Concept of Multistatic Passive Radar Based on Wireless Packet Communication Systems

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Abstract

In this paper a concept of passive radar system based on packet wireless network illuminators is presented. The network consists of several transmitters/receivers using the same bandwidth, exchanging data packets. The passive radar listens to the communication, and decoding packets determines the source transmitter. The time windows are used to select transmission form single source and window signal is processed using Passive Coherent Localisation methods to localise targets of interest. Paper presents details of the proposed methods, theoretical background, simulations and preliminary measurement results.

Keywords: Passive Radar Systems, WiMAX and WIFI signal decoding, Passive Coherent Location, CLEAN.

1. Introduction

Passive Covert Radars (PCR), known also as Passive Coherent Location (PCL) radars or Passive Bistatic Radars (PBR), were under intensive research in the last decade. They do not radiate electromagnetic energy by themselves, but exploit the transmitters of opportunity. All passive radar exploit bistatic radar concept [1] – emitters are in different position than receivers. The long range passive radars use high power commercial FM [2], TV [4], DVB-T and DAB transmitters [5]. This technology is well developed now. While more and more effort is spent towards short-range sensors working in urban environment, there is a growing interest in passive sensors exploiting low-power emitters. There are several potential candidates: cellular phones base station transmitters using different modulation schemes, WiMax [9] transmitters and WiFi [12] transmitters. WiFi transmitters are nowadays more popular in the urban environment, and they can be used as illuminators both indoors and outdoors. They are using relatively wide band (up to 20 MHz – equivalent to 7.5 m range resolution in monostatic mode) and low transmitting power. The FCC regulations for Point to Multi-Point allows 36 dBm (4 watts) EIRP, so using high gain receiving antennas the theoretical detection range can be up to several kilometres. Most of the commonly used transmitters use much lower power (100-250 mW) with 3-6 dB gain antennas, and expected range of 1 km is adequate in urban environments, however, shadowing limitations are usually more strict then power budget limits.

The main problem using WiFi or WiMax illuminators are that they work using packet mode, shearing common spectrum among many transmitter. The passive radar processing scheme must be adopted to that mode.

The packet systems that are commonly used today are WiFi IEEE 802.11a/b/g/n (CSMA/CA - BPSK, QPSK, OFDM) and WiMAX 802.16 a/d (TDD/FDD - (S)OFDMA). The data contents of transmitted frames can be treated by the passive radar as random noise with some exception. Each data frame has a preamble and apart from data frames, special frames for network management (beacon frames with wireless network identifier – SSID) are sent periodically in time. Inside each frame there is address of a source and destination node. By decoding the frame, it is possible to identify source node that has sent the frame. Having source node address established, it is possible to assign geometrical location of the transmitters, if the geometry of network is known in advance. If the network topology is unknown, the location of transmitters can be estimated using e.g. triangulation, however, this topic is beyond the scope of the paper.

Multipath in urban environment is also a problem that should be taken into account. WiFi was designed as Line of Sight system, therefore signal originating from multipath effect should be much lower in comparison to direct signal collected by PCR. Also PCR system should be equipped with a set of antennas (covering whole area around PCR), which receives direct signal as strongest signal source. Signals from multipath will be also collected, but it is expected that they will be received with much lower power. In the case of PCR based on WiMAX signal (which is non-Line of Sight system) similar solution should solve multipath problem. The multipath effect can be minimised by digital reconstruction of the reference signal.

The goal of the paper is to present the idea of short-range passive radar using stationary WiFi transmitters as the illuminator. At least 3 transmitters are needed to localise targets in 3D space. For each transmitter-receiver pair, target bistatic range and velocity is estimated, and Cartesian position of the target and full velocity vector is constructed in data fusion unit [4, 10, 11]. The passive radar receiver is equipped with the set of directional antennas. Some of them pointing to the transmitters of opportunity, and the rest are used as the surveillance beams. Instead of using directional antennas set, it is possible to use an array of omnidirectional antennas with digital beam forming [6]. It is also possible to use omnidirectional antenna to receive the direct signal in case when direct signal will be digitally reconstructed.

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2. Target detection and localisation

In this paper it is assumed that both localization of wireless network nodes and their physical network address are known. Fig. 1. presents classical passive radar principle, where four transmitters and a single receiver are used. The target position is estimated by finding the intersection of four bistatic ellipsoids, whose parameters are based on bistatic range measurements. In the presented case, all transmitters use the same carrier frequency and are multiplexed in time. Thus, the transmitter separation must be carried out in the time domain. To perform such separation it is necessary to analyse each transmited frame and decode the transmitter physical address. As the result, the binary time window is created for each transmitter, where "1" means, that transmitter is active in that moment.

2.1. Decoding Frames

In WiFi transmission several modes differ with transmission speed and modulation scheme. The most popular are QPSK, DQPSK, OFDM. Each frame consists of a header and the data body. An example of 802.11b standard frames with transmission speeds of 1-2 Mbps is presented in Fig 2.

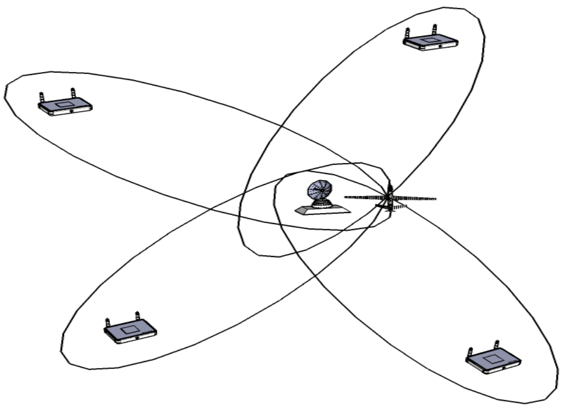

Fig.1 Passive radar system sketch with ellipsoids and their intersection showing target position

Typical frame [13] that is sent in WiFi consists of PPDU (PLCP Protocol Data Unit). In the PLCP frame, the fields consists of 144 bit preamble (Fig. 3) and 48 bit header transmitted with 1Mbps. After PLCP there is MPDU – MAC Protocol data unit, which might be sent with different transmission speed (and in fact modulation and coding). Information about MPDU transmission speed is embedded in PLCP preamble – SIGNAL field (see Fig. 3 and Fig. 4).

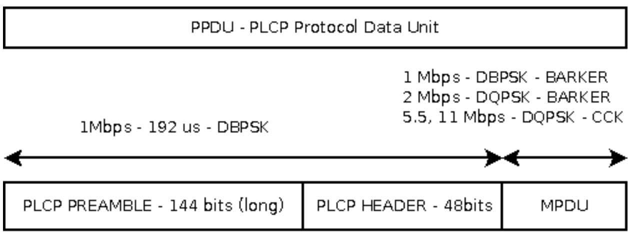

Fig. 2. PPDU WIFI frame structure

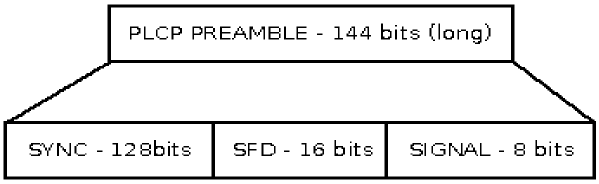

Fig. 3. PLCP Preamble structure

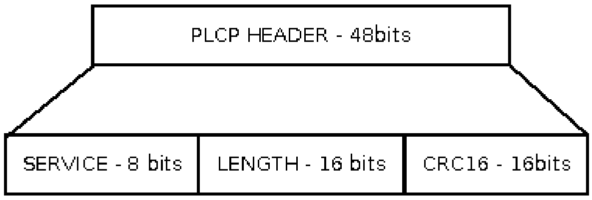

Fig. 4. PLCP Header structure

Information important for MPDU decoding is embedded in LENGTH field in PLCP Header – number of microseconds for which MPDU will last. The most important information for the described passive radar systems is inside MPDU field -address fields – they contain BSSID – Basic Service Set Identifier, Source Address, Destination Address, Transmitting STA (station) address and receiving STA (station) address. Having address values and BSSID, it is possible to determine source of the transmission (signal) out of whole wireless network. After decoding the received signal, passive radar identifies the illumination source and generates the time window for each transmitter. In addition it is also possible to reconstruct the direct signal (received directly from the transmitter) by decoding the signal to the bit level and coding it again. Such reconstruction removes noise and multipath effect from the reference signal and improves the detection and surveillance signal cleaning.

2.3. Range and Doppler estimation

The signal transmitted by *k*-th transmitter (after shifting to the baseband) can be expressed by the formula:

$$X_T^{(k)}(t) = X_T(t) w_i(t) \qquad (1)$$

where $w_i(t)$ is the binary time window and $X_T(t)$ is the original signal. The received signal [13] consists of white thermal noise ξ and a sum of time delayed and frequency shifted copy of the transmitted signal:

$$X_R(t) = \xi(t) + \sum_i A_i X_T^{(k)}\left(t - \frac{r_i(t)}{c}\right) e^{2\pi j F \frac{v_i}{c} t} \qquad (2)$$

where i is the target index, r_i is the *i-th* target bistatic distance v_i is the target bistatic velocity and A_i is the complex amplitude of the returned signal.

The detection in the PCR is based on the calculation of cross-ambiguity function for different bistatic ranges r and velocities v:

$$y(r,v) = \int_0^{t_i} w(t) X_R(t) \cdot X_T^*\left(t - \frac{r}{c}\right) \cdot e^{2\pi j \frac{F_t v_i}{c} t} dt \qquad (3)$$

where t_i is the integration time. In PCR practice, in place of X_T the reference antenna signal multiplied by windowing function $w_i(t)$ is used. The target range and velocity is estimated by finding the maximum of (3). While the ambiguity function is calculated for signals with limited bandwidth and limited time the time sidelobes depends of the shape of the spectrum, while the Doppler velocity sidelobes depends on time window. The mainlobe width in range dimension depends on signal bandwidth and in our case is 7.5 m, while in Doppler dimension depends on carrier frequency and illumination time. For WiFi working in 2.4 GHz band and 0.1 s of integration time, the Doppler resolution is 1.7 m/s. Increasing the integration time to 1 s will improved Doppler resolution to 0.17 m/s, and such resolution will be adequate to resolve walking persons.

For continuous illumination, the time window is selected by the radar designer, and Hamming, Blackman or Kaiser window is frequently used to decrease the Doppler sidelobes below predefined level (usually more than 50 dB). In the presented case, the transmission is divided into packages which is equivalent to applying of binary time window generated by transmitter. Lets analyse the influence of the binary window on the cross-ambiguity function shape. The signal envelope can be modeled as follows:

$$s(t) = \sum_{n=-\infty}^{\infty} a_n g(t - nT) \qquad (4)$$

where a_n is a binary random sequence and $g(t)$ is a rectangular shaping pulse with time duration T. Assuming that the elements a_n are uncorrelated, the power spectral density (PSD) of signal (4) is given by [14]:

$$\Psi_s(\omega) = \frac{\sigma_a^2 |G(\omega)|^2}{T} + \left(\frac{m_a}{T}\right)^2 \sum_{k=-\infty}^{\infty} \left| G\left(\frac{2\pi k}{T}\right)\right|^2 \delta\left(\omega - \frac{2\pi k}{T}\right) \qquad (5)$$

In the formula above, $G(\omega)$ denotes the Fourier transform of $g(t)$ and $m_a = E[a_n]$, $\sigma_a^2 = D^2[a_n]$ are the mean value and the variance of symbol a_n. It is seen from (5) that the PSD consists of two parts, continuous (first term in (5)) and discrete (second term in (5)). The continuous part depends on energy spectrum of the shape pulse and the variance of sequence a_n. The discrete part, in turn, depends on the mean value of a_n and consists of the pulse train at certain frequencies. The strength of each spectral line is determined by the magnitude of the energy spectrum of the shaping pulse at certain frequency. Assuming that a_n has the following probability distribution : 1 with probability p and 0 with 1-p we obtain, $m_a = p$ and $\sigma_a^2 = p(1-p)$. While $g(t)$ is a standard rectangular pulse, $|G(\omega)| = |T\sin(\omega T/2)/(\omega T/2)|$ and $G(2\pi k/T) = 0$, for $k \neq 0$. Thus, the PSD (5) for this case has the following form:

$$\Psi_s(\omega) = \frac{\sigma_a^2 |G(\omega)|^2}{T} + \left(\frac{m_a}{T}\right)^2 |G(0)|^2 = p(1-p)T\left|\frac{\sin\frac{\omega T}{2}}{\frac{\omega T}{2}}\right|^2 + p^2 T\delta(\omega) \qquad (6)$$

The comparison between the velocity spectrum obtained directly from (6) and simulated spectrum presented in Fig. 5 shows good agreement between theory and practice.

Because the Doppler sidelobes are rather significant, there is the need to remove the sidelobes originating from strong targets to be able to detect the week ones. One method to overcome this problem is to use CLEAN technique [7]. After removal of the ground clutter e.g. using adaptive filtering [8] the cross-ambiguity function (3) is calculated. Then the highest peak is detected and bistatic range and velocity are estimated.

Having estimated the target echo parameters, the signal is estimated according to (2) with zero thermal noise level. Then the estimated signal is subtracted from the received one. The amplitude A_i is chosen to minimise the power of resulting signal. Then the cross-ambiguity function is calculated again and weaker targets are detected. The procedure is repeated until the last target is detected and removed.

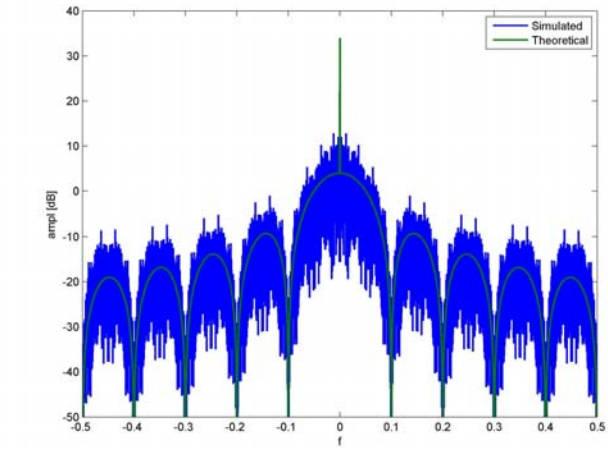

Fig. 5. Theoretical and simulated velocity spectrum

4. Simulation and measurement results

To verify the proposed method a series of Monte-Carlo simulations was performed. The transmitted signal was modelled by white noise and time window was generated taking the mean pulse width as 0.1 ms and mean time between pulses 2 ms. The simulations have shown, that it is possible to detect moving targets using proposed methods.

Fig. 6. The receiving antenna and the scene observed by passive radar

The theoretically developed method has also been validated using real-life signals. A high-gain receiving antenna presented in Fig. 6 was connected to the double channel vector signal analyser. The second input of the analyser was connected to the splitter, directing part of the illumination power to the analyser. The area under test, also presented in Fig. 6, consists of several buildings and the road.

The cross-ambiguity function between reference and measured signal is presented in Fig. 8. The direct signal (shifted from zero by the effective length of the cable) and the echoes from buildings are clearly visible. Also the Doppler sidelobes are clearly visible.

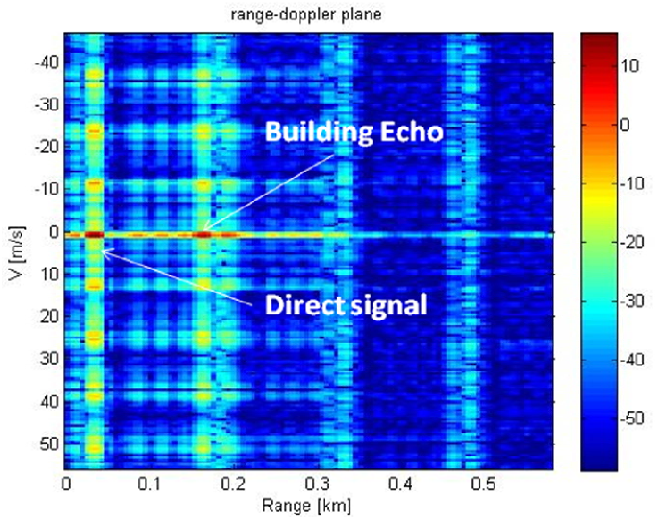

Fig. 7. Range-Doppler processing results (without CLEAN processing), colour scale in dB

The dynamic range of the passive radar system using cross-ambiguity function for target detection is limited by time-bandwidth product. In presented case the effective integration time is the sum of length of non-zero window elements. To increase the dynamic range, CLEAN methods are used [8]. The application of the CLEAN algorithms removed the direct signal and buildings echoes almost completely. The result of the processing is presented in Fig. 8.

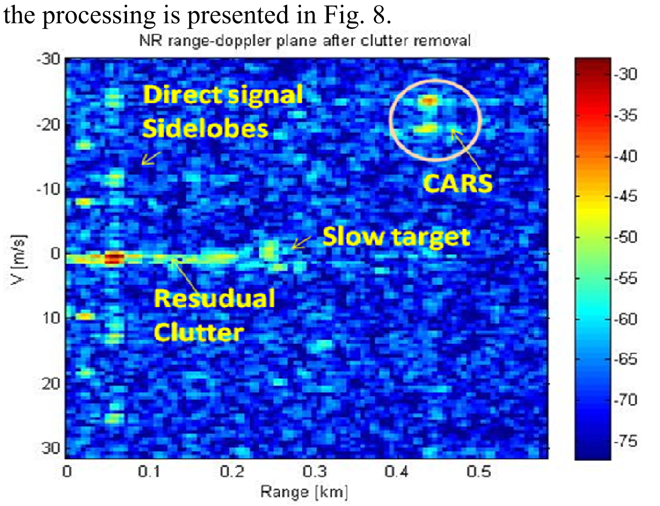

Fig. 8. Range-Doppler processing results (after CLEAN processing), colour scale in dB

The direct signal was cancelled by 40 dB, but the residual of the direct signal and residual clutter is visible. The processing floor was suppressed by 25 dB and moving objects are now visible.

9. Conclusions

The paper presents the concept of Passive Covert Radar using WiFi Network as the net of illuminators of opportunity. The presented theoretical analysis highlights the problem of the velocity sidelobes caused by the packet nature of the transmission and proposed the use of CLEAN processing for problem mitigation. The paper proposed also the method for target localisation. The problem of very high required computational power can be solved using dedicated hardware, such as net of GPUs.

Acknowledgements

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