Target Detection in High Clutter using Passive Bistatic WiFi Radar

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Abstract— **The rapid rollout of wireless local area networks (WLANs) has provided a ubiquitous source of signal transmissions that may be exploited for surveillance applications using passive bistatic radar (PBR) and passive multistatic radar (PMR) systems. In this study, a series of experiments were conducted to examine the feasibility of using IEEE 802.11 wireless fidelity (WiFi) transmissions for detecting uncooperative targets in high clutter indoor environments. The range and Doppler characteristics of the system were also assessed theoretically from an ambiguity function analysis on WiFi signals having similar transmission parameters. Through-wall detections of personnel targets moving at differing velocities within an indoor environment are presented for the first time. The work demonstrates the feasibility for developing a low cost surveillance device that utilises WiFi networks as transmitters of opportunity.**

I. INTRODUCTION

The IEEE 802.11 protocol [1] defines the standards for wireless local area networks (WLANs). In the UK the most commonly deployed versions are 802.11g and the newer 802.11n standard which has multiple-in, multiple-out (MIMO) functionality. Both standards operate within the Industrial, Scientific and Medical (ISM) spectral band between 2.4 and 2.4835 GHz, employ orthogonal frequency division multiplexing (OFDM) and direct sequence spread spectrum (DSSS) modulations in conjunction with a variety of coding schemes [2]. Each modulation-coding combination defines a specific data transfer rate and is dependant on factors such as the number of users on the WLAN and received signals strengths between the transmitter and WiFi device. The 802.11 standard specifies a 20 MHz spectral mask per channel and a channel separation of 5 MHz. The nominal bandwidth for each channel is 16 MHz.

Non-cooperative identification and tracking of goods and people, both indoors and outdoors, has fostered a growing interest for applications in the security and surveillance industries. Furthermore, the proliferation of WLANs in public and private areas has enabled a widely and easily accessible source of transmissions for passive radar systems. Such radar systems have the ability to measure range, velocity and track movements. This type of sensing could be used in public areas such as railways and airport terminals or private commercial premises such as office buildings or warehouses.

Passive bistatic radar (PBR) eliminates the requirement for cooperative active devices such as those used in RFID based detection systems and thus requires no a-priori information about the targets of interest. Additionally, the receive-only nature of the system makes it low cost and robust to electronic counter measures. Doppler performance is also typically orders of magnitude more accurate than conventional microwave radar [3] owing to the increased integration times possible. The geometries of PBR systems are inherently bi- or multi-static [4] due to the requirement for having at least one reference receiver to detect and correlate the transmission signal with the scattered target signals received from the N number of surveillance channels.

A major drawback associated with PBR arises from the direct signal interference (DSI) component which undergoes perfect correlation with the reference signal, producing large range and Doppler sidelobes that can mask the weaker target echoes. Furthermore, the DSI increases the dynamic range requirement of the system. However, angular nulling with the antenna and interference cancellation techniques in the receiver [5] can be used to suppress the unwanted effects and improve system performance. Other disadvantages include poor range resolution, uncontrollable transmission signals and the necessity to perform some form of synchronization between the receivers [6].

In our previous work [7] [8] we have carried out a detailed ambiguity function analysis of the WiFi beacon signal and shown that it can be utilized by a PBR system to detect personnel targets in a low clutter outdoor environment. The work reported here focuses on detecting personnel targets in a more challenging high clutter indoor environment using WiFi data transmission signals. The results show that there is good potential for the use of passive WiFi PBR as a low cost surveillance tool with widespread applicability.

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II. INDOOR DETECTION EXPERIMENTS

A. Experimental Setup and Method

The detection experiments were set up in a typical indoor office environment at University College London (UCL) to provide significant clutter and multipath returns. The data was acquired using UCL's 2.4 GHz synchronized multistatic radar system (NetRad) which was configured to operate in *passive* mode. Detailed technical specifications of NetRad are given in [9]. The bistatic topology of the surveillance area is shown in Fig. 1.

A 15 dBi gain, 30º beamwidth antenna (SD15. Stella Doradus Ltd, Ireland) was positioned 6 meters away from a public WiFi access point (Aironet 1200 series, Cisco Systems, UK) to record the reference signal. The access point was stimulated to transmit an OFDM, 64 quadrature amplitude modulation (QAM) waveform which has a typical bandwidth of ~16 MHz and data transfer rate of 54 Mbps. Signal transmissions conformed to the 802.11g standard, were on WiFi channel 8 (centre frequency of 2.447 GHz) and had an EIRP of 10.2 ± 0.1 dBm.

A higher gain, narrower beamwidth (24 dBi, 8º) surveillance antenna (SD24, Stella Doradus Ltd) was placed in another room and focused toward the target position 7 meters away. The bistatic baseline was 7.6 meters and the bistatic angle was 46º. The surveillance antenna was positioned so that the through-wall DSI component from the WiFi transmitter was directed into a sidelobe approximately 60 dB below its mainlobe. Illumination of the target from the transmitter was also through-wall. A preliminary analysis of the test site using an open source WLAN detection tool suggested that each wall attenuates the signal by approximately 10 dB.

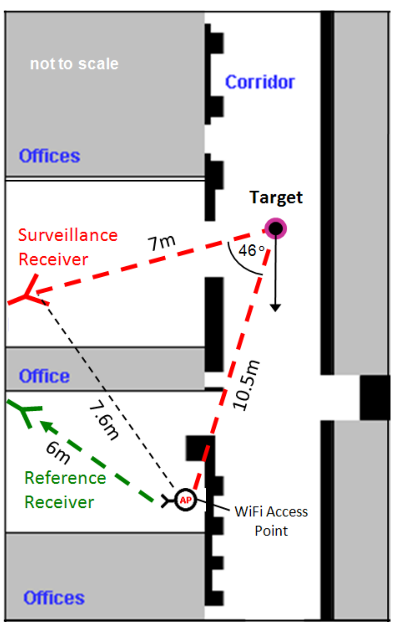

Figure 1. Geometry of the surveillance test site. The bistatic baseline, range and angle was 7.6m, 17.5m and 46º respectively.

Control measurements were initially taken without any target present to determine the noise level of the system and clutter response of the environment. For each of the proceeding experiments, NetRad was set to record the scattered signals for 100 ms giving a Doppler resolution of 10 Hz. Each experiment was repeated 3 times.

The first series of experiments focused on a target having a large radar cross section (RCS). Signals scattered from a person holding a metal cylinder were recorded whilst the target was both stationary, and moving towards the transmitter with a walking and running pace. This was repeated with only the person for the second series of experiments. Finally detection of two people walking in opposite directions was attempted. Table 1 summarizes the measurements taken.

In order to perform a theoretical analysis on the transmitted signal using the ambiguity function [10], transmissions were then fed directly into the reference receiver (no propagation through free space) and recorded with identical parameters to those used in the detection experiments.

For the surveillance geometry described in Fig. 1, measured Doppler shifts of the target can be translated into corresponding target velocities using (1) the bistatic Doppler equation [4].

$$f_B = \frac{2v \cdot \cos(\beta/2)\cos(\alpha)}{\lambda} \tag{1}$$

where f_B is the bistatic Doppler shift, v is the target velocity, λ is the wavelength equal to 0.125 meters, β is the bistatic angle and α is the angle between the bistatic bisector and the direction of target motion.

B. Data Processing

The measured data sets were exported to a PC for offline processing in MATLAB®. The recorded signals were processed using the cross ambiguity function to generate Doppler-range cross-correlation plots. Target responses could then be identified from peaks causing an asymmetry in the Doppler sidelobes. The cross ambiguity function is given by (2)

$$|\chi(\tau, f)|^2 = \left| \int_{-\infty}^{\infty} s(t) u^*(t-\tau) \exp(j2\pi f t) dt \right|^2 \tag{2}$$

where *s(t)* is the reference signal and *u(t)* is the echo signal recorded from the surveillance receiver.

III. RESULTS

A. *Ambiguity Funcion Analysis*

Fig. 2 shows the ambiguity function for a recorded 100 ms OFDM, 64 QAM transmission signal. Analysis of the zero Doppler cut shown in Fig. 3 indicates a bistatic range resolution of 14 m, with the peak sidelobe being -19 dB from the mainlobe peak. Similarly, the zero range cut (Fig. 4) suggests a Doppler resolution of 10 Hz with the peak sidelobe being -8 dB below the mainlobe peak.

TABLE I. EXPERIMENTAL MEASUREMENTS. TESTS 1-4 WERE CONTROLS TO DETERMINE SYSTEM NOISE AND CLUTTER RESPONSE OF THE ENVIRONMENT. TESTS 5-12 EXAMINED THE INDOOR DETECTION CAPABILITY OF PASSIVE WIFI RADAR.

Test	Target	Target Pace	Notes
1 [Control]	No Target	-	Noise measurement. No antennas connected.
2 [Control]	No Target	-	Noise measurement. Antennas connected.
3 [Control]	No Target	-	Antennas connected. Idle connection to WLAN.
4 [Control]	No Target	-	Antennas connected. Data transfer across WLAN.
5	Metal Cylinder	Stationary	Personnel target holding a metal cylinder
6	Metal Cylinder	Walking	
7	Metal Cylinder	Running	
8	1 Person	Stationary	
9	1 Person	Walking	
10	1 Person	Running	
12	2 People	Walking	Targets walking in opposite directions

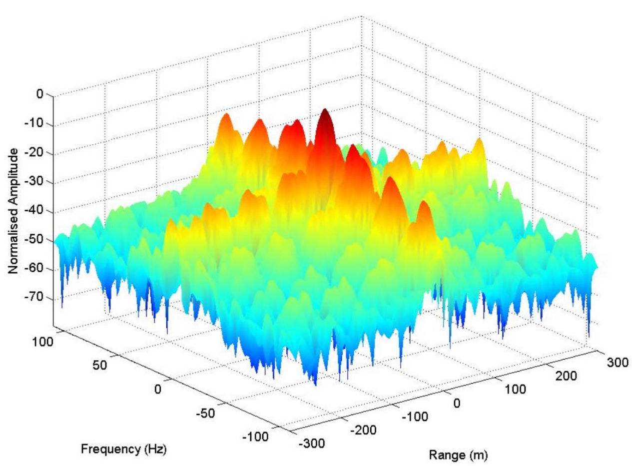

Figure 2. Ambiguity function for an OFDM, 64 QAM, 802.11g transmission signal. The WiFi signal has a maximum data transfer rate of 54 Mbps and was recorded for 100 ms.

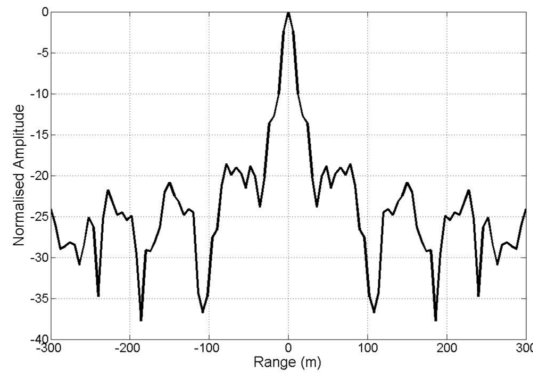

Figure 3. Zero Doppler cut of the ambiguity function shown in Figure 2. The -3 dB point on the mainlobe suggests a bistatic range resolution of 14 m. The peak sidelobe is -19 dB below the mainlobe peak.

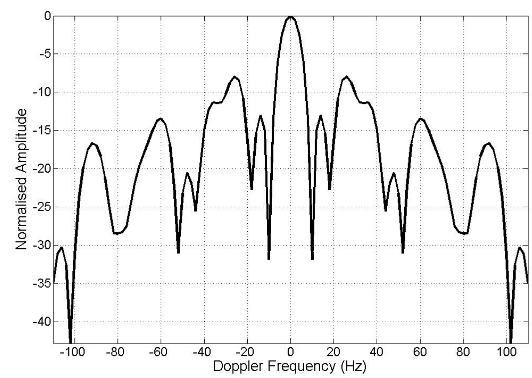

Figure 4. Zero range cut of the ambiguity function shown in Figure 2. The -3 dB point on the mainlobe suggests a Doppler resolution of 10 Hz. The peak sidelobe is -8 dB below the mainlobe peak.

B. *Clutter Response of the Environment*

Fig. 5a shows the Doppler-range plot generated for WiFi transmissions when no target was present (Test 4 in Table 1). The clutter response on the zero Doppler line is masked by a large peak, also at zero Doppler, which results from a good correlation between the DSI and reference signals. Fig. 5b shows the same plot after applying a simple DSI cancellation technique in which the self-ambiguity function of the reference signal is subtracted from the cross ambiguity function result. A peak in the clutter profile of this plot can be more easily identified at 24 ± 6m bistatic range and is circled by the dotted line. Note that for all subsequent plots shown, this DSI cancellation method has been applied. Also note that in all plots, the amplitude scale has been normalised to the peak value.

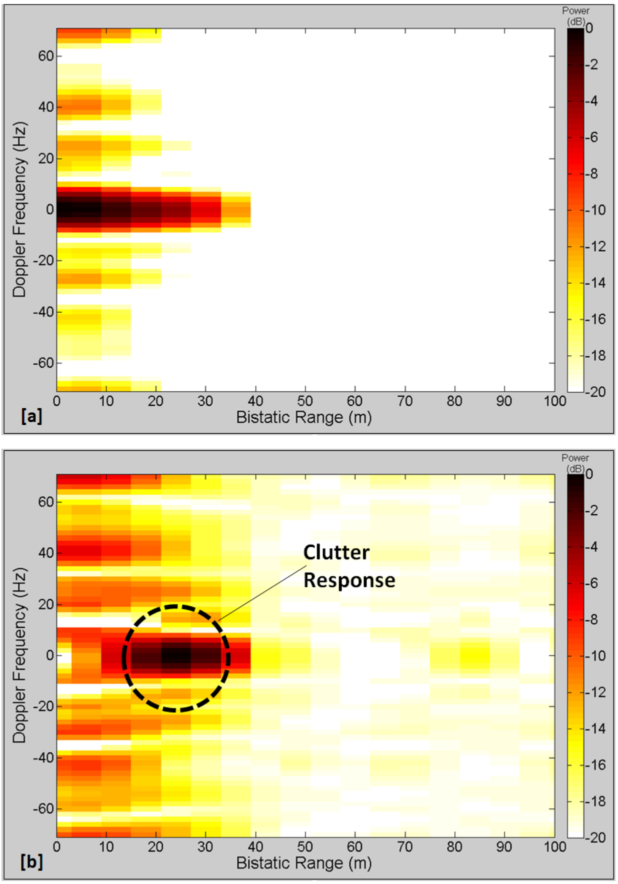

Figure 5. Clutter profiles for the test enviroment when no target was present. The Dopppler-range plot before [a] and after [b] application of a direct signal rejection technique is shown. The rejection method [b] reveals a peak in the clutter response (dotted circle).

C. *Target Detections*

Fig. 6 shows the result for a walking person (Test 9 in Table 1). The response of the target can be distinguished by an asymmetry in the Doppler sidelobes (dotted circle). This peak occurs at a Doppler frequency of 16 ± 2 Hz, corresponding to a target velocity of 1.1 ± 0.1 ms^{-1}. The bistatic range of the target was output as 14 ± 6 m.

Figs. 7a and 7b compare the results obtained for a person running with and without the cylinder respectively (Tests 7 and 10 in Table 1). Again the targets can be identified by the correlation peaks shifted from the zero Doppler line (dotted circles). The target in Fig. 7a has a Doppler frequency of 32 ± 2 Hz (2.3 ± 0.1 ms^{-1}) while the target in 7b shows 38 ± 2 Hz (2.7 ± 0.1 ms^{-1}). Again the bistatic range of both targets are at 14 ± 6 m. As expected the target response for the metal cylinder case (Fig. 7a) was larger than the corresponding test in which no cylinder was used (Fig. 7b) owing to the increased RCS of the target. Additionally, it was observed during the experiments that the target was unable to maintain a full running speed whilst holding the metal cylinder and this is confirmed by the lower Doppler shift in Fig. 7a.

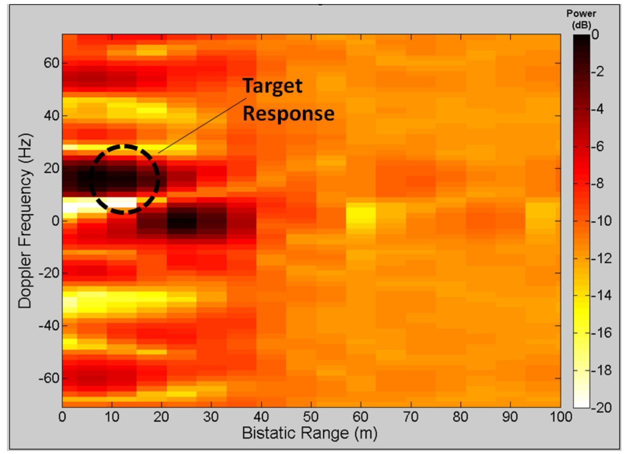

Figure 6. Doppler-range plot for a personnel target walking through the surveillance test area. The target response (dotted circle) is seen at 14 ± 6m bistatic range and 16 ± 2 Hz Doppler frequency.

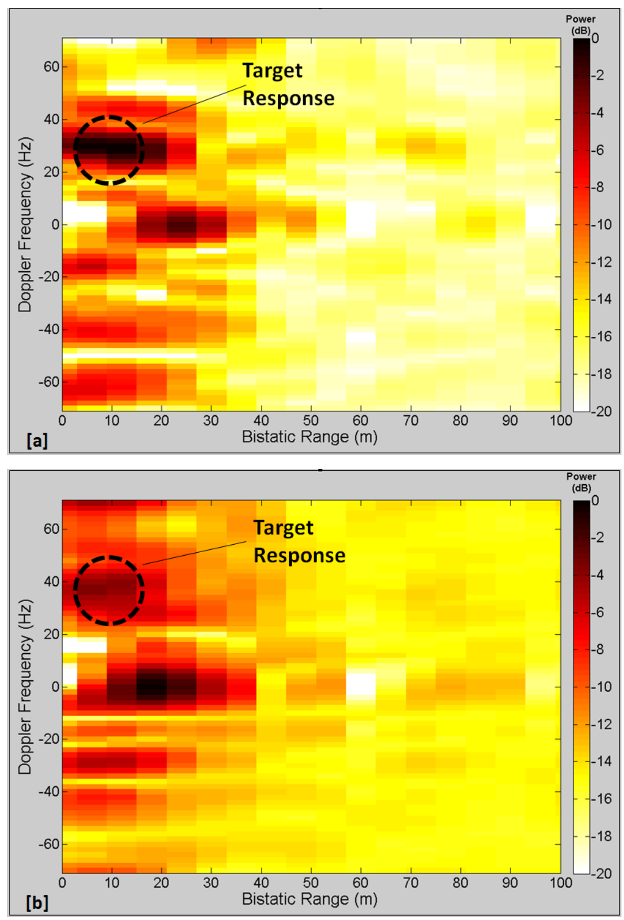

Figure 7. Doppler-range plots for targets moving through the surveillance test area at a running pace. The target in [a] consists of a person holding a metal cylinder whilst in [b]; the same person is without the cylinder. Target responses are seen at [a] 32 and [b] 38 ± 2 Hz (2.3 and 2.7 ± 0.1 ms^{-1} respectively) and at a bistatic range of 14 ± 6 m.

Finally, Fig. 8 illustrates the result for two people walking in opposite directions. Detection of both targets is achieved at +22 and -18 ± 2 Hz (1.6 and -1.3 ± 0.1 ms^{-1} respectively) and 14 ± 6 m bistatic range, however the target responses are somewhat masked by the Doppler sidelobes.

IV. Conclusions & Future Work

The results presented in this paper demonstrate the capability of exploiting 802.11 signals as transmitters of opportunity for detecting targets moving within high clutter indoor environments (Figs. 6 and 7). Additionally, Fig. 8 shows that two targets moving in opposite directions can be detected and distinguished. The bistatic ranges of targets output after processing were found to agree with the true bistatic range (within the specified error) and the measured Doppler shifts were found to correspond with pre-measured walking and running velocities. The clutter response of the environment was also obtained and we hypothesize that the main peak shown in Fig. 5b arises as a result of a strong reflection from the back wall of the building (not shown in Fig. 1). This peak was seen in all subsequent plots.

As predicted from the theoretical analysis (Fig. 2), the results obtained suffered significantly from poor range resolution owing to the limited bandwidth of the waveform. However, the location accuracy of the system could be improved by applying triangulation algorithms on time difference of arrival (TDOA) measurements from multiple transmitters and/or receivers [11]. The Doppler resolution could be improved by simply increasing the integration time. Future experiments will exploit NetRad's full recording capability and give a Doppler resolution of 3 Hz.

The problematic breakthrough signal was minimised in this investigation by steering a null on the surveillance antenna toward the WiFi transmitter. An interference cancellation method, based on subtracting the ambiguity function of the reference signal from the Doppler-range plot, was also implemented to supress the unwanted effects of the DSI. This method was however found not to work effectively for all cases (e.g. Fig. 7) and we postulate that this may be due to its sensitivity to noise. Currently, we are investigating the use of adaptive filtering techniques [12] [13] in the post processing stages as a more efficient approach for removing the interference component.

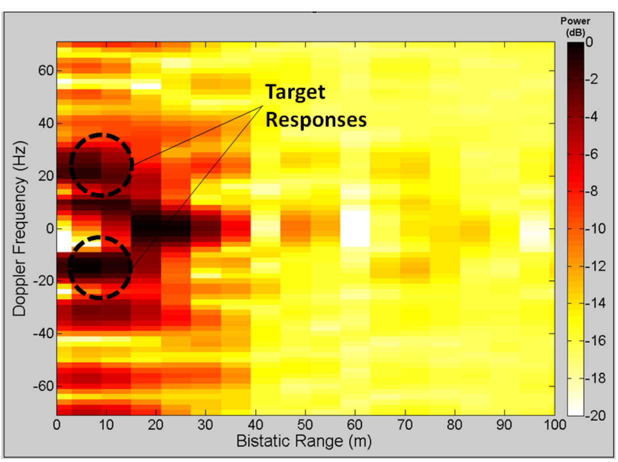

Figure 8. Doppler-range plot for a personnel target walking through the surveillance test area. The target response (dotted circle) is seen at 14 ± 6m bistatic range and 16 ± 2 Hz Doppler frequency.

The surveillance antenna used in the experiments was of high gain and directionality which increased the probability of target detection. Now that detection has been realised, future experiments will concentrate on degrading system parameters i.e. increasing DSI levels, extending the geometry to longer ranges, lowering the antenna gains and RCS of targets etc to quantify the detection limits of a passive WiFi radar system. Additionally, a full ambiguity function analysis of all the modulation-coding permutations in the 802.11 standard is underway to gauge the potential performance of the system under the various WLAN operating conditions.

We have shown the feasibility of a low-cost, WiFi based PBR system for indoor surveillance applications. Future work aims to develop methods for improving system performance, with an overall goal of developing a prototype system that detects and tracks targets in real time.

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