Enhanced WiFi-based passive ISAR for indoor and outdoor surveillance

T. Martelli, D. Pastina, F. Colone, P. Lombardo

DIET Dept., University of Rome "La Sapienza"
Via Eudossiana, 18 – 00184 Rome, Italy
e-mail: {martelli, pastina, colone, lombardo}@diet.uniroma1.it

***Abstract*— In this paper we examine the potentiality of passive coherent location (PCL) exploiting WiFi transmissions for indoor and outdoor area monitoring. Particularly, we investigate the advanced capability to obtain high resolution cross-range profiles of the observed targets via Inverse Synthetic Aperture Radar (ISAR) techniques. To these purposes, appropriate processing techniques are introduced and their effectiveness is tested against real data sets concerning both human and man-made targets. The reported results clearly show that the proposed technique allows to effectively discriminate closely spaced human targets moving in a hall, whereas they could not be resolved by a conventional processing. In addition reliable and stable profiles are obtained for the man-made targets moving in the surveyed scene which might fruitfully feed a classification stage. This contributes to demonstrate the effective applicability of the passive radar concept for improving internal and external security of private/public premises.**

Keywords—ISAR, PCL, resolution

I. INTRODUCTION

Passive coherent location (PCL) exploits existing illuminators of opportunity to perform target detection and localization thus embracing the current trend of using standard, low-cost, and already deployed technologies. PCL has been mostly investigated for long or medium range applications by exploiting the proliferation of RF systems for telecommunications [1].

Aiming at short range surveillance (both indoor and outdoor), the IEEE 802.11 standard-based (WiFi) technology has been considered as potential source of opportunity since it offers reasonable bandwidth (range resolution), coverage and wide accessibility [2]. The possibility to exploit such a ubiquitous and easily accessible source has been shown to be an appropriate choice for the detection and localization of designated vehicles, human beings or man-made objects within short ranges using the passive radar principle [3]-[4].

With reference to WiFi-based PCL being the resolution limited to tenths of meters it is of great interest to provide the sensor with the advanced capability to obtain high resolution cross-range profiles of detected moving targets. This would yield an improved resolving capability to be exploited against potentially high concentration of targets moving in the surveyed scene. For these reasons, in [4] we investigated the possibility to exploit the motion of man-made targets (vehicles) in order to achieve a high resolution in the cross-range direction (up to tens of centimeters) by applying Inverse Synthetic Aperture Radar (ISAR) processing techniques.

In this paper the effectiveness of ISAR techniques is demonstrated against both human and man-made targets. Particularly, with reference to moving human targets, experimental tests have been performed in indoor environment: obtained results clearly show that, by extending the coherent processing interval up to a few seconds allows to effectively discriminate closely spaced targets moving in a hall, whereas they could not be resolved by a conventional processing.

In addition, with reference to man-made targets, we observe that the capability to obtain high resolution cross-range profiles would potentially enable the automatic classification of designated targets. Preliminary results along this line have been reported in [4] proving that the disturbance cancellation stage is a mandatory step not only for target detection but also for the ISAR profiling; nevertheless the background removal can have a non negligible effect on the target signal in input to the ISAR processing thus potentially degrading its cross-range profile formation. As a consequence, the processing techniques described in [4] might yield limited performance especially when accurate profiling is required. Therefore in this paper, an alternative cancellation approach is introduced to obtain an effective removal of such disturbance while preserving the target contribution and, consequently, the quality of the ISAR processing. Based on an iterative target preserving algorithm, the proposed processing strategy is shown to overcome the limitations of the other cancellation approaches. The effectiveness of the proposed technique has been preliminary verified against data sets obtained by injecting synthetic target returns into the real background; then it has been tested against real vehicular targets moving in a parking area. The reported results prove that reliable cross-range profiles can be achieved, fruitfully exploitable by a classification scheme based on an appropriate signatures database.

II. WIFI-BASED PCL PROCESSING SCHEME

The basic WiFi-based PCL processing scheme for target detection designed by the authors has been fully described in [3] whereas in [4] we define the required steps for obtaining a cross-range profile of the observed targets via the application of ISAR techniques. The resulting overall processing scheme is depicted in Fig. 1 and main steps are here summarized. The signal reflected from the target is collected by the main PCL receiver (known as surveillance channel) while another receiver (known as reference channel) is adopted to collect the transmitted signal.

Since the transmitted waveform is not within the control of the radar designer, the reference signal must undergo a modulation-dependent conditioning stage aimed at improving the resulting mismatched Ambiguity Function in the range dimension. Then the reference signal is exploited in the disturbance cancellation step, the Extensive Cancellation Algorithm (ECA) [4], which operates by subtracting from the surveillance signal $s_{surv}(t)$ proper scaled and delayed replicas of the reference signal $s_{ref}(t)$. For the considered application, the ECA-Batches version is adopted, which requires the filter weights to be estimated over smaller portions of the integration time. It has to be noticed that the batch duration affects the width of the filter cancellation notch in the Doppler dimension, so that it should be traded with the minimum target detectable velocity to be guaranteed. After the cancellation stage, target detection is sought by evaluating the bistatic Range-Velocity map over short coherent processing intervals (CPI typically between 0.1 s and 0.5 s). A constant false alarm rate (CFAR) threshold is then applied on the obtained map to automatically detect the potential targets. The measures collected at consecutive observations can be used to perform a line tracking over the range/velocity plane. By combining the measures available at multiple PCL sensors, the target 2D localization in local Cartesian coordinates can be obtained.

Obviously the WiFi-based passive radar guarantees a limited resolution in the range dimension (equivalent monostatic range resolution of 11 m or 18 m by exploiting the bandwidth of DSSS or OFDM transmissions, respectively [2]) and so it is of great interest the study of alternative processing techniques able to provide an improved resolution capability on the observed targets, along the line investigated in [4].

III. ISAR TECHNIQUES FOR IMPROVED CROSS-RANGE RESOLUTION

A. Resolution improvement via ISAR techniques

Additional resolution in cross-range direction could be achieved by resorting to ISAR techniques, namely by exploiting the motion of the target itself, [5]. Therefore in [4] we have shown that a cross-range resolution considerably higher than the range resolution can be achieved by applying ISAR techniques to targets with a motion component in the cross-range direction.

The main processing steps are sketched in Fig.1 in the dashed frame. Once a moving target has been detected, the corresponding range strip is selected from the compressed data and fed in input to the ISAR processing block constituted by the cascade of target motion estimation, cross-range profile focusing and scaling. The target phase history in the ISAR CPI is approximated by an *M* degree polynomial law. Consequently the target motion is estimated by searching for the set of coefficients that better compensates the migration through both range and Doppler resolution cells and thus provides the best quality of the focused profile according to a specific cost function. Once the target motion parameters are available, the cross-range profile is

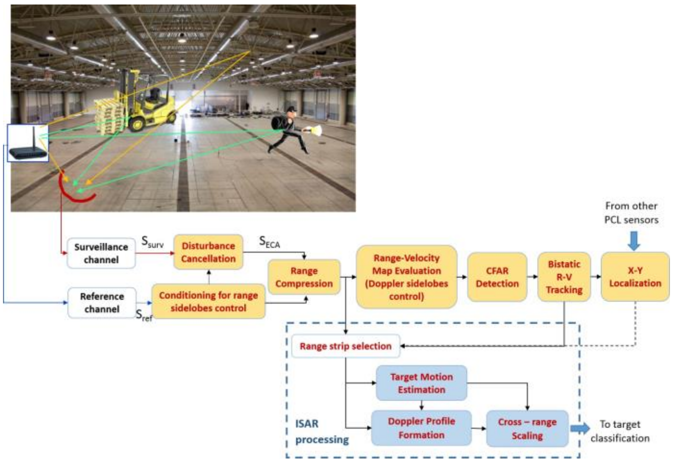

Fig. 1. WiFi-based PCL processing scheme.

formed and properly scaled by mapping Doppler frequencies into cross-range distances.

The results in [4] showed that: (i) the disturbance cancellation stage is essential for target detection and motion estimation, (ii) the disturbance cancellation has a non negligible effect on the target signal fed in input to the ISAR processing so that it might reduce the quality of the ISAR products. Basically, the adopted cancellation algorithm (ECA or ECA-Batches) strongly attenuates the target signal components at low Doppler frequencies since they are recognized as stationary contributions and included in the adaptive estimation of the cancellation weights. As a consequence, a considerable part of the target Doppler chirp can be lost and this potentially causes a degradation of the ISAR profiling. This degradation can occur in the case of targets moving along the cross-range direction that is the most interesting one to apply the ISAR processing schemes.

Obviously different applications impose different constraints and requirements on the quality of the ISAR products so that this potential degradation might be appreciable or not. Particularly when considering human targets the strong requirement is on the resolution capability enabling the separation of the different targets. In contrast, when dealing with man-made targets (such as vehicles), the requirement is on the accurate separation and extraction of the different scattering centres of the same target so that ATR (Automatic Target Recognition) procedures could be enabled. While standard quality ISAR products can allow the separation of different targets, enhanced quality products are essential for classification purposes. Therefore in the remaining part of this section we focus our attention on the case of human targets; then the case of man-made targets is considered in the following where an enhanced ISAR profiling technique is proposed and the results achievable via its application are presented.

B. Experimental results against human targets

Potential of ISAR techniques in resolving closely spaced human targets moving in a cluttered indoor scenario is here demonstrated by using live data acquired by means of the passive radar prototype developed at the DIET Department of the University of Rome "La Sapienza", [6]. It consists of four receiving channels providing a fully coherent base-band down-conversion of the input signals; these are then synchronously

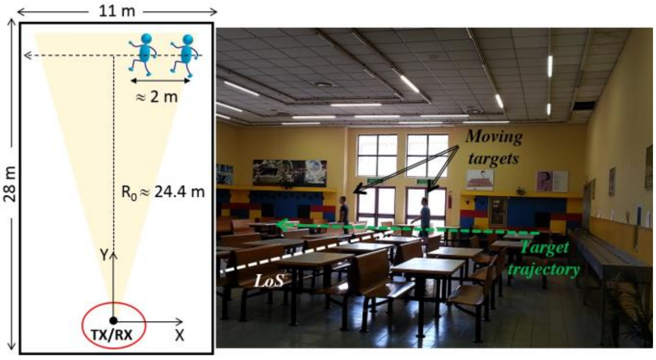

Fig. 2. Sketch of acquisition geometry.

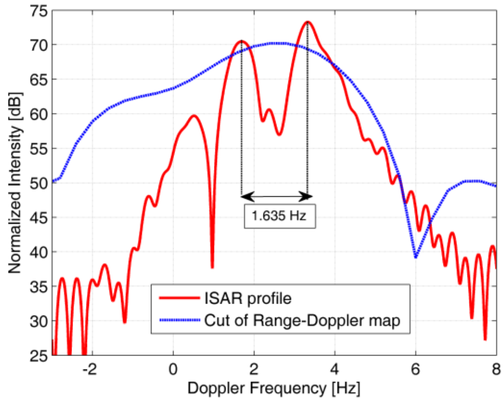

Fig. 3. Cut of the Range-Doppler map (CPI=0.5 s) and ISAR profile (CPI=3 s) comparison.

sampled at 22 MHz and stored for off-line processing. The PCL receiver has been fielded in the canteen of the School of Engineering whose size is approximately equal 11 m wide and 28 m long (Fig. 2). Tests have been performed using two human targets about 2 m apart moving in cross-range direction (i.e. trajectory parallel to X axis, Fig. 2) with approximate speed 1.3 m/s, distance of minimum approach R_0=24.4 m and overall test duration equal 10 s.

The acquired data has been processed via the processing scheme in Fig. 1 with ECA applied with a batch duration set to 400 ms over a range of 300 m and the bistatic range-velocity map evaluated over a CPI of 0.5 s. A cut of the bistatic range-Doppler map at the range bin interested by the two human targets is reported in Fig. 3 (blue curve). We observe that the two targets give rise to the presence of a single strong peak meaning that the two targets can be detected but not resolved. By increasing the CPI (3 sec) and feeding the ISAR processing block (with M=3) the red curve in Fig. 3 is obtained. We observe that the increased CPI provides an improvement in terms of both Doppler resolution and target peak power. Particularly, the two targets give rise to the presence of two clearly resolved peaks whose Doppler separation (1.635 Hz) scaled accordingly to the estimated cross-range speed (1.313 m/s) provides 1.865 m which is largely in agreement with the actual separation between the targets. The reported results clearly show that the target motion can be fruitfully exploited to improve cross-range resolution so that closely spaced targets can be effectively discriminated. Moreover the characteristics of the considered indoor scenario demonstrates the potential of the proposed approach in cases of practical interest.

IV. Enhanced ISAR profiling technique

When dealing with man-made targets ISAR techniques are typically employed to achieve high resolution products to be exploited by ATR procedures. In this case high quality products are needed in order to assure reliable performance. As mentioned before ISAR techniques applied in cascade with conventional ECA can result in a quality degradation. Therefore, in [4], an alternative cancellation approach has been presented based on the estimation and update of the cancellation filter weights only at signal fragments not containing target contributions at low Doppler frequencies (being this information available from the tracking stage). This in principle allows to remove the strongest disturbance components in the observed scene as they are stationary during the ISAR CPI. In contrast this prevents the cancellation of the target echoes as it crosses the zero-Doppler along its motion.

Unfortunately, this approach has some limitations that may make it ineffective in a number of situations. In particular, in scenarios with possibly high density of targets, it could be very unlikely to identify a signal fragment that does not include low Doppler target echoes. Moreover the slowly varying characteristics of the stationary background can be also ascribed to the instability of the employed receiver (phase noise of local oscillators, time jitter of ADC, etc.) so that the possibility to frequently update the filter coefficients is critical.

For the reasons above, we present here an innovative target preserving disturbance cancellation technique able to overcome the above limitations and to provide enhanced quality profiles of moving man-made targets. Particularly sub-section IV.A describes the new technique while sub-section IV.B analyses the corresponding Point Spread Function (PSF) by injecting a moving point-like object into the real background.

A. *Iterative target preserving cancellation algorithm*

To preserve the target signal for the following ISAR processing, its contribution to the received signal should be properly reduced prior to estimating the cancellation filter coefficients. To this purpose, the proposed approach exploits the output of the ISAR profiling stage to retrieve from it the signal contribution concerning the considered target and uses this recovered component to clean the received surveillance signal. In this way the estimation of the cancellation filter weights can be repeated using a signal with "target reduced" characteristics. By iteratively repeating the above steps, progressively a "target free" signal is made available for filter weights estimation and the low-frequency components of the target returns are better reconstructed. Thus the proposed technique somehow follows a CLEAN-like philosophy [7].

The block diagram of the proposed iterative target preserving (ITP) technique is sketched in Fig. 4. First of all we observe that the disturbance cancellation has to be repeated at each iteration of the proposed algorithm. According to the processing scheme in Fig. 1, this stage precedes the range compression so that an iterative cancellation approach would require a high computational load. However, we point out that the two stages above can be nicely swapped by observing that the cancellation filter can be applied against the range compressed data $\chi[q,n]$, (being q and n respectively the range bin and slow-time index), and the estimation of the filter weights might follow the

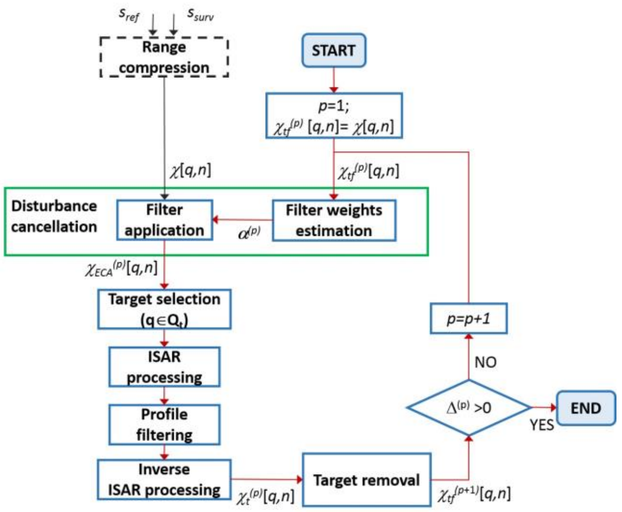

Fig. 4. Block diagram of the ITP ISAR profiling technique.

evaluation of both the reference signal autocorrelation and the cross-correlation between the reference and the surveillance signal.

At the *p*-th iteration the following steps must be performed:

1) The weights of the ECA are adaptively estimated based on the current "target free" version of the surveillance signal $\chi_{tf}^{(p)}[q,n]$ after range compression. This signal coincides with the original range compressed signal when p=1.

2) The filter weights are applied against the original surveillance signal to obtain its disturbance free version $\chi_{ECA}^{(p)}[q,n]$. At the first iteration, this output coincides with the standard ECA applied against the original data.

3) The signal at the selected target range strip is extracted (i.e. $\chi_{ECA}^{(p)}[\bar{q},n] \mid \bar{q} \in Q_t$, where Q_t identifies the range bins spanned by the target) and fed in input to the ISAR stages.

4) The target profile is properly filtered to reject the residual background and to enhance the selected target contribution.

5) A reverse focusing is applied to the filtered ISAR profile to recover the current estimate of the target signal in the range-compressed slow-time domain ($\chi_t^{(p)}[\bar{q},n] \mid \bar{q} \in Q_t$).

6) Finally, the recovered signal is subtracted from the original surveillance signal to provide the new "target free" version to be exploited at the following iteration:

$$\chi_{tf}^{(p+1)}[q,n] = \begin{cases} \chi[q,n] - \chi_t^{(p)}[q,n] & q \in Q_t \\ \chi[q,n] & q \notin Q_t \end{cases} \quad (1)$$

Notice that, as the target return is better recovered, its contribution to the ECA weights estimation is progressively limited thus reducing its "auto-cancellation" effect. In contrast, the target-free signal can be successfully exploited to estimate the stationary disturbance characteristics so that its removal is kept guaranteed, or even improved, as the algorithm progresses.

The algorithm should be arrested when the signal $\chi_{tf}^{(p)}[q,n]$ likely contains only stationary contributions (or contributions from other targets). To this aim, a simple stop condition can be based on the estimated power level of the target-free signal at the range bins of interest along the whole ISAR CPI:

$$P_{tf}^{(p)} = \sum_{q\in Q_t} \sum_n \left|\chi_{tf}^{(p+1)}[q,n]\right|^2 \quad (2)$$

We have experimentally verified that this parameter usually exhibits a minimum as a function of the iteration number. Consequently, a reasonable stop condition can be based on the following rule:

$$\Delta^{(p)} = P_{tf}^{(p+1)} - P_{tf}^{(p)} > 0 \quad (3)$$

When such condition holds, the output target Doppler profile is assigned to the last ISAR stage output and, as the final step, undergoes cross-range scaling. Obviously the enhanced quality of the achieved ISAR profile is paid in terms of an increased computational cost of the iterative technique with respect to the standard one. However typically few iterations (10÷20) are needed to reach the stop condition. Therefore we can conclude that the increase of the computational cost required by the iterative technique is still manageable and therefore the proposed approach is suitable for application to solve real-word problems.

B. Results against synthetic target echoes injected in real stationary background

In order to understand the effect of the cancellation techniques on the ISAR PSF, some controlled tests have been performed. To this purpose, from the same experimental campaign described in section IV.C, an acquisition of duration 6 s is considered in the following that contains only the returns from the stationary scene (namely, no targets where employed in this test). The echoes of a fictitious point-like target has been then injected in the collected data. In particular it is assumed that, during the ISAR CPI of 6 s, the target moves from point (x_A, y_A)=(-13.5m, 50m) to point (x_B, y_B)=(13.5m, 50m) with constant velocity v_x=4.5 m/s, distance of minimum approach R_0=50 m and signal-to-noise ratio SNR=-20 dB, see Fig. 7.

Fig. 5 shows the Doppler spectrum of the overall signal containing both target and clutter contributions (green curve) obtained after standard cancellation (ECA); for comparison the theoretical Doppler spectrum of the target only signal (red curve) is also reported. As expected, the cancellation filter has dramatically distorted the target spectrum at low Doppler frequencies by inserting a cancellation notch: this clearly shows the "auto-cancellation" effect of the target echoes. Such effect certainly degrades the effectiveness of the subsequent ISAR processing which needs the entire Doppler frequency history of the target to generate the clairvoyant cross-range profile. Specifically, this yields a corresponding SNR loss that in turn results in a reduced accuracy in the target motion estimation and in a corresponding loss in terms of cross-profile amplitude. Moreover, depending on the portion of the target spectrum that has been cancelled (i.e. central or side part), the above effect might cause severe ambiguities or cross-range resolution degradation.

In the considered case-study, the observed warp of the target spectrum mainly yields an increased sidelobe level in the achievable cross-range profile. This is shown in Fig. 6 that reports the cross-range profile obtained for the fictitious target after the application of the conventional ECA (green curve) compared to the clairvoyant, target only, profile (red curve) which represents the ideal ISAR PSF of the system. The reported profiles have been obtained by setting *M*=3.

As is apparent, the achievable PSLR is 4.17 dB when a conventional ECA approach is adopted for disturbance cancellation; this value has to be compared to the theoretical 12 dB obtained in the target-only case (notice that, by setting M=3, uncompensated phase terms of higher orders are responsible for a slight PSLR degradation with respect to the 13.26 dB expected for a point-like scatterer in the ideal case). Moreover a significant amplitude loss is observed since much of the target spectrum has been cancelled by the ECA. Finally, it is to be noticed that the slight increase in terms of cross-range resolution is just a misleading effect of the profile warp.

The results obtained after the application of the ITP technique are shown in Fig. 5 and Fig. 6 for an increasing number *p* of iterations. As is apparent, as *p* increases, the target "auto-cancellation" effect is progressively smoothed so that the Doppler spectrum is comparable with the theoretical one (see Fig. 5). Correspondingly, the obtained cross-range profile resembles the clairvoyant target-only profile with only small deviations in the low side-lobes region (see Fig. 6). This depends on the threshold adopted in the ITP approach to identify the target contribution (in this case 20 dB below the highest target peak) which sets the dynamic range for the recovery of the target signal.

As is apparent, the main target contributions are rapidly gathered at the first iterations; however at least 20 iterations are required for the target signal to be better reconstructed. The stop condition is met at p=24: therefore, the algorithm can be arrested after p=24 iterations since this stage yields the best reconstruction of the target signal. This is also confirmed by the results obtained in terms of cross-range profile and its characteristics (see Fig. 6). In particular, after p=24 iterations, the amplitude loss and the PSLR degradation have been almost totally recovered and the obtained cross-range profile concides with the theoretical one in the region encompassing the main lobe and first sidelobes.

C. *Experimental results against moving man-made targets*

In this section, the performance of the proposed strategy is analyzed against live data. The considered data set has been collected by means of the same PCL receiver described in section III. Specifically, the tests were performed in a parking area in front of a private building (see Fig. 7). A single surveillance antenna has been employed, mounted just below the transmitting antenna in a quasi-monostatic configuration. An (X,Y) coordinate system is defined with the origin in the TX/RX antennas location.

Cars have been used as cooperative targets to demonstrate the practical effectiveness of the proposed approach. Two different tests (M1 and M2) were performed using one or two identical cars (i.e. Fiat Punto Evo) with length of about 4 m. In both cases the vehicular targets move along the axis $y=y_0=50$ m (red dashed line in Fig. 7) at about v_x=4.5 m/s. Specifically, in test M1, a single car was present approximately crossing the point $(x_0;y_0) \equiv$ (0 m; 50 m) at the middle of the acquisition. For

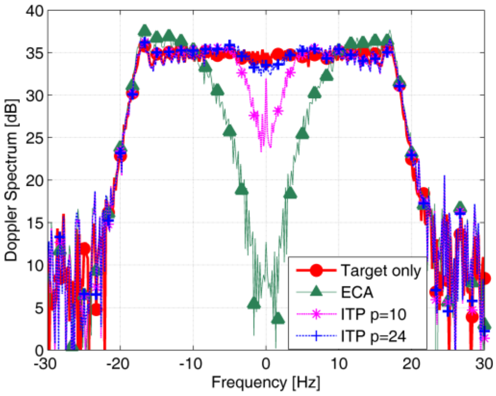

Fig. 5. Doppler spectrum after different disturbance cancellation techniques.

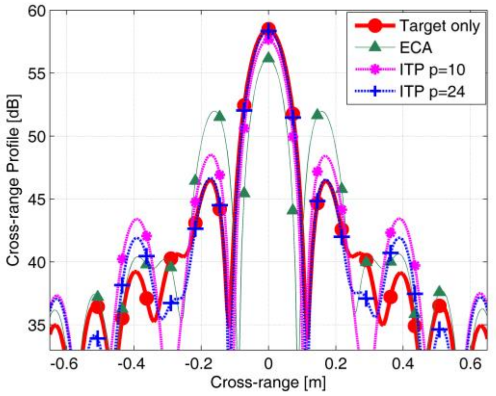

Fig. 6. Cross-range profiles for the fictitious target.

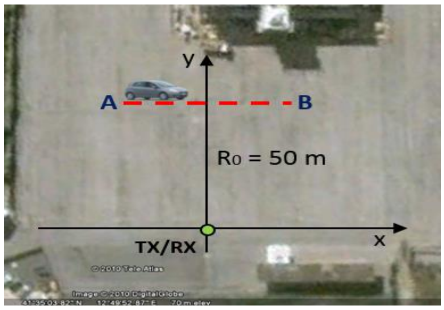

Fig. 7. Sketch of the acquisition geometry.

test M2 a second identical car was employed moving behind the first car with a separation of about 2-3 m along the x-axis so that, at the middle of the acquisition, they were almost symmetrically displaced about the point (0 m; 50 m). The overall duration of each acquisition is 10 s; the results shown in the following have been obtained by using an ISAR CPI set to 6 s properly selected from the whole recording.

The cross-range profiles obtained for test M1 are shown in Fig. 8a. The latter algorithm has been arrested after 8 iterations according to the proposed stop condition. We observe that, as for the case of the fictitious target, the newly proposed ITP strategy yields an improvement of few dBs in terms of profile amplitude. In fact, the capability to preserve a greater portion of the target spectrum has been shown to improve the performance of the subsequent ISAR processing in terms of both target motion estimation and target focusing. This in turn should lead to the formation of more stable profiles to be exploited for the extraction of reliable information on the observed targets. To further demonstrate the reliability of the achieved results, Fig. 8b shows the cross-range profiles achieved for experiment M2.

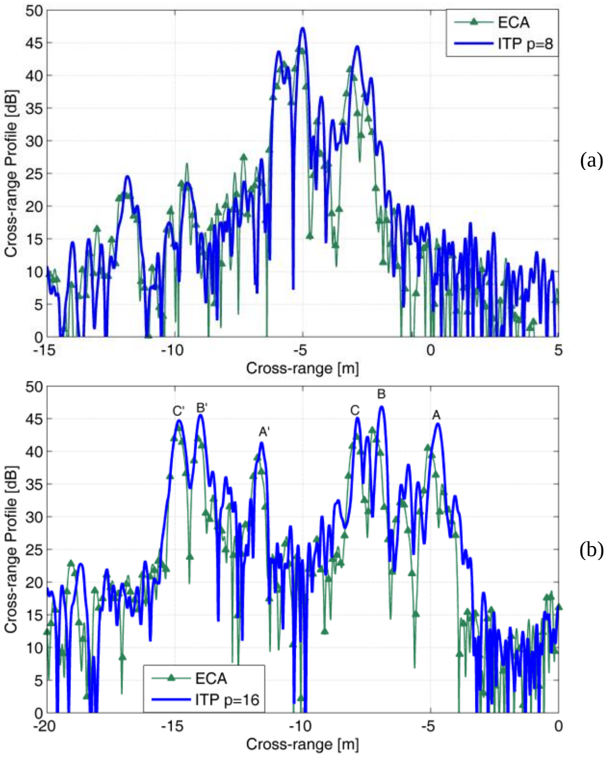

Fig. 8. Cross-range profiles comparison for the real data. (a) Experiment M1; (b) Experiment M2.

In this case the ITP algorithm stops after 16 iterations. As it is apparent, with both the ECA and the ITP cancellation approach, the profiles reveal the presence of two similar patterns characterized by three main peaks (labeled with capital letters) which correspond to the main scattering centers of the two identical cars used for the considered experiment.

As an example, in Table I we evaluate the distances between homologous points of the cars (i.e. profile peaks) from the cross-range profiles obtained with the ECA and the ITP approaches, respectively. Even if the actual value of this distance is not available, it is expected to be constant independently of the considered pair of peaks. Apparently, the values obtained for the three pairs of peaks are well in line with the test geometry (we recall that the length of each car is 4 m and their separation along the path is about 2-3 m); however, for all the three considered pairs, the use of the iterative technique provides less scattered values, when compared to ECA, thus proving a more accurate extraction of the target scattering centres by means of ITP technique.

The reported results demonstrate the effectiveness of the proposed experimental setup and processing scheme and support the practical application of the WiFi-based passive ISAR for short range (both indoor/outdoor) surveillance applications. In particular the comparison above clearly shows the reliability and stability of the achieved profiles which might fruitfully feed a classification stage based on appropriate signatures database.

TABLE I. CROSS-RANGE DISPLACEMENTS OF HOMOLOGOUS POINTS OF THE PROFILES OBTAINED FOR TEST M2

	ECA	**ITP (iter p=16)**
D_A = |A'-A|	6.67 m	6.88 m
D_B = |B'-B|	6.84 m	7.08 m
D_C = |C'-C|	7.03 m	6.97 m

V. CONCLUSIONS

In this paper suitable ISAR techniques to obtain high resolution cross-range profiles of the detected targets in a WiFi-based passive radar have been presented. Their effectiveness is demonstrated against both human and man-made targets. In particular, the application of ISAR techniques against the echoes from human targets moving indoor clearly shows the improved resolution capabilities which could enable the separation of closely spaced targets, otherwise not separable by a conventional processing. Moreover, in order to obtain high quality ISAR products of moving man-made targets, a new iterative target preserving technique have been proposed suitable for the simultaneous rejection of the background disturbance and profiling of the targets; reliable and stable profiles of moving man-made objects are achieved with a cross-range resolution up to about 10 cm. This allowed us to preliminary verify that these profiles could be exploited for classification purposes. The results shown support the practical applicability of the WiFi-based passive radar concept for improving internal and external security of private/public premises.

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