Design and Implementation of an RFI Direction Finding System for SKA Applications

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1 Introduction

1.1 User Requirements

1. A system to perform direction finding of both impulsive and continuous wave (CW) RFI sources is to be designed.
2. They key deliverables of this project are a software package and a thesis report.
3. The software package should have the following functions:
   a) It should take in input from a correlator. This could either be time domain cross correlation for impulsive sources or frequency domain cross correlation for continuous sources.
   b) It should parse a configuration file which contains information about the array configuration and information about the output from the correlator.
   c) The data from the correlator should be used to ascertain the direction of the detected signals.
   d) The software should be designed to fit into a system which has a 100% probability of intercept.
4. The software should have the following user interface features:
   a) The user should connect to it via a web interface.
   b) A streaming waterfall plot of frequency vs amplitude should be displayed to the user to serve as monitoring of the RFI environment.
   c) The user should be able to select a band of interest from the waterfall plot.
   d) The direction finding should then be computed for the signal in that band.
   e) The result of the DF should be presented to the user. An investigation must be done into the best way to present this information to the user.
   f) Where appropriate, additional meta information should be displayed to the user, such as measurement accuracy or signal strength.
5. The system should be designed to find terrestrial RFI sources.
6. The system should be designed to be location independent. It could either be deployed to a fixed location or as a mobile device deployed on a vehicle.
7. This project should be able to interface easily with other systems requiring its data. Specifically, it should be designed to interface with and pass its data on to an allied project which is doing classification of RFI.
8. The system should be real-time, where real-time is defined as having a latency in the order of a few seconds from receiving signals to displaying results to the user.

9. The hardware and software used should be in line with what is used at MeerKAT. This implies the ROACH platform for hardware, Python for back end software and JavaScript for front end software.

10. This system must operate in the context of the MeerKAT site, implying the following:
    a) In general, the RF environment is sparse. While there will be multiple simultaneous transmitters, it can be assumed there will only be one transmitter in a channel and one source of transients at a given time.
    b) The sources of the emissions will be relatively slow moving, up to the maximum speed of a vehicle on a dirt road; 60 km/h.

11. Once the software has been completed, its performance on real life data should be quantified in the following way:
    a) A prototype-stage 4-element antenna array should be connected to a 400 MHz baseband digitiser and correlator.
    b) The correlator need not be real time for the demonstration.
    c) As the goal of this project is not to develop a hardware system, there is no specific requirement on receiver sensitivity or noise figure. Whatever the best available hardware is should be used for the antennas, front end and digitiser.
    d) The performance of the hardware used should be analysed.

12. Mitigation of the effects of performance degradation due to multipath is outside of the scope of this work.

13. The report produced should contain a theoretical analysis of the performance of the system, as well as an analysis of the performance of the prototype on site with real signals.

2 Review of Current Direction Finding Systems

2.1 Introduction

The purpose of this chapter is to provide a discussiong into current strategies and implementations of direction finding systems. An analysis of the advantages and disadvantages of the various systems will take place which will aid in the later descision of which strategy to adopt for this project

2.2 Signals

As discussed by [1]:

We are interested in extracting the parameters of a signal. This is what sensor array signal processing does.

We model the E-field of a narrow-band signal by:

$$E(\vec{r},t) = s(t)\exp\left\{j(\omega t - \vec{r}^{\intercal}\vec{k})\right\} \tag{2.2.1}$$

Where:

- $s(t)$ is the slow (compared to the carrier) modulating signal with bandwidth B
- ω is the carrier frequency
- $\vec{r}$ is the radius vector, of form $\left[x, y, z,\right]$.
- $\vec{k} = \alpha\omega$ which is the wave-vector where $\alpha = \frac{1}{c}$ pointing in the direction of propagation. Note that the magnitude of the wave-vector is known as the wave-number: $|\vec{k}| = k = \frac{\omega}{c} = \frac{2\pi}{\lambda}$. This implies: $\vec{k} = k(\cos\theta \sin\theta)^{\intercal}$ where θ is the angle of the incident wave.

If we have a receiver with a radius vector $\vec{r_r} = \left[x_r, y_r\right]^{\intercal}$

Note that as per the narrowband assumption is is assumed that the array aperture be much less than the inverse relative bandwidth (f/B)

It is shown that the output of an L-element array a L-dimensional vector of the steering vector scalar multiplied by the incident signal, given by

$$\vec{x}(t) = \vec{a}(\theta).s(t) \tag{2.2.2}$$

Here, $\vec{a}(\theta) = \left[a_1(\theta), a_2(\theta), ..., a_L(\theta)\right]^{\intercal}$ which is the steering vector.

Furthermore, it is shown that the principle of superposition applies. If there are M incident signals they are simply summed together:

$$\vec{x}(t) = \sum_{m=1}^{M} \vec{a}(\theta_m)\vec{s_m}(t) \tag{2.2.3}$$

This can be re-written in a more compact form (now adding noise to the model):

$$\vec{x}(t) = \mathbf{A}(\vec{\theta})\vec{s}(t) + \vec{n}(t) \tag{2.2.4}$$

Where:

- we have re-written $\sum_{m=1}^{M} \vec{a}(\theta_m)$ as a matrix of steering vectors

$$\mathbf{A}(\vec{\theta}) = \left[\vec{a}(\theta_1), \vec{a}(\theta_2), ..., \vec{a}(\theta_M)\right] \tag{2.2.5}$$

- we have re-written $\sum_{m=1}^{M} s_m(t)$ as a vector:

$$\vec{s}(t) = \begin{bmatrix} s_t(t) \\ .. \\ s_M(t) \end{bmatrix} \tag{2.2.6}$$

2.3 Overview of Direction Finding

2.3.1 Model

The model which will be discussed here is that presented in [2].

Let there be N individual signal sources, where $\vec{s}(t)$ represents the resultant signal, being

$$\vec{s}(t) = \begin{bmatrix} s_1(t) & s_2(t) & s_3(t) & ... & s_N(t) \end{bmatrix} \tag{2.3.1}$$

Now let there be an array of M antenna elements receiving the signals, where the position of of the ith element is $\vec{x}_i = \begin{bmatrix} x_i & y_i & z_i \end{bmatrix}^{\mathsf{T}}$. The signal received by this ith element is influenced by the element position. This can be represented as $\vec{s}_i(t, \vec{x}_i)$, showing that the signal at an element is a function of the position of the element. As discussed by [1], as this model contains both spacial and temporal information, it is sufficient to be able to attain spacial information about the signal.

It is shown that the delay time for a signal arriving at the mth element is

$$\tau_m(\vec{\theta}) = \tau_m(\begin{bmatrix} \phi \\ \theta \end{bmatrix}) = \frac{1}{c}[x_m \cos(\phi)\cos(\theta) + y_m \sin(\phi)\cos(\theta) + z_m \sin(\theta)] \tag{2.3.2}$$

Where ϕ is the azimuth angle of the source and θ is the elevation angle. For a 2D space we let $\theta = 0$ and hence simplify to:

$$\tau_m(\phi) = \frac{1}{c}[x_m \cos(\phi) + y_m \sin(\phi)] \tag{2.3.3}$$

The $M \times 1$ steering matrix is

$$\vec{a}_k(\vec{\theta}_k) = \begin{bmatrix} e^{-j\omega_c \tau_1(\phi_k)} \\ e^{-j\omega_c \tau_2(\phi_k)} \\ ... \\ e^{-j\omega_c \tau_M(\phi_k)} \end{bmatrix} \tag{2.3.4}$$

2.4 Antenna Array Fundamentals

Here should be a discussion about how why arrays are necessary for DF. Then a discussion about some of the characteristics of an array.

2.4.1 Array Manifold

As discussed by [3] [4] [5].

The antenna array manifold is said to be useful for direction finding systems, as signal subspace techniques such as MuSIC rely on searching for the best $\vec{a}(p)$ for the detected signal [4].

It is shown by [5] that the output of an array of N sensors receiving M signals in the presence of noise is

$$\vec{x}(t) = \mathbf{A}(\vec{p})\vec{m}(t) + \vec{n}(t) \tag{2.4.1}$$

Where $\vec{x}(t)$ is the N-dimensional output of the array, $\vec{m}(t)$ is the M-dimensional set of signals received by the array, and $\mathbf{A}(\vec{p})$ is a $N \times M$ matrix of source position vectors (SPV). A given SPV, $\vec{a}(p_i)$, shows how the array responds to a source at location p_i, where p_i is often an azimuth and elevation pair: $p_i = (\theta_i, \phi_i)$.

For the case of a terrestrial-only system (which this project will be concerned with), ϕ can be set to 0, meaning that $p_i = \theta_i$, the azimuth angle of source i, typically in the range $[0, 2\pi]$. Here, a SPV can be simplified to $\vec{a}(\theta_i)$.

It is shown that if the N antennas are positioned symmetrically, the antenna array manifold is reduced from complex space $\mathbf{C}^N$ to real space $\mathbf{R}^N$ [5].

The response of the array to a source from a certain location, (θ, ϕ) is:

$$\vec{a}(\theta, \phi) = \vec{g}(\theta, \phi) \odot \exp\left\{-j\mathbf{X}^\intercal \vec{k}(\theta, \phi)\right\} \tag{2.4.2}$$

[5].

Where:

- $\vec{g}(\theta, \phi)$ is a N-dimensional vector of complex number being the gain and phase response of each element in the direction (θ, ϕ).
- $\mathbf{X}^\intercal$ is a $(N \times 3)$ matrix containing the x, y and z coordinates of each of the N elements of the form $\left[\vec{x}, \vec{y}, \vec{z}\right]^\intercal$
- $\vec{k}(\theta, \phi)$ is the wavenumber vector given by $\vec{k}(\theta, \phi) = \pi\left[\cos\theta\cos\phi, \sin\theta\cos\phi, \sin\phi\right]^\intercal$. Graphically, this equates to the

For the purposes of this research the elements will all be located at the same elevation as we only with to locate terrestrial signals. Hence, this may be simplified to:

$$\vec{a}(\theta) = \vec{g}(\theta) \odot \exp\left\{-j\mathbf{X}^\intercal \vec{k}(\theta)\right\} \tag{2.4.3}$$

Here, $\mathbf{X}^\intercal$ is now a $(N \times 2)$ matrix of the form $\left[\vec{x}, \vec{y}\right]$ and $\vec{k}(\theta) = \pi[\cos(\theta), \sin(\theta)]^\intercal$.

Furthermore, the $\vec{g}$ term may be excluded if we assume omnidirectional elements. Although it is rare to deal with true omnidirectional antennas, for an antenna which is required to receive signals only in the azimuth plane, omnidirectional antennas such as dipoles might very well be used in practice. This hence simplifies to:

$$\vec{a}(\theta) = \exp\left\{-j\mathbf{X}^\intercal \vec{k}(\theta)\right\} \tag{2.4.4}$$

Or, more expressively:

$$\vec{a}(\theta) = \exp\left\{-j\begin{bmatrix} x_1, y_1 \\ x_2, y_2 \\ .., .. \\ x_N, y_N \end{bmatrix}\begin{bmatrix} \cos(\theta) \\ \sin(\theta) \end{bmatrix}\right\} = \exp\left\{-j\begin{bmatrix} x_1\cos(\theta) + y_1\sin(\theta) \\ x_2\cos(\theta) + y_2\sin(\theta)) \\ .., .. \\ x_N\cos(\theta) + y_N\sin(\theta) \end{bmatrix}\right\} \tag{2.4.5}$$

Clearly, this is simply a vector of phase shifts introduced by each element in the array as a function of both the location of the element and the angle of the incident wave relative to some defined zero location and zero direction. It is said by [5] that this array manifold completely characterises the array. That paper goes into additional details on how the manifold may simplified for linear arrays, as well as the special properties which a manifold of a linear array possesses. This will not be discussed here as the array used for this DF system is not likely to be linear.

2.5 Geolocation

Geolocation refers to the process of finding the absolute position of a target, often in terms of a coordinate system like latitude/longitude/elevation. This information is often more useful than only knowing the direction which an emitter lies in. However, it is shown that by having multiple DF stations, the process of triangulation may be used to geolocate a device from direction bearings [2].

This process is shown graphically in Figure 2.1, where multiple DF stations (S_1 through to S_M) are used to locate the x,y,z coordinates of the target x_T. Note that this geolocation process in the figure is for airborne DF systems searching for a ground based target. However, the system could easily be simplified to a purely terrestrial process.

The relevance of this note about geolocation to this work is that it is not necessary to attempt to design a system which can do geolocation natively. Rather, a DF system can be design which can later be duplicated in order to provide geolocation capabilities.

2.6 Overview of Direction Finding

In this section, an analysis is made of different the direction finding techniques which exist. The most applicable of these will be examined in more details following. Classical methods of direction finding algorithms [6].

- Beamforming: by introducing the correct phase delay to each channel of the array, the array factor can be made to be such that the signal in quesetion is added coherently by each element of the array. This phase delay indicates the direction of arrival of the signal. The coherent addition of the signals allows for much higher SNR.

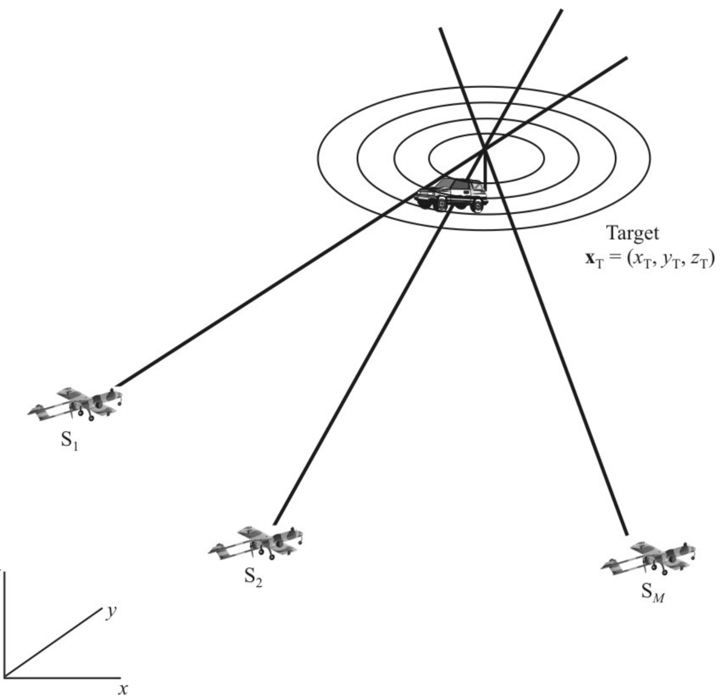

Figure 2.1: Using triangulation from multiple DF stations to ascertain the geographic location of a target. Source: [2]

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