WiFi-based PCL for monitoring private airfields

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I. INTRODUCTION

In recent years, a number of studies have looked at the use of passive coherent location (PCL) radar systems for short range surveillance applications [1]-[8]. In such applications, the transmitters for mobile personal communication and network connection have been successfully exploited as illuminators of opportunity; these include the base stations of Global System for Mobile Communications (GSM), Universal Mobile Telecommunications System (UMTS), Worldwide Interoperability for Microwave Access (WiMAX), and Long Term Evolution (LTE).

In addition, the IEEE 802.11 Standard based (WiFi) transmitters have been considered for very local parasitic exploitation since they provide a limited coverage but potentially wide bandwidth and well-controlled signals useful when aiming at indoor surveillance or at monitoring small external areas [9]. The possibility to exploit such an ubiquitous and easily accessible source has been shown to be an appropriate choice for the detection, localization and imaging of designated vehicles, human beings or man-made objects within short ranges using the passive radar principle. To this purpose, many effective signal processing techniques and advanced solutions have been proposed in order to increase the reliability of the PCL system, improve its potentialities, and hence widen the range of uses for both indoor and outdoor applications [10]-[22]. However the effectiveness of the conceived solutions has been typically shown in very specific case studies with the sole aim to provide a proof of concept.

In this article, the potential exploitation of WiFi-based PCL systems is investigated with reference to a real-world civil application where these sensors are expected to nicely complement the existing technologies adopted for monitoring purposes, especially when operating against non-cooperative targets. In particular we consider the monitoring application of small private airstrips or airfields. With this terminology we refer to open areas designated for the taking-off and landing of small aircrafts, but which, unlike an airport, have generally short and possibly unpaved runways (e.g. grass, dirt, sand, or gravel surfaces) and do not necessarily have terminals. More important, such areas usually are devoid of conventional technologies, equipment, or procedures adopted to guarantee safety and security in large aerodromes.

There exist a huge number of small, privately owned and unlicensed airfields around the world. Private aircraft owners mainly use these "airports" for recreational, single-person or private flights for small groups and training flight purposes. In addition, residential airparks have proliferated in recent years, especially in the US, Canada, and South Africa. A residential airpark, or "fly-in community", features common airstrips where homes with attached hangars allow owners to taxi from their hangar to a shared runway. In many cases, roads are dual-use for both, cars and planes.

In such scenarios, it would be of great potential interest the possibility to employ low-cost, compact, non-intrusive, and non-transmitting sensors as a way to improve safety and security with limited impact on the airstrips users. To this purpose WiFi-based passive radar sensors appear as good candidates [23].

Therefore we investigate their application against typical operative conditions experienced in the scenarios described above. The aim is to assess the capability to detect, localize and track authorized/unauthorized targets that can be occupying the runway and the surrounding areas.

The study has been conducted against the data sets collected during a dedicated experimental campaign that has been performed in a small private airfield for light/ultralight airplanes. Aircrafts, cars, and people have been employed as targets of opportunity to simulate different operative conditions of interest. The results obtained with the conceived sensor support the practical applicability of the WiFi-based passive radar concept for improving safety and security of small private airfields and demonstrate its suitability to be usefully employed in such scenarios in the near future.

II. Ultralight airfields monitoring application

As previously mentioned, ultralight airfields, small private runways, and even airparks, are usually devoid of conventional technologies adopted to guarantee safety and security in large aerodromes, there including navigation aids, signs and lighting. The use of the runways is usually limited to the daylight hours and mostly controlled by dedicated operators equipped with radio transceivers in the HF/VHF band to communicate with the pilots of the aircrafts. These are expected to be cooperative, expert, and well-intentioned users, and to adhere to basic procedures during landing/taking off, taxiing, etc. The operator visually verifies that the runway is empty before authorizing an interested user to occupy it.

Depending on the length of the runways and visibility conditions, several operators might be required to monitor the whole area of interest in order to avoid runway incursions by other aircrafts, vehicles, people, and even animals. In this regard, it is worth mentioning that many of the considered “small airports” are rarely enclosed in a monitored perimeter (e.g. barrier, fencing, etc.) and the edges between runways and taxiways are not clearly indicated. Therefore it is possible that vehicles or beings intrude onto the runways either intentionally or accidentally. In addition, it would be desirable to monitor the airstrips and neighboring zones also when they are not being used by conventional users (i.e. night-hours, closing times, etc.) in order to avoid an illicit use by ill-intentioned people.

A pictorial view of the scenario considered in this article is reported in Figure 1. The figure sketches both the conventional activities and possible hazards related to different users of the airstrips, either allowed or not permitted.

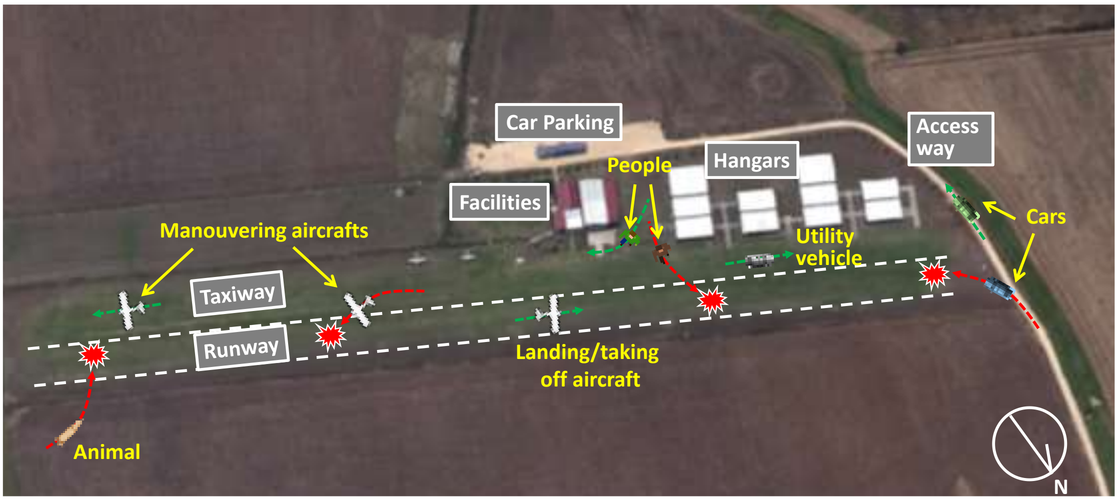


Figure 1 – Scenarios of potential interest in small private airfield monitoring application.

As is apparent, there is substantial scope for an improvement in situational awareness in such scenario. In particular, the probability of accidents could be significantly reduced if an automatic control is implemented on the activities that occur on the runway and in neighboring zones.

To this purpose, the use of passive radar sensors should be considered because they in principle provide a reliable surveillance capability with low cost and limited impact on the airstrip users. Specifically the opportunistic exploitation of transmissions for networking (WiFi, WiMAX, LTE, etc.) is especially attractive since they have been proliferating at a very rapid rate for both commercial and private use and nowadays represent a widely accessible source of opportunity.

Among them, the IEEE 802.11 Standard based (WiFi) transmissions seem to be an appropriate choice in the considered scenarios. Basically, even though they do not feature real terminals, airstrips owners eventually began to offer services and facilities to its users. These typically include the WiFi connection that sometimes is also adopted for pre-flight briefing. Based on the passive radar principle, the same WiFi access point (AP) might be exploited to provide the required radar surveillance capability in the area of interest. The requirement for a continuous coverage of the airfield might result in a suitable number of passive receivers to be deployed along the runways and neighbouring zones. However, differently from other PCL systems based on alternative illuminators of opportunity, the PCL operation can be largely simplified. In fact, since a very local, privately owned and operated illuminator is exploited, this can be supposed to be partially cooperative, so that, for example, a quite pure copy of the emitted signal can be assumed available at each PCL receiver thus avoiding the limitations related to the synthesis of a reference signal of high quality. Finally, it is worth noticing that the use of such illuminators potentially enables a hybrid active and passive localization of the targets based both on self-reported positions and radar measurements.

Given these considerations, we investigate in the following the performance of a WiFi-based PCL sensor in small private airfield monitoring application.

III. THE WIFI-BASED PCL RECEIVER AND THE EXPERIMENTAL TESTS

In this article we report the results obtained in the test campaign performed in a small airfield named “Aviosuperficie Monti della Tolfa” [23] located in Santa Severa (about 60km North of Rome). Figure 1 shows an aerial view of the airfield area. The airfield is only used for recreational and training flight purposes. It features a single runway, 520 meters long and 20 meters wide, with a grass surface. Depending on wind direction, take-offs and landings are performed with heading 120° or 300° w.r.t. North. A dedicated operator is in charge of the control of the traffic on the runway and neighboring areas.

In the performed test campaign, we employed the experimental PCL receiver developed at the DIET Dept. of the University of Rome "La Sapienza" [25]. It consists of four parallel receive (rx) channels providing a fully coherent base-band down-conversion of the input signals; these are then synchronously sampled at 22 MHz and stored for off-line processing.

The adopted experimental setup and the basic signal processing stages are sketched in Figure 2.

A commercial WiFi Access Point (AP) is used as transmitter of opportunity. Its output is connected to the transmitting antenna while a directional coupler is used to send a -20 dB copy of the transmitted signal (the reference signal) to the first rx channel of the quad-channel PCL receiver. The router was configured to transmit in channel 7 of the WiFi band (2442 MHz). It was set up to roam for connected devices emitting a regular Beacon signal exploiting a direct sequence spread spectrum (DSSS) modulation at 3 ms intervals.

Other two rx channels are connected to commercial WiFi panel antennas to collect the surveillance signals; the employed antennas are characterized by a gain of 12 dBi, a front-to-back ratio of 15 dB and beamwidths equal to about 80° and 23° on the horizontal and the vertical plane, respectively. The surveillance antennas were mounted at a height of about 1.6 meters from ground, about 40 cm below the transmitting antenna, in a quasi-monostatic configuration, and they were pointed at 345° N. Moreover they were displaced in the horizontal direction by 12 cm, which gives a 45° ambiguity for the target direction of arrival (DoA) estimation, based on an interferometric approach.

Each surveillance signal separately undergoes the signal processing stages illustrated in Figure 2, [10], [18]: the reference signal is first conditioned to improve the resulting ambiguity function (AF), by proper techniques introduced to reduce the high sidelobes structures appearing in the AF of WiFi signals based on different modulations, [10]. In practical applications, the transmission content affects the modulation adopted by the AP thus leading to consecutive transmitted pulses characterized by AF with varying characteristics. However, we observe that the DSSS modulation represents a worst-case condition in term of resulting AF (narrower bandwidth and higher sidelobes), so mixing with orthogonal frequency division multiplexing pulses would result in improved performance [26].

The removal of undesired contributions (direct signal leakage and strong clutter/multipath echoes) that have been received on the surveillance channels along with the moving target echo is performed via the extensive cancellation algorithm (ECA) which operates by subtracting from the surveillance signal properly scaled and delayed replicas of the reference signal. Specifically, the Sliding version of the ECA is adopted, [28] over a range of 600 m with a batch duration equal to 0.2 s, whereas the filter update rate is equal to the beacon emission rate of the exploited AP. A coherent processing interval (CPI) of 0.3 s is then used to evaluate the bistatic range-velocity map over consecutive portions of the acquired signals with a fixed displacement of 0.1 s.

Possible limitations to the WiFi-based PCL operation at these stages might be due to interference from other APs or WiFi devices used in the same area. However, if the interfering sources operates on adjacent (partially overlapped) frequency channels, its transmission is expected to yield just a limited increase in the system noise floor. This can be explained by observing that (1) the received interfering signal does not correlate with the reference signal adopted for matched filtering, and (2) the probability of collision between the same pair of devices is usually low. Different considerations apply when the interfering sources operates in the same wireless local area network channel used by the AP of opportunity. In this case, the occurrences of collisions are substantially avoided thanks to the implementation of carrier sense multiple access protocols. Therefore, the effect of an interfering AP would be to inhibit a high rate transmission of pulses by the AP of opportunity. From a radar application point of view, this might upper limit the equivalent pulse repetition frequency and yields a highly variable temporal separation among consecutive pulses. In typical situations, this effect is responsible of a target energy loss within the CPI and very high sidelobes to appear in the AF of the WiFi signal along the Doppler dimension [22], [27]. In principle, the former effect can be in principle recovered by extending the CPI [15], whereas in [27] we have shown that it is possible to design effective taper functions to control the undesired Doppler sidelobes at least in the Doppler range of interest.

Successively, a constant false alarm rate threshold with a probability of false alarm equal to 10^{-4} is applied on the obtained map to automatically detect the potential targets thus providing a first target localization over the bistatic range/velocity plane. A conventional Kalman tracking algorithm can be applied after this stage to reduce the false alarms while yielding more accurate range/velocity measurements. The target two-dimensional localization in local Cartesian coordinates is finally obtained by exploiting the range and azimuth measurements provided by the two horizontally displaced surveillance antennas [18].

Several tests have been performed against different targets of interest aiming at assessing the suitability of the conceived system with reference to typical operative conditions. Some examples are reported in the following section.

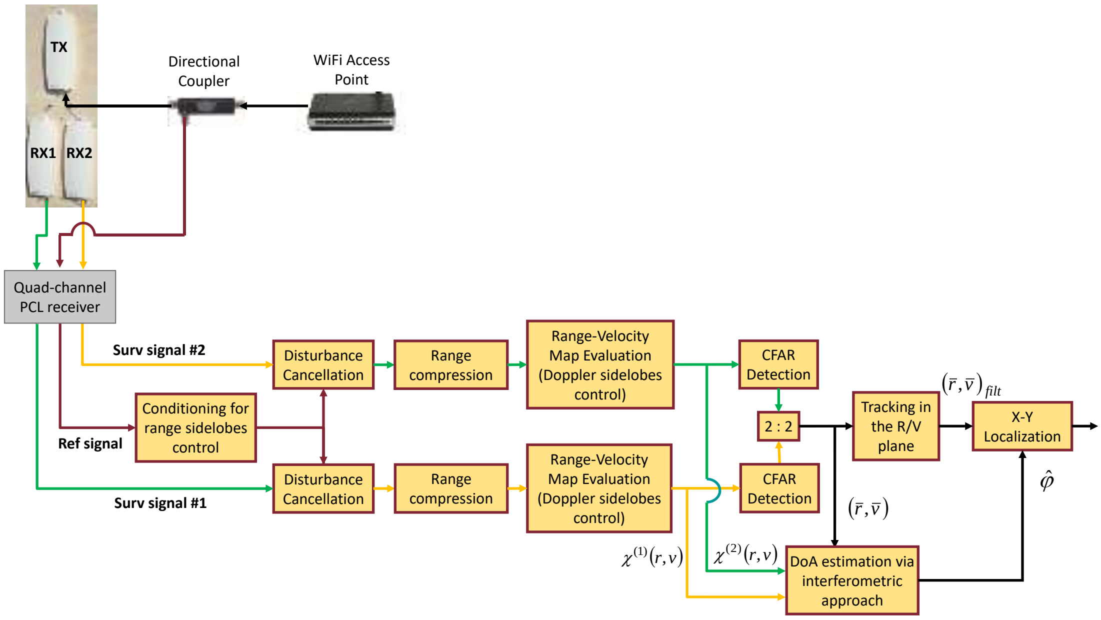


Figure 2 – WiFi-based PCL receiver set-up and signal processing scheme.

IV. RESULTS AGAINST EXPERIMENTAL DATA

The experimental results reported in this section refer to the following test types:

- Test A: Small aircrafts moving on the runway for landing/taking-off
- Test B: Small aircrafts maneuvering in different areas of the airfield
- Test C: Vehicles moving in the proximities of the runway/taxiway
- Test D: People walking around the airfield

Different tests are addressed in the subsequent dedicated sub-sections.

A. *Test against a landing aircraft*

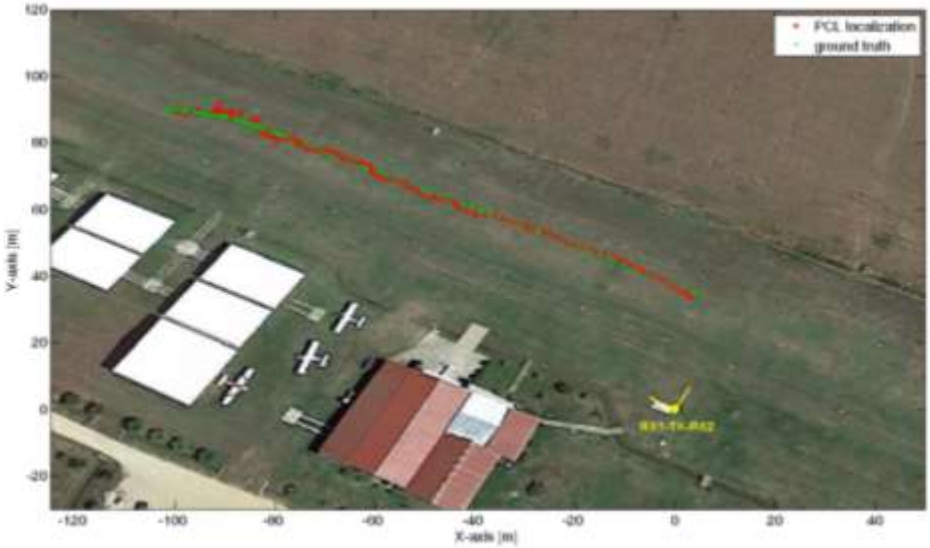
The first test employed a small aircraft as a cooperative target (Figure 3a), equipped with a global positioning system (GPS) receiver that continuously recorded its position (green markers in Figure 3b). The WiFi-based PCL receiver performed a 20-s registration; during this period the aircraft moved on the runway just after landing, travelling a distance of about 110 meters, away from the receiver location. The position and the main beam angular coverage of the PCL antennas is sketched in yellow in Figure 3b.

The results obtained after the basic processing stages illustrated in Figure 2 are reported in Figure 3b as red markers. The good agreement with the available ground truth demonstrates the capability of the PCL system to monitor conventional activities occurring on the runway.

The small aircraft is continuously detected along its trajectory and its position is estimated with good accuracy at least when it is included in the receiver antennas beamwidth. For the most part of the target trajectory, the positioning errors are largely comparable with the target size. As expected the target localization accuracy rapidly degrades as the aircraft gets far away from the PCL receiver; this is due to the decrease in the target echo power level and to the widening of the uncertainty x-y area caused by a given DoA error.

Obviously, better results could be obtained by applying a second tracking stage over the x-y plane and/or jointly exploiting the range and angle measurements provided by multiple PCL sensors properly dislocated on the area to be surveyed [18].

(a)



(b)

Figure 3. Test against a landing aircraft: (a) picture of the performed test; (b) PCL results compared to the available ground-truth.

B. Test against two small aircrafts maneuvering along the airfield

This second test was performed against two targets of opportunity taken during a typical operative condition of the airfield. Specifically, during the PCL receiver registration of 20 s, a small aircraft, after leaving the hangar, was moving toward the taxiway (see the aircraft on the ground on the left side of Figure 4a). Contemporaneously, an ultralight aircraft, a powered paraglider, was flying over the runway involved in a ‘touch and go’ landing maneuver.

The output yield by the PCL sensor fielded in that area is shown in Figure 4b. Specifically, different colors are used for the different sequences of plots identified by the tracker on the range/velocity plane. Once converted in Cartesian coordinates, the two sequences of plots clearly reveal the presence of the two observed targets with a reliable indication of their instantaneous positions.

(a)

(b)

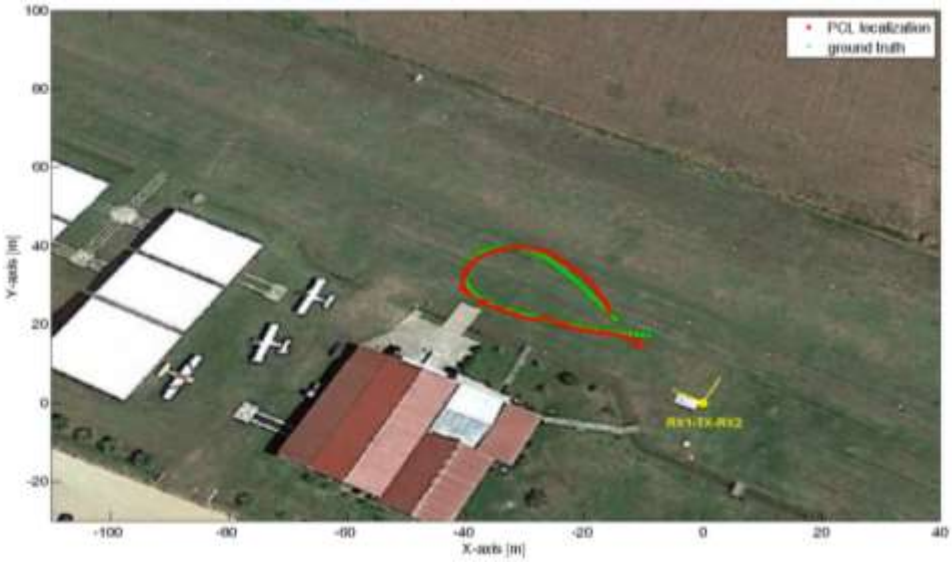
Figure 4. Test against two maneuvering aircrafts: (a) picture of the performed test; (b) PCL results compared to the available ground-truth.

In this particular test, it would have been of great interest the capability to measure the target height above ground. This could be in principle obtained by exploiting an additional surveillance antenna displaced in the vertical direction in order to estimate the elevation angle of the target's echo. Unfortunately, such additional antenna was not available during this test as it was mostly intended to demonstrate the ground targets surveillance capability of the PCL sensor. Nevertheless, the results obtained with the adopted setup show that the conceived system can be effective in monitoring aircraft activities in the proximity of the runway in order to avoid accidents due to intentional/unintentional runway incursions.

C. Test against an utility vehicle

As mentioned previoulsly, various ground vehicles might be moving on the airfield surface or in its neighboring areas. Such vehicles might include private cars belonging to the airfield users or utility vehicles employed within the airfield for maintenance, service and rescue activities.

(a)



(b)

Figure 5. Test against an utility vehicle: (a) vehicular target employed; (b) PCL results compared to the available ground-truth.

To verify the possibility of the PCL sensor to effectively control the ground vehicles traffic along the airfield, the third reported test employed an utility car as cooperative target (see Figure 5a). During this test the car performed a U-turn during which it got very close to the runway. The comparison between the PCL results and the GPS based ground truth is shown in Figure 5b, where again we observe that they are in large agreement.

Notice that the successful application of the WiFi-based passive radar for vehicular traffic monitoring has been already demonstrated in previous works [10]-[11], [16]-[18]. However the performed test clearly reveals the potential benefits of its use in the considered scenario.

D. Test against human targets

In typical operative conditions, many people might be walking around different airfield areas. Therefore, aiming at improving safety and security in such scenarios, the capability to reliably detect, localize and track human targets might be crucial.

This possibility is proved in this last reported test, where the PCL sensor is operated against three people walking in the proximity of the airfield facilities (club-house, restaurant, etc.) along different trajectories (Figure 6a). The PCL results are reported in Figure 6b where different colors are used to indicate different tracks. For illustration purposes, ideal boundaries have been defined between an allowed area (close to the airfield facilities) and a forbidden area (that adjacent to the runway) and the red color has been used for the tracks of the targets crossing the boundaries.

Apparently the accuracy of the sensor is not extremely high when operating against human targets; however it is worth recalling that all the reported results do not include a tracking stage in the x-y plane which might increase the final positioning accuracy.

Despite this limitation, the performed exercise resembling a possible security application proves the suitability of a WiFi-based passive radar in the considered scenarios. The same approach can be exploited to prevent runway incursions by ill-intentioned people and wild animals living in neighboring areas.

(a)

(b)

Figure 6. Test against human targets: (a) picture of the performed test; (b) PCL results employed for the security exercise.

For security and logistic reasons, all the performed tests include targets moving not too far from the receiver (this especially applies to human and vehicular targets). Therefore, the collected data set is not sufficient to provide an assessment of the sensor detection range. However, the Wi-Fi based passive radar coverage is expected to be limited to a few hundreds of meters. Therefore the considered system is mostly intended for monitoring the surface movement of a small airfield.

Nevertheless, a number of strategies can be adopted to extend the expected coverage and to improve the achievable accuracy aiming at guaranteeing its applicability to larger airfields or continuous monitoring of the aircrafts also during take-offs and landings phases. Among them are the following:

- The use of a network of passive receivers properly deployed in the considered area [18]-[21]. This is a viable solution particularly when monitoring areas of small dimensions, since the network geometry can be carefully designed to limit the system complexity while guaranteeing the availability of measurements with a sufficient degree of spatial diversity. Moreover, for larger airfields, also the possible presence of multiple WiFi APs could be considered to provide connection to the airfield users, which might enhance the potentialities of the resulting multistatic system.
- The exploitation of longer CPIs, which allows a corresponding increase of the resulting integration gain [15]-[17]. This is obtained at the expense of an increased complexity of the signal processing stages since proper techniques should be adopted in order to compensate for the expected range and Doppler migration of the observed targets. However, notice that this could be a simpler task during take-offs if the target was already tracked along its movement on the runway.
- The joint exploitation of WiFi transmissions and other technologies for metropolitan area network (MAN) connection (e.g. LTE).

V. CONCLUSIONS

In this article, the suitability of a WiFi-based passive radar has been investigated for a civil application related to small airfield or private runways monitoring. The tests performed in a real scenario have proven the capability of the passive sensor to detect and accurately track typical users of the airfield, there including small or ultralight aircrafts, ground vehicles, and people. Therefore it could be successfully employed as an automatic, low-cost, compact, and non-intrusive sensor to improve safety and security in such scenarios with limited impact on its users. Moreover, since the transmissions for wireless networking are exploited, symbiotic operation can be foreseen between communication, navigation and security tasks thus potentially enabling the concept of a ‘smart airfield’ in the close future.

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