of RF signal emitters has the following advantages [6],[7]: (i) the number of samples acquired from the sensors are drastically reduced, (ii) the power consumption of the CS-based acquisition system is reduced, (iii) the processing time required for the elaboration of the desired algorithms is reduced, and (iv) the observed bandwidth of the entire acquisition system is increased. On the other hand, CS framework does not dispose of unified data acquisition model for the compressed sampling process and the reconstruction algorithm needs to be well tuned according to the monitored RF signals. Therefore, today, the research activities in this area are growing fast with the aim of developing reliable CS framework for RF signal emitters localization.

The paper aims to present an overview of the research trends for designing novel CS based RF instrumentation systems, having potential to RF signal processing, such as for emitter localization and tracking applications.

In the following, the paper organization is presented. Four emerging application fields, that could use successfully the CS technologies for RF source localization and tracking are presented in Section II. In Section III, a short overview of the source localization and tracking techniques of the RF signals emitters is presented. Section IV presents several aspects regarding the RF sensing hardware such as an short overview of CS, the working theory of an AIC architecture, and the signal reconstruction issues from compressed measurements. Several conclusions about the carried research investigation and few key tasks for future work are described in the last Section of the paper.

II. Emerging Application Fields Requiring RF Source Localization

A. Autonomous Vehicles

Autonomous driving could be securely achieved if [8]–[27]: (i) vehicle localization, (ii) path perception, (iii) path planning, (iv) engine control, and (v) vehicular system management, are reliable and precisely achieved. RF spectrum for autonomous vehicles represents a wireless connectivity

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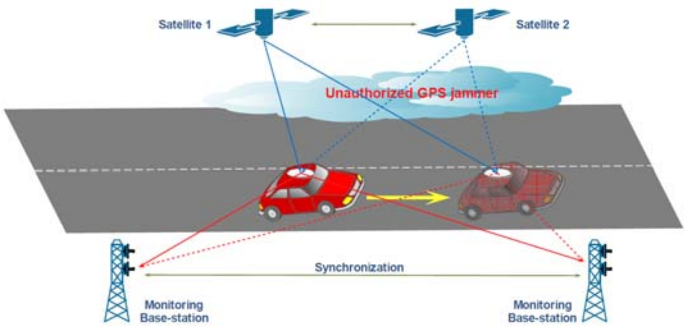

Fig. 1: Generic overview of RF based localization and tracking for autonomous vehicles driving systems.

paradigm, regarding the development of safely RF environments for radio based communication. Vehicular Wireless Networks (VWN) need to operate in time/space dynamic topologies which makes them challenging to implement. Deployment of practical VWN requires at least several technologies, such as for: (i) dedicated and guaranteed RF spectrum portions, i.e. vehicular RF spectrum, (ii) low latency communications, (iii) high robustness to missing/error communication links, and (iv) accurate localization by satellite (e.g. GPS) or by road infrastructure base-stations.

To this aim, autonomous vehicles require a robust localization system having centimeter level accuracy. The GPS represents the most commonly used vehicle localization system, since it represents an accessible and cheap solution. However, the GPS inadequate accuracy and its multiple limitations (e.g. signal missing/jamming), makes it less reliable for fully autonomous vehicles. To this aim, ground base-station providing full capabilities for precise localization are needed [26], (see Fig. 1). Communication standards like IEEE 802.11p and 5G are representing options to support Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications.

However, in order to meet these performance requirements, new high bandwidth RF sensing systems and low latency algorithms are needed to be designed and applied to monitoring stations and to vehicular platforms. CS techniques could bring several advantages to address the above mentioned requirements. In particular, CS allows to reduce the amount of data required for the estimation of the vehicle position thanks to the implementation of high compression ratio CS algorithms. Furthermore, the data rate is reduced, and therefore the payload too. This will guarantee to reduce network congestion events and to manage a larger number of autonomous vehicles on the road.

B. Unmanned Aerial Vehicles (UAVs)

Beyond their pacifist uses, the civilian UAVs (i.e. drones) have been used as devices for penetrating restricted areas (e.g. airports, nuclear power plants, military camps, etc.). Various anti-drone systems were designed and are available in commerce [8]. A fundamental assumption is regarding the presence of a drone and its position to be known *a priori* by the defender [29]. Scientific papers proposing such drone

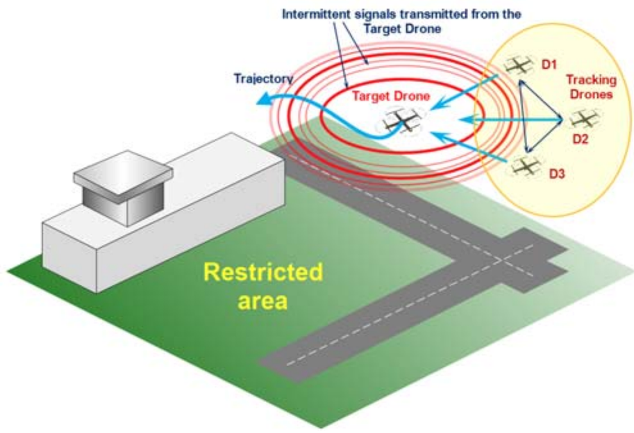

Fig. 2: Generic overview of swarm of drones used for localization and tracking of a drone approaching a restricted flight area.

detection systems using their wireless signature are available in literature [25]–[30].

In Fig. 2, a generic overview of swarm of drones used for localization and tracking of a drone approaching a restricted flight area is depicted. Listening the communication channel between drone and its controller (e.g. usually manned by a person), could be a simple solution to detect the presence of a drone. However, drone's communication frequency should be known *a priori*. Problems could arise when the communication frequency is not a licensed one. To this aim, wideband capabilities of RF spectrum sensing systems for monitoring the link between the drone and its controller became a desideratum.

Designing proper RF sensing instrumentation system that could be easily mounted on a drone used as a defender, represents a key challenge. Being mounted on-board at the drone defender, these systems would allow to rapidly scan over a huge spectrum bandwidth in order to observe unusual radio traffic, in the surveyed geographical space.

CS technologies can be adopted in order to increase the monitored real-time bandwidth and to reduce the cost of a single monitoring unit. Furthermore, the RF sensing block could embedded on each defender drone by taking into advantage of the lower power consumption exhibited by the CS hardware. Since, the drone time of flight depends on its payload, too, CS technologies for RF sensing could be easily embedded on board without deprecating it.

C. Rescue Operation

In case of emergency scenarios, due to the aftermath of a natural or human disaster, rescue teams must deploy (or, make use of) fast communication systems [12]. In this case, the communication infrastructure (e.g. wired or wireless) may be totally/partially damaged. Recently, the technological advancement has enabled commercially available robotic platforms (terrestrial or aerial ones), which are capable of providing a variety of missions for critical support cases, to rescue teams. Herein, technological developments such as: (i) RF sensing, (ii) energy storage, (iii) real-time signal

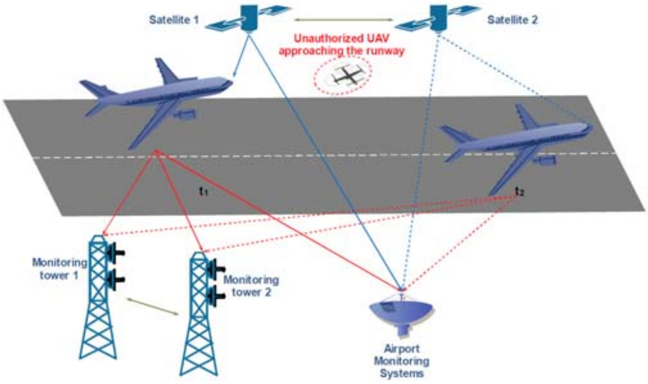

Fig. 3: Increased risk to commercial aviation is represented by unauthorized utilization of drones in restricted area.

processing power, and (iv) extended wideband communication capabilities, have enabled the development and use of Wireless Robotic Networks (WRNs). For example, in hazardous terrain and confined spaces, by using WRNs prior to deployment of rescue teams on field, information about the [8]: (i) environmental monitoring, and (ii) target localization, could have an essential role in determining the next action steps. To those aims, the precise real-time localization of each WRN node represents a real challenge, especially in case of missing (or less accurate) GPS measurements.

However, the WRN requires radio connectivity and a dense number of RF sensors or relay communication stations for real-time localization of the WRN nodes, which could be expensive and impractical to on field deployment. Furthermore, this application field requires a working time ranging from hours to days. The power consumption of each WRN node should be as low as possible due to the fact that they are battery powered systems.

CS technologies could be used for implementing the RF sensors or base stations by reducing their effective costs and making them more efficient in the case of monitored RF bandwidth. In this way, the transmitted amount of data to the control base station is drastically reduced and the data rate of the communication link, too. Therefore, the power consumption of the WRN nodes could guarantee longer working time during the deployment of the specific mission.

D. RF Environment Mapping

DARPA affirmed that the RF spectrum management represents a hot topic of todays interconnected wireless world [24]. The RF spectrum management requires the radio mapping of geographical regions in order to be able to detect and localize the RF interferences of non-authorized emitters. Regardless of how many measurements of RF environment in a specific area are performed, updated measurements should be carried out: (i) at various times of day, (ii) on various days of the week, and (iii) periodically into the future.

Malicious RF emitters have already proven to disrupt airports by GPS jamming. Also, an increased risk to commercial aviation is represented by unauthorized utilization of drones in restricted area, (see Fig. 3).

In order to fast mitigate this risk, RF sensing instrumentation capable of wideband, real-time RF spectrum analysis is needed. By adopting CS framework, novel RF sensing sensor could be developed to perform rapid localization and real-time tracking of GPS jamming devices, or to provide counterfight measures in case of the presence of unauthorized radio links in a restricted area. In literature, the development of RF sensing instrumentation for mounting on a UAV is reported in [25]–[29]. In such situations, prolongation of the battery lifetime, together with the downsizing of the payload, could be determined by adoption of AIC based sampling techniques.

III. Challenges of Sensing RF Signals

As reported in the above mentioned applications, a key point for the development of a RF source localization system is related to the design of the RF receivers that will be embedded on base stations or mobile stations (such as drones).

Existing trends in radio communications systems design indicate that future implementations of the RF receivers part will be based on digital signal processing techniques [ref]. Thus, the analog interfaces will be reduced to a minimum hardware architecture allowing: (i) low-power consumption, (ii) small size, and (iii) wider instantaneous bandwidth usage. As it can be observed from the present state of the art of digital radio receivers, massive interest is directed to develop applications based on Cognitive Radio (CR) and Software Defined Radio (SDR). This research interest has started due to the scarcity of available RF spectrum, since this is a limited physical resource. The CR/SDR performance is limited by nonlinearities in the analogue front-end hardware building blocks and by the used Analog-to-Digital Converter (ADC), since their architecture requires working with large signal bandwidths. Moreover, usually, in the frequency domain the representation of RF signals is sparse, thus large parts of their spectral content are empty like.

Securing the geographic areas where radio based communication systems are used (e.g. airports, maritime ports, military camps, intelligent transportation systems etc.) represents a key challenge. Fast detection of: (i) signal energy, (ii) energy variations, (iii) frequency occupancy, (iv) receiver Signal-to-Noise Ratio (SNR), and (v) modulation classification (e.g. spread spectrum type), represents a desideratum in designing of RF monitoring/sensing instrumentation systems for aerospace/defense radio based communications.

The localization and tracking of the emitted RF signals is an issue faced in many application fields, including those related to safety, emergency, and security. Traditional task of localizing an emitter of a particular RF signal requires expensive and calibrated sensing equipment. For example, in Fig. 4, the architecture of a Time Difference of Arrival (TDoA) system is depicted. The RF sensor is composed by heterogeneous parts [2]–[5]: (i) hardware for RF signal acquisition, and (ii) hardware/software for RF signal processing. The radio waves are collected by *N* antennas, where RF front-end electronics process them prior to digital conversion at Nyquist rate by ADC. The acquired samples are locally processed or remotely.

Dedicated hardware for signal processing such as Digital Signal Processors (DSPs), Field Programmable Gate Arrays (FPGAs) help to perform algorithm techniques which may include, but are not limited to: (i) TDoA, and (ii) Angle of Arrival (AoA), (see Fig. 4). For measuring the TDoA of a received signal at multiple RF receivers, each individual receiver (i.e. RF sensor) needs to be synchronized precisely. This synchronization should be realized in a easy way and should guarantee that data collection can be done synchronously [2]. However, in practice this tasks can be quite difficult to be achieved, due to the various reasons, for example such as: (i) missing Global Positioning Systems (GPS) satellite signals, (ii) less-accurate geographical deployment, (iii) non-uniform static positioning of RF sensors. In the other case, if the AoA technique is used, an expensive, highly directive receiving antenna is needed to be installed, having a narrow bandwidth (i.e., 1° or less). In Fig. 5, the block diagram of a cross correlation switched beam system for N antenna elements, implementing an example of the TDoA algorithm is presented. Here, as in previous case, the signal is sampled by means of a Nyquist rate ADC. In both cases, depending upon the desired bandwidth, the outcome could be a very large number of digital samples.

In contrast to the fixed RF signal sensing stations, in scientific literature, proposals for mobile RF sensing units, which can be easily deployed on light remotely controlled platforms (e.g. drones, rescue robots, etc.), have been presented. Mobility of such RF sensing systems is limited by the available power supply capacity, weight, size, and data transmission links to control stations.

In order to overcome the disadvantages related to the use of common RF sensors for source localization, the CS technologies can be adopted. In particular, they allow: (i) to increase the real-time monitored bandwidth of the RF sensor, (ii) to reduce the data rate and the total amount of data transmitted between the base stations, (iii) to reduce the power consumption of each base station, and (iv) to reduce the RF sensor cost. In the followings, the CS theory is presented and a review of CS systems, which could be adopted for the implementation of a RF source localization system, is described.

IV. Sampling and Compressed Sensing of RF Signals

A. CS overview

In about a decade, CS has gained wider acceptance as a sampling technique allowing the acquisition of signals at their information rates [7]–[22]. An universal CS based framework for signal acquisition is missing in literature. However, there are many practical approaches presenting the use of CS–based sampling methods. The adoption of CS framework varies from application to application and from signal to signal [9]. However, natural or man-made signals present a sparse representation in a certain domain, i.e. where their information (e.g. signal's features) is presented. RF spectrum signals make use of such sparse representation in Fourier (or Wavelet) domain prior to signal processing tasks. The signal processing tasks offered by CS framework facilitate the design of Analog-to-Information Converter (A2I or AIC) architectures for signal conversion from analog to digital information.

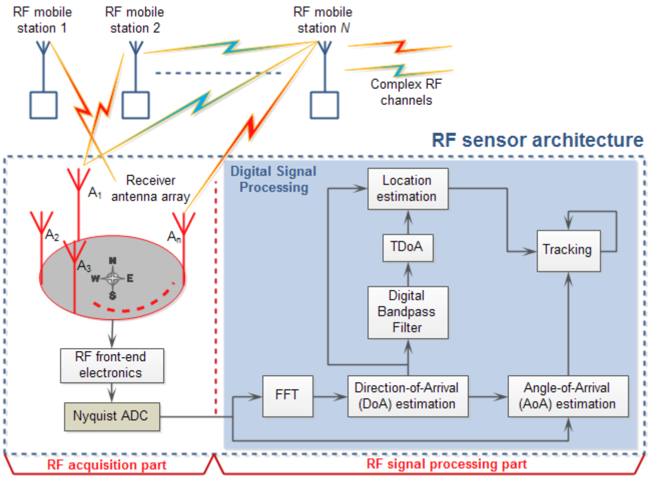

Fig. 4: Overview of a TDoA RF sensor architecture for localization/tracking of emitter.

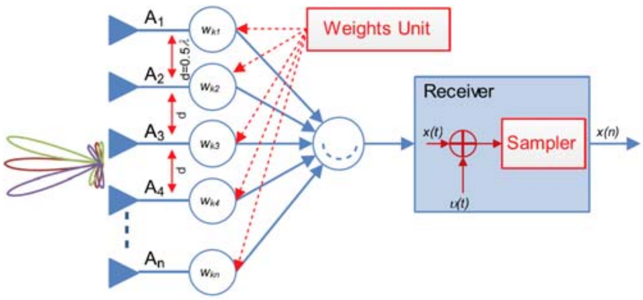

Fig. 5: Generic overview of cross correlation switched beam system for N antenna elements.

The presented aspects, above, have already opened new research paths in order to investigate the adoption of Compressed Sensing (CS) framework for radio transceivers and RF sensing systems. CS techniques could be applied in order to acquire the information content which is carried out within their physical support (e.g. radio waves). In order to make use of CS framework in practice, CS sampling circuits (i.e. CS samplers) are needed. Such samplers are usually working at sub-Nyquist rates, freeing up the ADC working speed. Thus, the motivation of pursuing the adoption of CS is two-fold: (i) wideband receivers must sample rapidly without being forced to use the Nyquist rate, and (ii) the resulting dataset could be at a minimum, even if the observation has been performed upon a large spectrum bandwidth. For example, these observations allows us to rethink the remote RF sensors architecture in order to make them more capable in wideband RF sensing and real-time signal processing. Moreover, CS could demonstrate the usefulness in application fields where RF sensing is: (i) too expensive (e.g. using of very high-

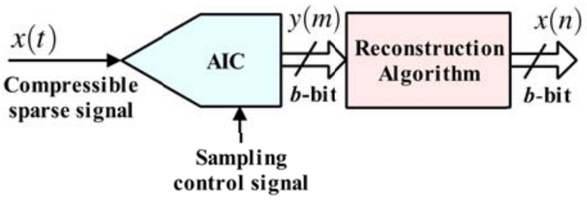

Fig. 6: Signal sampling overview by means of Analog-to-Information Converter.

speed ADC), (ii) time consuming, (iii) power constrained (e.g. battery powered), and (iv) limited by the used number of RF sensors. For all those reasons, CS is a promising technology for implementing RF source localization systems.

B. Sampling by means of Analog-to-Information Converters

An AIC represents a hybrid data acquisition system, composed by hardware and software, which acquires samples related to the signal's information. An overview of sampling and reconstruction of sparse signals by means of AIC is presented in Fig. 6.

1) Nyquist representation of x(t). Generally, the vector of N discrete-time samples obtained by sampling at Nyquist rate, $f_{Nyquist}$, of the analog signal $x(t)$ is $\mathbf{x} \in \mathbb{R}^N$:

$$\mathbf{x} = \left[x_{(1)}, x_{(2)}, \ldots, x_{(N)}\right]^T \tag{1}$$

If $\mathbf{x}$ has a K–sparse representation, this could be expressed by a vector of elements $\mathbf{s} \in \mathbb{R}^N$, having at most K non-zero dominant values in a known transform basis representation, $\Psi \in \mathbb{R}^{N \times N}$, i.e. $\mathbf{x} = \Psi \mathbf{s}$.

2) Compressed Sensing representation of x(t). By adopting CS as sampling protocol for *x(t)*, the vector of discrete-time samples $\mathbf{y} \in \mathbb{R}^M$ is obtained, and in contrast to the Nyquist representation of *x(t)*, it contains only $M \ll N$ compressed samples:

$$\mathbf{y} = \left[y_{(1)}, y_{(2)}, \ldots, y_{(M)}\right]^T \tag{2}$$

In this way, CS allows the obtaining of a reasonably measurement vector containing fewer discrete-time samples, $y(m)$ with $m = 1, \ldots, M$, than those provided by a Nyquist sampling process. CS framework describe the sampling process as [9]:

$$\mathbf{y} = \Phi \mathbf{x} \tag{3}$$

where, $\Phi \in \mathbb{R}^{M \times N}$ represents the "sensing" matrix. The imposed sensing matrix is chosen (i.e. designed) together with the adopted CS protocol. If the CS protocol is performed by means of an AIC system as presented in Fig. 6, the measurement process is generally modeled as:

$$\mathbf{y} = \Phi \mathbf{x} + \mathbf{n} = \Theta \mathbf{s} + \mathbf{n} \tag{4}$$

where, $\Theta = \Phi \Psi$ represents the joint mathematical representation of the CS framework and sparsifying transform of *x(t)*, and $\mathbf{n} \in \mathbb{R}^M$ represents the additive measurement noise.

Lastly, by assuming that all the necessary information from the observed signal *x(t)* is enclosed into the compressed samples, $y(m)$, CS allows the digital reconstruction of the signal $x(n)$, with $n = 1, \ldots, N$, i.e. to produce a digital representation of $x(t)$. From the above mathematical description of the signal processing steps, in terms of CS, signals sampling using AICs implies the *a priori* Θ "sensing" matrix design. This task will guarantee the compression process of CS by mapping N samples of a *x(t)* signal in a $\mathbf{s}$ representation of its K-sparse possible representation, which could be embedded onto *x(t)* physical support (e.g. bandwidth), to a set of M discrete-time samples.

C. Sensing of RF signals from compressed measurements

Since CS is possible due to sparse representation of signals, in case of RF sensing applications, the: (i) signal availability, (ii) spectral information content, (iii) bandwidth under observation, and (iv) proper "sensing" matrix availability, represent key factors in order to proper design the AIC. Moreover, the error in information and signal reconstruction will depend on the adopted AIC model. Starting from the compressed measurements, $\mathbf{y}$, the reconstruction (see Fig. 6) is done by using non-linear numerical methods, which provides the sparse vector $\mathbf{s}$ representation of the observed signal *x(t)*. Commonly used numerical algorithms are based on the following categories [22]: (i) greedy, (ii) convex relaxation, and (iii) non–convex local optimization. In case of efficiency versus computational load, among greedy algorithms, the Orthogonal Matching Pursuit (OMP) presents superior performances.

In literature, many applications reports that it is not needed a full signal reconstruction from compressed measurements. By using CS framework, RF sensing systems may benefit of a direct representation of signal's information rates in their sparse domain, i.e. Fourier, and Fast Fourier Transform based algorithms will not be needed. This could lead to the massive reduction of the time/hardware resources for processing of the amount of samples delivered by a Nyquist sampling process.

D. CS for RF source localization

In [31], an algorithm based on CS technique that uses AoA and Received Signal Strength (RSS) measurements from mobile sensors embedded on drones to geolocate RF emitters on the ground is proposed. The drones receive and transmit telemetry data to a central station, including position and heading information. A direction finding system provide a rough estimate of the emitter's AoA relative to the drone position. In addition, the sensors collect the RSS of the emitter as function of the sensors' position. The authors assume that few emitters are in the region under surveillance but many possible emitter locations can be occupied by them. This geolocation problem can be posed as that of solving an undetermined system of linear equations, where one of the most components of the vector solution are zero. Thus, the geolocation problem fits the CS framework. The authors have implemented the CS process for RF emitters localization in MATLAB and show the results obtained from simulations by considering a single emitter, multiple emitters, and a mobile emitter. The authors reached a position accuracy, in simulation, in the order of 10 cm. In that case, the method is based on the fact that the carrier frequency of one or more emitters is known. Another RF localization system based on CS and that supposes that the carrier frequency of the target emitter is known is described in [32]. In particular, the authors propose an algorithm for the localization of a RF target by taking RSS measurements provided by RF sensor nodes placed along the edges of a rectangular area.

V. Conclusions

RF source localization and tracking represents a desideratum in case of several application fields. In this paper, a general idea of the emerging technologies and challenges, having potential for the next aerospace and defense RF sensing systems, has been presented. The opportunities of CS framework for acceptance as a technical solution for designing of novel RF instrumentation system was discussed.

Moreover, several emerging application fields that could use the CS based designs of RF sensing systems, are presented and discussed. Depending upon specific application, challenges like RF spectrum sensing using CS techniques do not require full signal reconstruction from the compressed measurements, $y(m)$. Detection of interference problems, signal classification, estimation and filtering may use the direct representation of the acquired signal in its sparse domain representation.

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