SIGNAL PROCESSING CONSIDERATIONS FOR PASSIVE RADAR WITH A SINGLE RECEIVER

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ABSTRACT

Processing of passive radar signals is hindered by the presence of clutter and sensor noise in the reference signal, and by strong direct and zero–Doppler clutter returns in the surveillance signal. Previous research has addressed methods of removing or mitigating unwanted components in either signal. However what is considered as interference in one signal may be considered as information in the other. In this study we investigate under what conditions both surveillance and reference information may be extracted from a single signal, thus enabling passive radar processing with a single receiver.

***Index Terms*—** passive radar, signal processing

1. INTRODUCTION

Passive radar is characterised by the absence of a dedicated transmitter. An emitter of opportunity, such as a radio or television transmitter, is used instead. Advantages of passive radar include low cost due to no transmitter hardware, the ability to operate covertly, and the ability to use portions of the RF spectrum not otherwise available to radar.

In order to do radar processing it is necessary to have knowledge of the transmitted signal. In passive radar a reference signal is formed by steering an antenna at the signal source and sampling the direct line–of–sight (LOS) signal. This is disadvantageous compared with active radar since a reference signal obtained in this manner will suffer from sensor noise and returns from clutter. Some improvement can be obtained by demodulation and remodulation of the reference signal to obtain a pristine copy of what was transmitted [1, 2]. Postprocessing may be required in order to account for phase differences between the transmitted and reconstructed signals [3, 4]. Some mismatch can be introduced to the remodulated signal in order to shape the delay–Doppler output, for example one could weight the pilot carriers in a DVB–T signal to suppress ambiguities [5, 6]

Illuminators of opportunity are often communications transmitters which operate continuously. As a result the surveillance signal is typically contaminated by a strong direct–path component and returns from clutter. These returns mostly have zero Doppler and thus do not eclipse moving targets. However the strength of these returns is typically much larger than returns from targets and their contribution to the ambiguity floor can completely obscure target returns. One way to handle this is to cancel clutter returns from the surveillance signal [7, 8, 9]. Another option available if the signal is a form of OFDM involves exploitation of the orthogonality of individual carriers to nullify the floor resulting from zero–Doppler clutter [10, 11].

Ideally the reference signal would contain only the LOS component (*i.e.* what was transmitted) and the surveillance signal would contain only returns from targets. In practice the requisite components are all present in both the reference and surveillance signals at varying levels of power. We hypothesise that it might be possible to extract the necessary components from one or other of these signals, or more generally from a single omnidirectional receiver, and adequately perform delay–Doppler processing. Single–receiver processing has been considered with ATSC signals [12]; in this study we consider specifically OFDM signals.

In the sequel we consider the signal processing which is necessary for passive radar and examine how this would be affected when working with a single generic OFDM signal. We suggest conditions which must be fulfilled for single–receiver passive radar to be successful. We present some examples of delay–Doppler processing performed with a single receiver.

2. SIGNAL PROCESSING

The production of delay–Doppler maps in passive radar typically requires preprocessing of both the reference and surveillance signals, and computation of their cross–ambiguity surface. We consider how each of these stages would be performed when working with a single receiver.

2.1. Reference Signal Preprocessing

In standard two–receiver passive radar it is common to demodulate and reconstruct the reference signal in order to provide a pristine template signal for delay–Doppler processing. In this case it is desirable to have a direct–path Signal to Interference & Noise Ratio (SINR) as high as possible.

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However when working with a single receiver it is desirable that returns from targets be as large as possible. Maximising both direct SINR and target SINR is mutually exclusive; one is improved only at the expense of the other. In the single receiver case it is therefore desirable that the direct signal SINR be as *low* as possible while still being sufficiently powerful to demodulate. One might naïvely determine at what SINR a Symbol Error Rate (SER) of 0 is expected, but such a measure ignores the requirements of passive radar.

Assume that a received signal $r[n]$ has three components: direct path x, interference component y, and sensor noise z.

$$r[n] = x[n] + y[n] + z[n]$$

The direct path component x is an OFDM symbol having unit amplitude and no delay, and takes the form of an inverse Discrete Fourier Transform (DFT) of K data symbols c_k:

$$x[n] = \frac{1}{N_u} \sum_{k=0}^{K-1} c_k e^{i \frac{2\pi}{N_u} kn}$$

The power in any bin of an N_u–point DFT is thus dependent on the magnitude of the constellation symbol which was transmitted on the corresponding carrier:

$$|X[k]|^2 = |c_k|^2$$

The interference component contains returns from clutter and targets and is a superposition of delayed, Doppler–shifted and weighted copies of the direct component:

$$y[n] = \sum_{\ell=1}^{L} \frac{1}{N_u} A_\ell e^{i \frac{2\pi}{N_u} \nu_\ell n} x[n - d_\ell] \tag{1}$$

where A_ℓ is the amplitude of the ℓth component, $A_\ell \ll 1$, and d_ℓ is its delay in samples; we assume this does not exceed the OFDM guard interval for simplicity. ν_ℓ is normalised Doppler shift. The total power of clutter contributions in any bin is a function of the data transmitted on that carrier:

$$|Y[k]|^2 \le |c_k|^2 \sum_{\ell=1}^{L} A_\ell^2 \tag{2}$$

with equality occurring when all Doppler shifts are zero. We expect most interference to be zero–Doppler, so eq.(2) may be taken as an approximate equality.

Sensor noise is assumed to be complex Gaussian of power σ_n^2. The power of this component in the kth DFT bin is

$$E\left\{|Z[k]|^2\right\} = N_u \sigma_n^2 \tag{3}$$

We remark that since interference power depends upon the magnitude of the underlying data symbols, one can expect demodulation errors to be more likely at the extreme elements of the constellation. To illustrate this a random 64–QAM OFDM signal was generated and corrupted by adding in a number of delayed returns having a total power of -24 dB with respect to the main component. This was Fourier transformed and the values obtained from the DFT bins plotted in the complex plane in fig. 1 *(left)*. Conversely the presence of Gaussian noise affects all carriers equally. Demodulation errors are equally likely at central and extreme constellation points. This is evident from inspection of fig. 1 *(right)*, in which are plotted bin values from the DFT of a 64–QAM OFDM symbol suffering Gaussian noise of the same power, -24 dB.

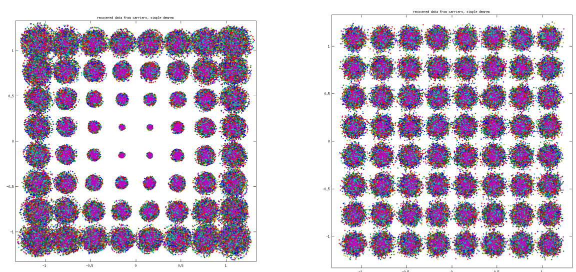

Fig. 1. 64–QAM OFDM in the presence of clutter returns *(left)* and Gaussian noise *(right)*.

Assuming hard demodulation, *i.e.* decoding each datum to the closest constellation point, errors at extreme points will cause only a small phase distortion on the corresponding carrier. Errors close to the centre of the constellation may cause phase errors up to π radians. It is known that phase mismatch on the reference signal causes performance degradation in passive radar output [3, 4]. Thus we expect that errors due to interference will have less effect on passive radar output than errors due to noise. It is therefore necessary to consider interference and noise power separately; a single measure of SINR does not capture the nature of signal power adequately for passive radar. Furthermore a standard communications performance measure like SER is not a sufficient metric for passive radar; we require a measure of how well the eventual reconstructed signal matches the transmitted signal, *e.g.* correlation strength. We expect that passive radar will suffer a graceful performance degradation as interference power increases, unlike recovery of the transmitted message which exhibits a "digital cliff": demodulation is tolerant of interference up to a point where performance collapses.

2.2. Surveillance Signal Preprocessing

Prior to delay–Doppler processing in standard two–receiver passive radar it is necessary to mitigate the direct–path and other zero–Doppler components in the surveillance signal. This clutter is commonly modelled by filtering a template of the transmitted signal (usually the raw reference signal) and subtracting it from the surveillance signal. The optimal filter coefficients for modelling the clutter can be derived from the Wiener–Hopf equations but this is imprecise and computationally cumbersome. Suboptimal numerical and adaptive alternatives exist [8, 9].

The single–receiver case is hampered by the lack of an independent signal for use as a template. The obvious solution is to use a reconstructed reference signal (*i.e.* demodulated and remodulated), but in our experience this yields poor cancellation of zero–Doppler components. Fig. 2 presents a delay–Doppler surface formed after cancellation of DPI from the surveillance signal using an independent reference signal (*i.e* from a dedicated reference channel), and after cancellation with a reconstructed reference. In this example the reference reconstruction has worsened the ambiguity floor by around 10 dB. The reason for this is not known and we anticipate this will be an area of future research. In the meantime we note that we might not perform surveillance preprocessing adequately enough for single receiver passive radar.

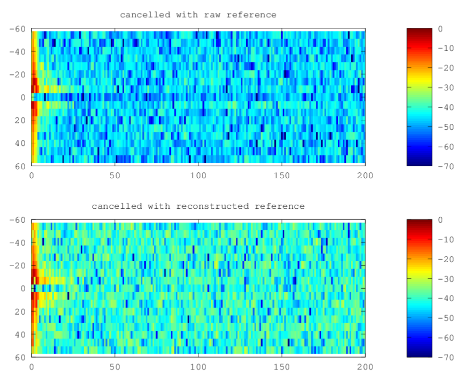

Fig. 2. Two receiver delay–Doppler, DPI cancellation with raw reference *(top)* and reconstructed reference *(bottom)*.

2.3. Ambiguity Processing

Delay–Doppler plots are formed in standard two–receiver passive radar by computing the cross–ambiguity of the reference and surveillance signal. Equivalently, the surveillance signal is processed by a bank of filters, each one matched to the reference signal at a given delay and Doppler shift. The discrete–time cross–ambiguity function can be written:

$$\chi_{rs}(d,\nu) = \sum_{n=1}^{N} s[n]r^*[n-d]e^{-i2\pi\nu n T_s} \tag{4}$$

In practice a computationally benign two–stage approximation may be used. First M consecutive equal–length blocks of r and s are cross–correlated:

$$\xi_m[d] = \sum_{n=0}^{N_c-1} r[n+mN]s^*[n+mN+d] \tag{5}$$

Secondly Doppler processing is performed by taking the DFT across the M blocks at each delay point:

$$\Xi[d,v] = \sum_{m=0}^{M-1} \xi_m[d]e^{-i2\pi mv/N} \tag{6}$$

When the underlying signal is OFDM, the orthogonality of the carriers may be exploited in order to improve the delay–Doppler floor [10, 11]. A summary of the method presented in [11] follows.

- Correlation blocks are organised so that the mth block begins at the start of the mth OFDM symbol.
- Correlation length is limited to the useful OFDM symbol length. This removes cross–carrier terms.
- The reference signal is mismatched upon remodulation; each carrier is weighted by the inverse of the square of the power of its datum. This removes dependence of the correlation on the underlying data.

Doppler processing is performed with a DFT as before. This method causes the theoretical ambiguity floor to be zero at all sample points not on the zero–Doppler axis and with delay less than the OFDM guard interval. This region can be extended in delay to the useful OFDM symbol length if circular correlation is used in place of linear.

The upshot for single–receiver processing is that the effect of zero–Doppler components in the signal may be mitigated despite the fact that they cannot be fully cancelled, provided that the underlying signal modulation is OFDM. Single–receiver passive radar is enabled by this method.

3. EXAMPLES

3.1. Simulated Example

A single 8K–mode 64–QAM DVB–T frame (74 ms) was generated from random input data. A simulated return signal was generated from this by adding on 8 target returns of delays between 50 and 500 samples, and Doppler shifts up to 300 Hz. The ratio of total target return power to direct–path power was -47 dB. Complex Gaussian noise of power -28 dB was added. No zero–Doppler clutter was generated.

Computing a standard ambiguity surface with correlation block spacing equal to the full OFDM symbol length (useful portion plus guard interval), the noise floor limit in delay–Doppler surfaces is expected to be about -85 dB with respect to the main return peak. The expected target return peaks range from -65.5 dB to -52.4 dB The floor level due to the direct return is estimated at -62 dB, and thus some targets are not expected to be apparent.

With the specified levels of interference and noise power the transmitted data could be recovered with SER of 0% so a reference signal could be reconstructed without error. A delay–Doppler surface computed as the cross–ambiguity of the reconstructed signal with the received signal is presented in figure 3. The positions of inserted returns in delay and

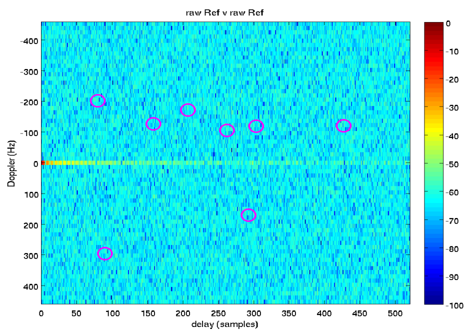

Fig. 3. standard single receiver delay–Doppler output

Doppler are marked with circles. Return peaks range from 9.5 to -8.1 dB relative to the measured floor level. Hence some targets are not detectable and none is obvious to the eye.

The reference signal is now reconstructed, this time mismatching the symbol amplitudes in the manner of [11]. Circular correlation is used in place of linear correlation. The resulting delay–Doppler surface is presented in figure 4. The

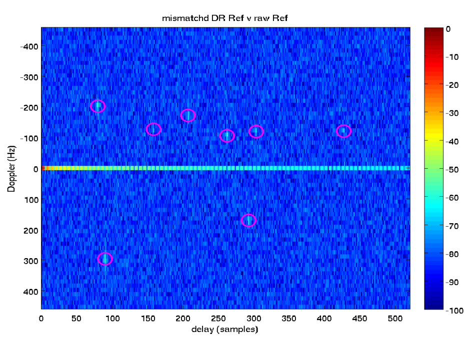

Fig. 4. OFDM–aware single receiver delay–Doppler output

direct–to–floor ratio is measured at 81.2 dB, which is close to the expected noise floor level of 85 dB, demonstrating that floor due to direct path return has been effectively suppressed. The measured return peaks vary from 25.6 dB to 14.6 dB relative to the ambiguity floor, and all are visible to the eye.

3.2. Real Data Example

Some frames of an OFDM–based digital TV signal (DVB–T) were captured. The signal was corrupted by strong returns from an extended target which is obvious in the auto–ambiguity surface of the signal (fig. 5). However the floor in this plot is relatively high, obscuring the full extent of the

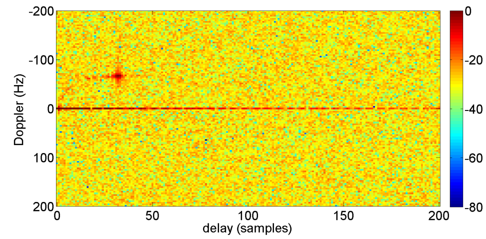

Fig. 5. Single receiver used as Reference and Surveillance, standard delay–Doppler processing

target. A reference signal was reconstructed via demodulation of the captured signal. The cross–ambiguity of this with the original signal was computed with OFDM–aware delay–Doppler processing and presented in fig. 6. The floor has been

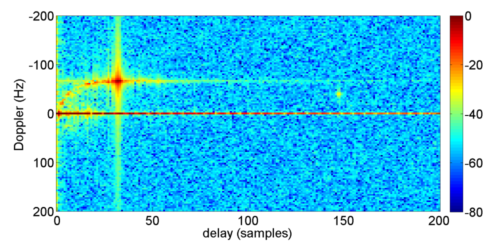

Fig. 6. Reference signal reconstructed from single receiver, OFDM–aware delay–Doppler processing

lowered by 20 dB, allowing better appreciation of the target's extent and uncovering a small secondary target which was not previously visible (delay 150 samples, Doppler -30 Hz).

4. CONCLUSION

This paper has examined the signal processing chain of passive radar and identified a number of issues which arise when delay–Doppler processing is performed with a single receiver. It has been suggested that for successful performance the direct–path component would be as low as possible, while high enough to permit successful reconstruction. A more in–depth study would consider noise and interference power separately and employ a metric pertinent to passive radar. Although adequate zero–Doppler cancellation is not yet achievable, sufficient delay–Doppler processing can still be achieved by exploiting properties of the OFDM signal. Future work will build on the ideas mooted in this study to find conditions under which single–receiver passive radar is feasible.

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