POST CORRELATION VERSUS REAL-TIME ADAPTIVE RFI CANCELLATION

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ABSTRACT

In radio astronomy real-time adaptive filters (and their post-correlation equivalents) can be used to model the RFI environment so that it can be cancelled from the astronomy signal path. In this paper we describe a modified filter which utilises an additional reference signal to improve the RFI excision. The trade-off is that the injected noise of the new filter is stronger than the total residual of the standard filter. We compare residual RFI and injected noise levels with that of the standard filter and the post-correlation approach. An example from the Australia Telescope Compact Array is also given.

INTRODUCTION

In radio astronomy, real-time adaptive filters and a reference antenna, in addition to the main astronomy antenna, have been used to reduce radio frequency interference (RFI) signals in astronomical voltage streams [1,2]. Cancellation in the post-correlation domain can give better suppression of the RFI signal [3]. Many applications require the recovery of the actual symbol stream, which is lost in post-correlation. We have devised a modified approach which gives improved RFI attenuation in the voltage domain. However, because there is an increase in the inserted noise, the residual power (compared with an RFI free situation) is always greater than that of the standard filter. In the following sections the standard adaptive filter is discussed, and the new approach is introduced. This is followed by an overview of how cancellation can be applied after the correlations are formed. Residual RFI power and added noise are investigated, and an example using voltage samples from the Australia Telescope Compact Array is given.

ADAPTIVE FILTERS

Signals containing astronomy will be referred to as the primary or main astronomy signals, and those containing the RFI reference, as reference signals. The IF voltage stream from an antenna contains three components: a noise voltage from the receiving system, \(n(t)\); a noise voltage from the sky, \(s(t)\); and interference, \(i(t)\). The geometric delay, \(\tau\), represents the difference in arrival times at different antennas, taken relative to the reference antenna. A frequency dependent coupling term, \(G\), describes the combined complex-valued gain of the receiver system and antenna, to the interference. Working in the frequency domain offers a more intuitive basis for discussion. Using upper case characters to denote transformed quantities, the signal in spectral channel, \(f\), from primary antenna \(P\) can be written \(V_P(f) = N_P(f) + GP(f)I(f)e^{j\phi(f,t)} + S(f),\) and the signal in spectral channel, \(f\), from the reference antenna can be written \(V_R(f) = N_R(f) + GR(f)I(f),\) where the phase term \(\phi = 2\pi f\tau\). We assume that there is negligible reference antenna gain in the direction of \(S\), i.e. the reference antenna is not measuring signal from the astronomical source. The time is included in the \(G\)-terms to account for the slow variations imposed as the RFI passes through antenna side lobes, and in \(\phi\) to account for motion through the reference-primary delay pattern.
MK1: Single Reference Adaptive Filters

In the frequency domain, the aim of real-time adaptive filters is to find the set of weights, $W$, which scale and phase shift the reference spectrum so that it best approximates the RFI in the main astronomy frequency channels. This model is subtracted from the primary spectrum. This is shown schematically in Fig.1a. Minimum output residual power, $< R_P^2 > = < (V_P - W V_R) (V_P - W V_R)^* >$, can be achieved by setting the cross-correlation between the residual and reference signals to zero, (i.e. $<(V_P - W V_R)V_R^* > = 0$) giving

$$W_{MK1} = < V_P V_R^* > / < V_R V_R^* >$$

(1)

$< ... >$ is the expectation operator, * denotes a complex conjugation, and the explicit frequency dependency of the terms has been removed to compress subsequent equations. It is assumed that the complex gains, delays, and weights are constant over the time integration (a finite approximation of $< ... >$), so they can be taken outside the integration. Since there is always some noise in the reference signal, setting the residual-reference cross-correlation to zero does not remove all of the RFI. There is always a trade-off between the RFI and the system noise. Substituting (1) into the residual signal auto-correlation spectrum, $< R_P^2 >$, gives

$$< R_P R_P^* > = < S^2 > + < N_P^2 > + \left( \frac{G_P/G_R}{1+INR_R} \right)^2 < N_R^2 > + \left( \frac{1}{1+INR_R} \right)^2 G_P^2 < I^2 >,$$

(2)

where the interference power to noise ratio of the reference signal, $INR_R = G_R^2 < I^2 > / < N_R^2 >$. The rightmost term in (2) is the residual RFI power, and the second term from the right is the injected noise power.

MK2: Dual Reference Adaptive Filters

To remove the correlated noise component from the denominator of (1), a second reference signal is added. The RFI in the primary spectrum is still estimated using a weighted version of the first reference, but now the cross-correlation between the second reference and the residual is set to zero (Fig.1b.) We will denote the first reference $X$, $V_X = N_X + G_X I e^{i \phi_X}$, and the second $Y$, $V_Y = N_Y + G_Y I e^{i \phi_Y}$, (since they are often two polarisations from a single antenna). Here the phase terms of the two references, $\phi_X$ and $\phi_Y$, have been included to allow for antennas with different delays. $\phi_p$ will be used to denote the primary signal RFI phase, now relative to an arbitrary reference point. Setting the residual-reference cross-correlation to zero (i.e. $<(V_P - W V_X)V_Y^* > = 0$) gives

$$W_{MK2} = < V_P V_X^* > / < V_X V_X^* > / < V_Y V_Y^* > / < V_X V_Y^* >$$

(3)

where the interference power to noise ratio of the reference signal, $INR_{XY} = G_{XY}^2 < I^2 > / < N_{XY}^2 >$. The rightmost term in (3) is the residual RFI power, and the second term from the right is the injected noise power.
\[ W_{MK2} = \langle V_P V^*_P \rangle / \langle V_X V^*_X \rangle \] \hspace{1cm} (3)

\( W \) is only constrained by the RFI, since the system noise terms in \( \langle V_X V^*_X \rangle \) are uncorrelated, so infinite RFI attenuation can (theoretically) be expected. To demonstrate this, the output power is calculated as,

\[ < (V_P - W_{MK2} V_X)(V_P - W_{MK2} V_X)^* >= S^2 + < N_P^2 > + \{ G^2_P / G^2_X \} < N_X^2 >. \] \hspace{1cm} (4)

Infinite RFI attenuation has been achieved, but there is still added noise. If one residual spectrum was filtered using reference \( X \), and another using reference \( Y \), then the injected noise in the two would be independent and so should average to zero when the spectra are cross-correlated. Note that the increased power over the RFI free situation is always greater than or equal to that of the MK1 filter, given in (2).

### Post-Correlation Adaptive Filters

Using (3), it can be shown that if the complex antenna gains and the geometric delay terms are constant over the time averages, then the RFI can be cancelled from the power spectra [3,4,5]. The modelled RFI power in \( < V_P V^*_P \rangle \) is given by \( M_P = < V_P V^*_P > + \{ G^2_P / G^2_X \} < N_X^2 >. \) Since the cancellation is only applied once per integration, this technique is generally less computationally intensive than the real-time filters. However, as mentioned earlier, information (other than the basic statistics) stored in the raw voltages is lost. Also, if the RFI environment is changing rapidly, the correlation times needed to generate \( M_P \) may become too short.

### RESULTS

Voltage samples recorded at the Australia Telescope Compact Array [6] were used to investigate the processes discussed in the previous section. A dual polarised antenna pointed at a microwave link (MW) transmitter was used for the references, and single polarisations from two astronomy antennas were used as the main astronomy signals. A sine wave was added to the main signals at 1502 MHz to simulate an astronomical source. The peak at 1502.7 MHz is an artifact in the astronomy antenna voltages.

Each of the cancellation techniques discussed were applied to the MW data. The filtered and un-filtered cross-correlation spectra of the main astronomy signals are displayed in Fig.2. Fig.2a is a plot of the un-filtered (black line), MK1 (blue line), MK2 (magenta line), and post-correlation (red line) residuals respectively. As stated in the previous section, the MK2 residual power is greater than the MK1 residual power. To emphasise the fact that there is still RFI present in the MK1 spectrum, but not the MK2 spectrum, one of the main signals has been filtered with reference \( X \), and the other with reference \( Y \). Only residual RFI should correlate. This is shown in Fig.2b. The MK2 residual power averages out with the post-correlation residual power, however the correlated RFI remains after MK1 filtering. This is particularly obvious in the parts of the spectrum where the interference to noise ratio is small, which is expected from (2). When the interference to noise ratio is large (at the centre of the MW peak), the MK1 RFI residual becomes very small. The output is dominated by injected noise (which is less than the MK2 noise). Both the MK2 and post-correlation filters required extra processing so that they "turned off" in parts of spectrum where there was no RFI [5].

The fact that there is complete cancellation of the RFI for the MK2 filter is important. In radio astronomy, it is only relevant if the injected noise is removed, (e.g. by swapping the references around). Otherwise we end up with more residual power in the spectra than we would using the MK1 approach. In other applications, however, one may need to correlated a template against a voltage stream so that a symbol stream can be recovered. While unwanted signals after MK1 filtering may still correlate with the template, the MK2 noise will not.
SUMMARY

It has been shown that a real-time pre-correlation adaptive filter which utilises two reference signals can completely excise RFI from a contaminated signal. However, the noise power injected by the MK2 technique is always greater than or equal to the total residual power from the MK1 technique. Since there is no correlated RFI remaining in the MK2 residual voltage, the MK2 algorithm could aid the extraction of a symbol stream in the presence of RFI. For radio astronomy, it is likely that two residual streams are needed in order to cancel the injected noise.

Throughout this paper we have assumed that the sampled voltages have been quantized with an infinite number of bits. This is never the case with digital sampling. In radio astronomy many systems use a small number of bits (e.g. three or four levels). Due to space limitations, quantization effects have been omitted. Briefly, since the post-correlation approach operates on the statistics of the voltages, it has a major advantage over the pre-correlation approaches. The MK1 and MK2 filters suffer because they are working on the quantized quantities themselves. The amount of residual power increases for the pre-correlation algorithms as the interference to noise ratio of the reference signal becomes large relative to that of the main astronomy signal.

REFERENCES