Reconfigurable Antenna based System for Spectrum Monitoring and Radio Direction Finding

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Abstract

A reconfigurable antenna based system for spectrum monitoring and radio direction finding is proposed. The proposed system provides lower complexity and smaller physical size compared to existing direction finding systems based on phase difference of multiple antenna elements or systems based on mechanically rotating antenna. Instead of using multi-element antenna arrays or rotatable directional antenna, we use reconfigurable antenna that has the capability to reconfigure its characteristics to match frequency and minimize polarization loss of incoming signals. The other main feature of the reconfigurable radio direction finder is the use of multiple directional antenna pattern states with multiple pointing directions that cover the azimuthal 360 degrees.

I. Introduction

Spectrum range dedicated for radio communications is scarce. Communications industry worldwide and new wireless services offered in market increased the demand for the RF spectrum. These demands have a major consequences on frequency allocations to meet no electromagnetic interference requirements. Spectrum management is helps to maintain interference free environment. Part of spectrum management process is spectrum monitoring to ensure proper operation of radio communication systems without harmful interference as required by spectrum management activities. Spectrum monitoring has the following the goals: 1) find out any interference on local, regional and global scale; 2) ensuring acceptable quality in operating systems; 3) provides information on actual use of spectrum bands; 4) provide measurement based inputs to programs organized by ITU to eliminate harmful interference. Hence, it is a process of inspection and meeting compliance set my spectrum management authority that enables to identification of accidental or intentional interference sources, verification of proper characteristics in terms of transmission power etc of radiated signals in addition to identification of illegal transmitters. Spectrum planners use reports from spectrum monitoring to understand level of spectrum usage compared to assignments and provides actual information on meeting the set polices [1]. Radio direction finder (RDF) [2] is a part of the monitoring system. It can operate in fixed, mobile and homing modes. RDF is needed to locate and position sources of interferences and illegal transmitters. RDF system has a vast range of applications in military and civilian commercial applications. These include emergency aid, which is usually deployed on civil aircraft, remotely guiding navigation system, locating and tracking interference sources (both accidental and malicious), locating illegal radio frequency transmitters, jammers, etc. It would have applications in search and rescue operations, when RF signals are transmitted. The system can be adopted for ships, small boats and aircrafts to find directions of defined beacon signals.

In this work, we propose a spectrum monitoring and RDF system based on reconfigurable antennas. The main advantage of the proposed system lies in providing lower complexity and smaller physical size compared to existing techniques based on phase difference of multiple antenna elements or systems based on mechanically rotating antenna.

II. Reconfigurable Antennas

Antennas have usually been considered to have a fixed radiation pattern at a specific operating frequency. Reconfigurable antennas [3] have introduced in literature as they have the capabilities to dynamically change their characteristics such as radiation pattern, polarization, and operating frequency. Reconfigurability aspect of antennas can be achieved via different techniques such as altering physical structure of the antenna, altering feeding methods, controlling current density, etc. The design requirement and performance level decides the reconfigurability method. The distribution of current in antenna and its geometry determines how the antenna radiates its energy into the radio channel, or how it captures energy from it. The complex far field radiation pattern of an antenna can be mathematically be expressed as [4]

$$\mathbf{F}(\theta,\phi) = \hat{\mathbf{r}} \times \left[\hat{\mathbf{r}} \times \left[\int_{\mathrm{v}'} \mathbf{J}_{\mathrm{v}'}(\mathbf{r}') e^{-j\beta\hat{\mathbf{r}}\mathbf{r}'} dv \right] \right]$$

where $\mathbf{F}(\theta,\phi) = \left(\mathrm{F}_\theta(\theta,\phi), \mathrm{F}_\phi(\theta,\phi)\right) \in C^{2\times1}$, $\mathbf{J}_{\mathrm{v}'}(\mathbf{r}')$ is the current distribution in the antenna, $\hat{\mathbf{r}}$ is the unit vector in direction of propagation to observation point, $\mathbf{r}'$ is a vector from coordinate system's origin to any point on the antenna. From the above equation, it is clear that by changing the antennas' physical configuration, $\mathbf{r}'$, then the current distribution $\mathbf{J}_{\mathrm{v}'}(\mathbf{r}')$ changes, which is reflected in altering the complex far field radiation pattern $\mathbf{F}(\theta,\phi)$. Hence, controlling distribution of current in antenna $\mathbf{J}_{\mathrm{v}'}(\mathbf{r}')$ leads to controlling the radiation pattern $\mathbf{F}(\theta,\phi)$**.** This current control process can be achieved by using micro-electromechanical system switches (MEMS) or active switches such as field effect transistor (FET) or diodes. The distribution of current in an antenna can be controlled by placing these switches in strategic locations to control current paths to generate a specific antenna characteristics. Implementation of reconfigurable antennas can be accomplished in three different processes; which 1) Design Stage, 2) Simulation Stage, 3) Optimization Stage [5]. Antenna design stage include selection of radiating structure of the antenna and reconfigurable aspects. Selection process is based on several performance parameters such as power consumption, directivity, bandwidth operating frequency, etc, in addition to design constraints such as antenna size, fabrication, cost, etc. These antenna performance parameters have to be fulfilled for every antenna state to make sure that the reconfigurable antenna has to work optimally as expected when it switches from antenna state to other. After selection of antenna structure, it is important to select reconfigurablility function and how it takes place. Antenna reconfigurability can be categorized into 4 different reconfigurability functions; which are 1) Reconfiguring resonance frequency [7], which usually takes place by changing physical planar that alters surface current distribution, 2) Reconfiguring radiation pattern [7,8], which usually takes place by changing radiating edges, slots, or feeding network, 3) Reconfiguring polarization state, which usually takes place via changing surface structure or the feeding network, 4) Combinations of reconfiguring the above listed characteristics, which takes place by using some of the aforementioned different techniques simultaneously. It is very difficult to configure frequency, radiation pattern and polarization independent of each other. Changing one characteristic will change others as a consequence. Therefore, careful design and analysis are important. Due to lack of space, the Simulation Stage and Optimization Stage are not discussed here.

III. Proposed System

The system would have a wideband omni-directional antenna to detect energy in electromagnetic spectrum of interest. The frequency and bandwidth of signal of interest are used as information to configure the resonance frequency of reconfigurable antenna. Then, the system switches to next mode of operation. The core idea in reconfigurable antennas is to control changing current distribution around the antenna, which leads to altering the radiated far field. These changes can be achieved by modifying antenna geometry or its material properties. The switching process between different antenna modes via different activated and deactivated switches distinguishes reconfigurable antennas from phased array antennas. Different antenna patterns with different pointing directions are configured to detect arrived radio energy and weight them differently based on different pointing directions. The other main feature of the reconfigurable radio direction finder is the use of multiple directional antenna pattern states with multiple pointing directions that cover the azimuthal 360 degrees. The re-configurability of pointing direction of antenna patterns may also take place in polar plane to find elevation angle of direction of radio signal. These multiple pointing directions of antenna pattern states have a predefined reference to determine the direction of incoming signal through processing in signal processing unit of the system. Reconfigurable antenna with multiple antenna pattern states and configurability of beam-width of antenna patterns improve the accuracy of the estimated direction that make the system self-dynamic with the environment and direction of arrival. These weighted energy power received from every antenna stated are used with their corresponding pointing direction to estimate direction of arrival of the signal of interest.

The proposed system works on three mode stages. The first mode is to detect spectrum energy and its bandwidth via wideband antenna detection system. The detected signal of interest is defined initially in terms of its frequency range, bandwidth and polarization. This information is fed to the reconfiguring unit of the system, which starts the second stage of mode of operation whereby, the reconfigurable antenna direction finder system dynamically reconfigure the reconfigurable antenna to resonate its operating frequency on the frequency and bandwidth of signal of interest and then reconfigure multiple-antenna patterns for best detection at the polarization state. The directional multiple antenna patterns have different pointing directions relative to a pre-defined reference direction. The signals from different antenna states are processed in a processing unit to estimate the direction of arrival based on their detected signal power and pointing direction of multiple directional antennas pattern states. The third stage of mode of operation is to reconfigure beam-widths [9] of the reconfigurable antennas pointing close to the estimated direction in stage of operation mode. This last stage of re-configurability refines the estimated direction by using estimated signals from refined third stage antenna patterns and their pointing direction. The more the multiple antenna patterns with narrower beam-width, the more accurate the system achieves better estimation the direction of arrival. Block diagram of the proposed system is shown in Figure 1.

The proposed system is based on estimating the direction of arrival of RF signal to the reconfigurable antenna at the receiver. Instead of using multi-element antenna arrays or rotatable directional antenna, we use reconfigurable antenna that has the capability to reconfigure its antenna characteristics, such as radiation pattern, pointing direction, resonance frequency, and polarization to match frequency and minimize polarization loss of incoming signals.

IV. Direction Finding Algorithm

The direction of arrival of signal propagation from a radio source can be defined by two angles; the azimuth and elevation angles. Our approach can be adopted in systems that use reconfigurable antennas that can use multiple antenna patterns sequentially. These antenna patterns are called antenna states. The reconfigurable antenna systems divides the angular range to *N* angular sectors. Each angular sector is centered with a pointing direction of a particular antenna state. The control unit sequentially sends different weights for optimum antenna states, their corresponding radiation patterns scan particular spherical sector. The principal of algorithm operation is shown in Figure 1. The control unit sends ON and OFF commands to switches that correspond to antenna state *k*. It stays there for a while and radio receiver makes received signal strength (RSS) measurements. Then, it sequentially sends other set of ON and OFF commands to the switches that correspond to other antenna state (say *k*+1), and stays there for a short while and make measurements. This process continues until it goes through all antenna states and start the operation again. For illustration as shown in Figure 2, based on direction of incoming signal, the highest signal level will be what is received from antenna state 1 and then, the next level is what is received from antenna state 4. Measurement data from antenna state 2 and 3, will be minimum. Each antenna state interact with electric field of the incoming signal differently due to their different antenna characteristics. The receiver measures the RSS of the incoming signal with every antenna state. The RSS is related to time dependent complex signal, $V_{oc}(t)$, which is given by the voltage induced at the local port of the antenna, which can be formulated as

$$V_{oc}(t) = \int \Im(\Omega) \cdot E_i(\Omega)\, e^{-jk\left(r_i - \mathbf{V}\cdot\Psi_i(\Omega)\right)} d\,\Omega$$

where $E_i(\Omega)$ is the electric field of the plane wave incident of DF antenna from direction of solid angle $\Omega = (\theta, \phi)$, θ is elevation angle, ϕ is azimuthal angle, $\Im(\Omega)$ is the far field amplitude of the antenna pattern, k is the wave number (i.e., $k = \frac{2\pi}{\lambda}$), $\Psi_i(\Omega)$ is for the arrival direction vector defined for incident ray for Cartesian coordinate as follows

$$\mathbf{\Psi_i} = \cos(\phi_i)\sin(\theta_i)\,\vec{x} + \sin(\phi_i)\sin(\theta_i)\,\vec{y} + \cos(\theta_i)\,\vec{z}$$

$\mathbf{V}$ is the velocity (speed and direction) of the RF source terminal, which is assumed as the receiver in this notation, and defined by

$$\mathbf{V} = v_x\vec{x} + v_y\vec{y} + v_z\vec{z}$$

The DF algorithm is based on reconfigurable antenna that can periodically switch pointing directions of its directional antenna pattern ($\Im_n(\Omega)$) of antenna state n that cover section of spherical angular space. There are *N* different antenna states that each have its own pointing direction that can be labeled as $\Im_n^{(\theta_n,\phi_n)}(\Omega)$, where $\Im_n^{(\theta_n,\phi_n)}(\Omega)$ is the far field amplitude of antenna patter of state *n*, whose point direction is (θ_n, ϕ_n). The DF receiver makes several measurements for every antenna state and then switches to the next and so on. Then, it repeats the cycle. The measurement vector of all *N* antenna states can be written as

$$M = [V_1\ V_2\ V_3\ \ldots.V_N\,]'$$

where V_N is the average of measurement time series of amplitude of signal measured with DF receiver while its antenna state is $\Im_n^{(\theta_n,\phi_n)}(\Omega)$. In order to estimate the direction or arrival of signal of interest, the measurement vector

M is processed while considering spherical properties of the data. Spherical properties invokes spherical statics, which is different from linear statistics. Spherical statics is also called directional statistics. Directional statistics [6] are concerned mainly with observations of unit vectors in a plane or three dimensional space to cover circle or sphere spaces, respectively. In this application, we have *N* directional measurements individuals. At a particular time, we have measurement $V_n(t)$ and associated with a unit direction vector that correspond to pointing direction of this particular antenna state *n*. This unit vector can be written as

$$\Upsilon_n = [\cos(\phi_n)\sin(\theta_n) \qquad \sin(\phi_n)\sin(\theta_n) \qquad \cos(\theta_n)\ ]'$$

The measured data that correspond to each antenna state can be combined with the known its pointing direction as follows

$$\chi_n = V_n \Upsilon_n$$

The χ_n vector may be described by direction cosines, which represent its components along the three coordinate axis, x-, y-, and z-axes. The χ_n vector contains the amount of projection of measured amplitude in the three principal axes The components of all $\chi_{1,}\chi_2, \ldots., \chi_z$ on each axis $(\mathrm{X}, \mathrm{Y}, \mathrm{Z})$ in Cartesian coordinates combined together allows us to compute the centroid of measured data along each principal axis. The center of gravity of set of projected measurement data has their mean of the x coordinate, mean of y coordinate, and mean of z coordinates as follows:

$$\mathrm{X}_{DF} = \frac{1}{N}\sum_{n=1}^{N} V_n \cos(\phi_n)\sin(\theta_n)$$

$$\mathrm{Y}_{DF} = \frac{1}{N}\sum_{n=1}^{N} V_n \sin(\phi_n)\sin(\theta_n)$$

$$\mathrm{Z}_{DF} = \frac{1}{N}\sum_{n=1}^{N} V_n \sin(\theta_n)$$

Then, we can estimate both the azimuthal and elevation angles of direction of arrival of signal of interest via the direction of the centroid of the measured data with multiple antenna states of reconfigurable antenna. The elevation angle (Ξ_{DF}) and azimuthal angle (Φ_{DF}) of signal of interest a can be estimated via conversion of Cartesian coordinates to spherical coordinates as follows:

$$\Xi_{DF} = \cos^{-1}\left(\frac{\mathrm{Z}_{DF}}{\sqrt{X_{DF}^2 + Y_{DF}^2 + Z_{DF}^2}}\right)$$

$$\Phi_{DF} = \tan^{-1}\left(\frac{\mathrm{Y}_{DF}}{\mathrm{X}_{DF}}\right)$$

These angles are based on conventional spherical coordinate. The range of elevation angle is from 0 to π and range of azimuth angle is from 0 to 2π. The resultant length that comes out from the three centroids in x, y, z-axis is related to dispersion of the measured data estimate. The mean resultant length (*R*) can be computed from its direction cosines as follows:

$$\overline{R} = \sqrt{X_{DF}^2 + Y_{DF}^2 + Z_{DF}^2}$$

The spherical variance of the estimated directional centroids can be computed with

$$\Lambda_{DF} = 1 - \overline{R}$$

The value of Λ_{DF} is always between zero and one inclusive. In order to increase the accuracy of the DF system, the system can be figured into two levels of DF estimation. In the first level, the Z_1 antennas states have wide beam-width that can determine the direction in coarse fashion, see Figure 2. The second level, the control unit of the reconfigurable antenna DF system send weights that optimize Z_2 antenna states that have narrow beam-widths that allows determining the direction more precisely than in first level antenna states, see Figure 3. The two levels approach takes longer processing time but it DF estimation is higher.

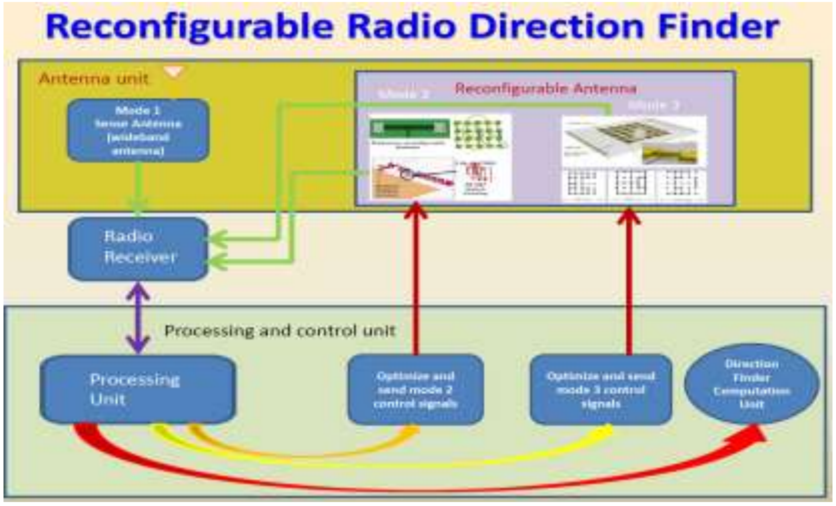

Figure 1. Block diagram of the proposed Reconfigurable Radio Direction Finder System.

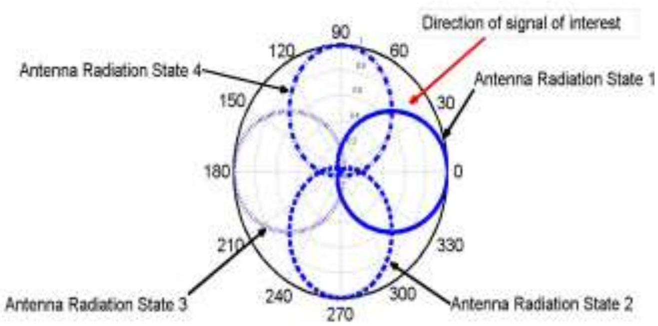

Figure 2. Sample of four antenna states pointing in different direction with a possible direction of incoming signal.

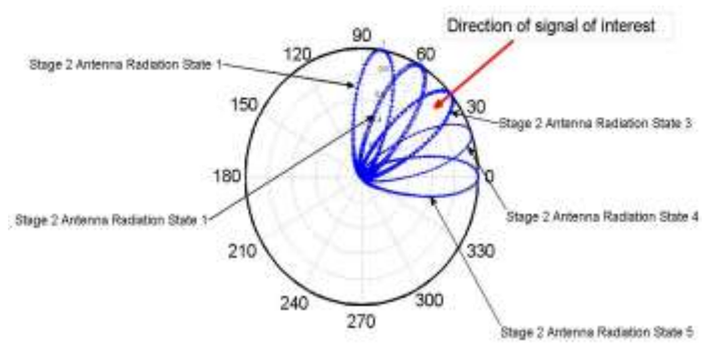

Figure 3. Sample of five narrow beamwdith antenna states pointing in different directions with a possible direction of incoming signal.

Conclusion

This work proposed spectrum monitoring and direction finder system based on reconfigurable antenna. The reconfigurable antenna can be reconfigured to work as wideband antenna for spectrum monitoring. Then, it can be reconfigured to a narrowband antenna to match a particular frequency of interest. The configurability also includes directional radiation pattern states, which each antenna state has a particular pointing direction. The system cycles all antenna states to scan the angular domain and find the RSS for every antenna state. This information is used to estimate the direction of arrival of signal of interest.

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