Developing a Low Cost, Portable Jammer Detection and Localization Device for First Responders

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***Abstract*—A low cost, portable, robust jammer detection, and localization device is proposed and developed in this work. Intentional or unintentional use of jammers is detrimental to the seamless operation of emergency rescue and public safety missions as it disrupts the critical communication devices. The proposed device employs robust parallel detection algorithms based on Kurtosis and FRactional Fourier Transform (FRFT) to detect the most common types of Radio Frequency Interference (RFI) that affects critical communication signals. As part of preliminary performance analysis, the proposed detection technique is compared to the conventional energy detectors (employed in many commercial interference detectors) and shown to achieve significant improvement (~ 40 dB) in probability of detection. The developed device is envisioned to revolutionize the low cost, portable spectrum interference monitoring sector.**

***Index Terms*—Signal detection, fractional Fourier transform, jammer localization, kurtosis, hardware implementation**

I. Introduction and Background

Radio Frequency Interference (RFI) is a subject of growing concern to uninterrupted wireless communication. Wireless communication is a critical component for law enforcement and public safety agencies to ensure swift and timely response to emergencies. Among the several communication technologies used by these agencies are Global Positioning System (GPS), Global navigational Satellite System (GNSS), Land Mobile Radio (LMR), LTE cellular, 802.11ac WiFi etc. These are most commonly affected by RFI which can be fatal amidst emergency rescue missions, 911 or other emergency calls thereby disrupting the harmonious operation of first responders and other emergency services. With the emergence of several cheap portable jammers (RFI sources), there misuse by unauthorized entities has surged at a rapid rate. Although, Federal Communications Commission (FCC) has issued regulatory notice prohibiting the use of such devices, they are misused by truck drivers to prevent employer from tracking, car thieves by blocking the GPS based anti-theft system and so on [1]. Several civilian jammers are pocket sized that can be easily hidden in pockets or bags. Jammers are classified based on their structure and signal into three categories; i) Group-I, ii) Group-II, and iii) Group-III [2]. Group-I jammers require an auxiliary power supply and emits continuous wave narrowband RFI. Jammers with rechargeable battery and external antenna belong to Group-II. These jammer signals are chirp with one or more sawtooth functions. Group-III are jammers with rechargeable battery and without external antenna. They cause chirp RFI with frequency bursts. The first responders need to be alerted or have prior knowledge of possible interferences at a given mission site. This will enable them to choose frequency bands that are known to be less susceptible to RFI and ensure reliable communication through the course of the mission.

Signal detection and classification problem has been studied for decades [3], [4], [5], [6], [7], [8], [9], [10], [11] through theoretical approaches, simulations and few experimental analysis [12], [13], [14], [15], [16]. Developing algorithms on an actual hardware for commercial use is significantly challenging and requires careful consideration of several factors viz. robust performance, computational complexity, ease of use, relevant features of the prototype and meeting size-weight-and cost (SWaC) constraints. Furthermore, most RFI detectors like CTL3520, CTL3510 predominantly depend on conventional energy detector to identify the presence of RFI. CTL3520 and CTL3510 are the commercial outcomes of the UK based SENTINEL project [17]. The SENTINEL system adopts an signal-to-noise-ratio (SNR) and Fast Fourier Transform (FFT) based algorithm to perform RFI detection. There is a lack of comprehensive detection and analysis technique designed, and developed specifically for first responders to tackle intentional chirp signal that sweeps through a wide band and narrow band signal generated by unintentional RFI sources. Most approaches that solely rely on RFI signal energy deteriorate in low SNR scenarios.

In this work, we propose a low cost, portable device that performs robust RFI detection and localization designed specifically for Group-I, II and III jammers. We prototype the envisioned device using Commercial Off-The-Shelf (COTS) components to establish feasibility. The utility of a RFI detector lies in its ability to detect very low power signals with exceptionally low false alarm rates. This requires adoption of a robust parallel detection module consisting of statistical techniques such as Kurtosis and time-frequency technique such as FRactional Fourier Transform (FRFT). To ensure lower complexity while ensuring high probability of detection, we implemented Golden Section Search (GSS) [18] to efficiently converge at the FRFT matched order. Additionally, we are exploring a RFI localization technique based on FRFT to estimate the direction of arrival of the RFI. Proposed detection outperforms the traditional energy detection widely used in commercial RFI detectors, so we envision the final product to be a low cost, light weight device that will enable first responders to operate efficiently in a more spectrum aware

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manner to save lives.

The rest of this article is organized as follows: system architecture is detailed in section II, section III enlists the hardware components and specifications, the results of preliminary over-the-air (OTA) testing is discussed in section IV and concludes with the summary and future work in section V.

II. System Architecture

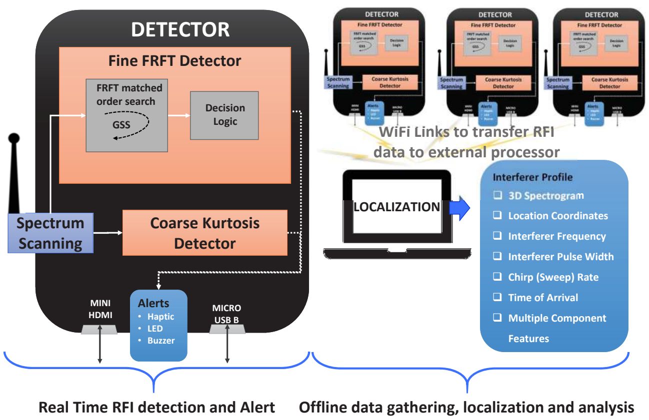

Fig. 1. System Diagram of Proposed Device

The design concept of the jammer detection and localization device (which we refer to as node hereafter) is shown in Fig. 1. Each node consists of two parallel detection paths, (i) Coarse kurtosis based detector and (ii) Fine FRFT based detector. Each individual node also performs a preliminary analysis of the detected RFI and saves this information as a detection report locally. This information is then gathered at a central processing unit with much higher processing power to perform higher accuracy localization using multi-node information.

A. Coarse Detector

The coarse detection module is a kurtosis detector which detects the RFI presence in the spectral samples by considering its fourth and second moments. Kurtosis is computed on the Fourier transform of the received Inphase-Quadrature (IQ) samples as follows,

$$\mathfrak{K} = \frac{\frac{1}{N}\sum_{n=1}^{N}(\mathcal{R}(n) - \bar{\mathcal{R}})^4}{(\frac{1}{N}\sum_{n=1}^{N}(\mathcal{R}(n) - \bar{\mathcal{R}})^2)^2} \tag{1}$$

where N is the number of IQ samples that are processed, $\mathcal{R}(n)$ denotes the absolute value of N-point FFT of the received samples and $\bar{\mathcal{R}}$ is the average FFT magnitude.

B. Fine Detector

Fine Detector performs an FRFT based GSS to process the incoming IQ samples with varying orders of FRFT and detects RFI presence once the matched order corresponding to a peak in the FRFT domain is obtained. To identify the peak efficiently, we compute kurtosis of the absolute value of FRFT. FRFT can give higher energy concentration of chirp signals in the FRFT domain once the transform order matches the chirp rate of the RFI. The GSS [18] in a closed interval searches for the order corresponding to the maximum FRFT value. In contrast to [18], we consider the kurtosis of the FRFT rather than the maximum value. In this context, GSS acts as a peak search algorithm whereby the order corresponding to the largest kurtosis value will be the optimal transform order. The FRFT of the IQ samples are evaluated as per the digital computation proposed by Ozatkas.et.al [19].

$$\mathfrak{F}^a[f(x)] = A_\alpha e^{j\pi\gamma x^2}\int_{-\infty}^{\infty} e^{j2\pi\beta x x'}[e^{j\pi\gamma x'^2} f(x')]dx', \tag{2}$$

where $\alpha = \frac{a\pi}{2}$ is the transform angle, $\gamma = \cot\alpha$, $\beta = \csc\alpha$ and $f(x)$ is the function that is being transformed. The discrete form of the transform requiring $O(N\log N)$ computations is expressed as

$$\mathfrak{F}^a[f(\frac{m}{2\Delta x})] = \frac{A_\alpha}{2\Delta x} e^{j\pi(\gamma-\beta)(m/2\Delta x)^2}. \tag{3}$$
$$\sum_{n=-N}^{N} e^{j\pi\beta((m-n)/2\Delta x)^2} e^{j\pi(\gamma-\beta)(n/2\Delta x)^2} f(\frac{n}{2\Delta x}),$$

This expression can be realized with simpler operations such as chirp multiplication and convolution. The convolution can be performed in $O(N\log N)$ time by using FFT keeping the overall complexity at $O(N\log N)$. The time-frequency ($x-\nu$) plane of a signal can be viewed in the FRFT domain as the rotation of the $x-\nu$ axes around the origin making an angle α with the x-axis. Readers are encouraged to read the work by Ozatkas.et.al [19] to gain more insight into the FRFT computation. The detection module logs the peak FRFT value, matched FRFT order, frequency bin corresponding to the peak FRFT value in the detection report.

C. Localization

We localize the wideband RFI source by taking an approach similar to generalized ESPIRIT algorithm [20] to obtain the direction of arrival and propose to extend it further to estimate range to resolve the coordinates of the RFI on (x, y) plane. We consider a far field wideband Linear Frequency Modulated (LFM) chirp signal impinging an arbitrary planar array comprising of M nodes on the (x, y) plane with a direction of arrival (θ). A reference node is located on the coordinate origin point and the coordinate of i^{th} node is (n_{ix}, n_{iy}). The chirp signal as received by the i^{th} node is expressed as

$$r_i = s(t - \zeta_i) + n(t) \tag{4}$$

where $n(t)$ is the additive white Gaussian noise, $s(t) = \exp[j2\pi(ft + \frac{\mu}{2}t^2)]$ is the chirp signal with initial frequency f and chirp rate μ, ζ_i is the propagation delay at the i^{th} node with respect to the reference node ($i = 1$ in this formulation) and can be expressed as

$$\zeta_i = [n_{ix}\cos(\theta) + n_{iy}\sin(\theta)]/c \tag{5}$$

where c is the speed of light. The localization module can retrieve the node coordinates, matched transform order (a), frequency bin (u_i) corresponding to the peak FRFT value and peak FRFT value ($R_i(u_i, a)$) from the detection report of each node i rendering the localization computationally lighter eliminating the need to recompute FRFT of the RFI for localization. Construct the peak value vector $\mathrm{R} = [R_1(u_1, a), R_2(u_2, a), ..., R_M(u_M, a)]^T$ and obtain the covariance matrix of the array space time-frequency for the wideband RFI source $\Theta = \mathrm{R}\mathrm{R}^H$. Eigen-decompose the covariance matrix $\Theta = \Omega\Sigma\Omega^H$ where Ω is the matrix containing the eigenvectors in its columns and Σ is the diagonal matrix containing its eigenvalues. Divide Ω into submatrices Ω_a and Ω_b such that

$$\Omega = \begin{bmatrix} \Omega_a \\ last\ row \end{bmatrix} = \begin{bmatrix} first\ row \\ \Omega_b \end{bmatrix} \tag{6}$$

Construct the steering matrix

$$\Psi(\theta) = diag[\Upsilon(\zeta_2), \Upsilon(\zeta_3), ..., \Upsilon(\zeta_M)/\Upsilon(\zeta_{M-1})] \tag{7}$$

where,

$$\begin{aligned}\Upsilon(\zeta_i) = &\exp[j\pi(-2\zeta_i u_i \sin(a\pi/2) f_s/\sqrt{N})]. \\ &\exp[-j\pi(\zeta_i^2)\sin(a\pi/2)\cos(a\pi/2) f_s^2/N]\end{aligned} \tag{8}$$

is the steering factor, N is the number of samples in the received vector and f_s is the sampling frequency. Perform a 1 dimensional search for θ on the spectral function

$$\mathcal{S}(\theta) = \frac{1}{|\Omega_a^H \Omega_b - \Omega_a^H \Psi(\theta)\Omega_a|} \tag{9}$$

where $|\cdot|$ denotes the matrix determinant. We are currently extending this to estimate the range of RFI. The range and direction of arrival can be jointly resolved to estimate the RFI coordinates.

III. Hardware development

In our design, the main board that will be used is a Raspberry Pi (RPI) 3 Model B with Quad Core Broadcom BCM2837 64-bit ARMv8 processor and weighing 41.2 g. The choice was motivated from the low cost, size and large open community support for RPI development. Additionally, it is enabled with WiFi (802.11 b/g/n). To reside within the SWaC constraints of the device, we will use AirSpy Mini which is compatible with RPI and weighs 50 g. The technical specifications include 3.5 dB NF between 42 and 1002 MHz, 12 bit ADC at 20 MSPS and 10, 6 and 3 MSPS IQ output.

The envisioned prototype is expected to have three types of feedback; (i) Visual: An LCD screen will be used to display basic information of the detected RFI, (ii) Audio: A buzzer will be used to indicate the detection of RFI in the given channel and (iii) Haptic: A vibrating mini motor disc will be used to provide haptic feedback to the end users. The protoype includes GPS and a nine degree of freedom inertial measurement unit (IMU) sensor (3-axis accelerometer, 3-axis magnetometer and a 3-axis gyroscope) to estimate location when GPS is temporarily unavailable. The current state of prototype is shown in Fig. 2.

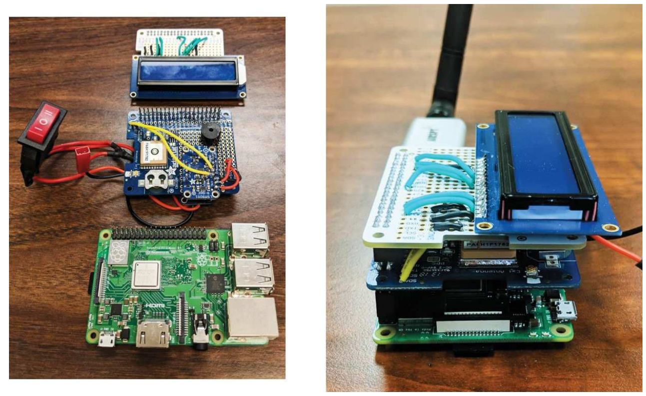

Fig. 2. System Diagram of the Proposed Device

IV. Preliminary Results

We have used Universal Software Radio Peripheral (USRP), a software defined radio, to generate few generic RFI waveforms to be transmitted in the industrial, scientific and medical (ISM) radio bands for the purpose of OTA evaluation. The waveforms were developed on GNU Radio platform (open-source signal processing software). The signal processing for generating the waveforms was written in Python and imported into GNURadio.

To evaluate the performance of the detector (implemented in C++) under varying SNR, we applied digital scaling factor to the generated RFI. The varying RFI amplitudes are represented as varying scaling factor using a dB scale. For the readers to visualize the operating conditions, three power spectrum plots of the RFI received at different scaling factors are shown in Fig. 4. The green color depicts the peak hold function at each frequency, whereas the blue color shows the instantaneous signal energy. The RFI generated is a Group-II waveform sweeping at a rate of 2 MHz/s. The AirSpy is tuned to listen to 6 MHz bandwidth with center frequency at 917 MHz. The performance is evaluated for three detectors, (i) conventional energy detector, (ii) proposed detector with coarse search and (iii) proposed detector with fine search. The coarse search performs a simple three order search at predetermined FRFT orders $[0.2, 0.3, 0.4]$ and used mean FRFT magnitude as the test statistic. The fine search employed the GSS algorithm to determine the matched order and uses kurtosis of FRFT as mentioned in subsection II-B. For each of these detectors, we evaluate threshold set accordingly for two false alarm rates $P_{fa} = [10^{-8}, 10^{-10}]$. Each data point in Fig. 3 corresponds to an average of 1095 spectral snapshots with receiver sampling at a rate of 3 MS/s. At each snapshot, the detector processes 4096 IQ samples. At very low SNR scenario (i.e. when Jammer scaling factor was set to -60 dB), the proposed solution with GSS renders a significant improvement as opposed to coarse search. The proposed detector with GSS starts to provide near absolute detection even at low SNR conditions which further saturates with increasing RFI power. Both versions of the proposed detector outperforms conventional energy detector which delivers acceptable detection rates only when the RFI power is high enough (i.e. when Jammer scaling factor was set to -20 dB to -10 dB). Therefore, our preliminary analysis has shown that the proposed device will significantly outperform (by 40 dB) devices that depend on conventional energy detector at a given P_{fa}.

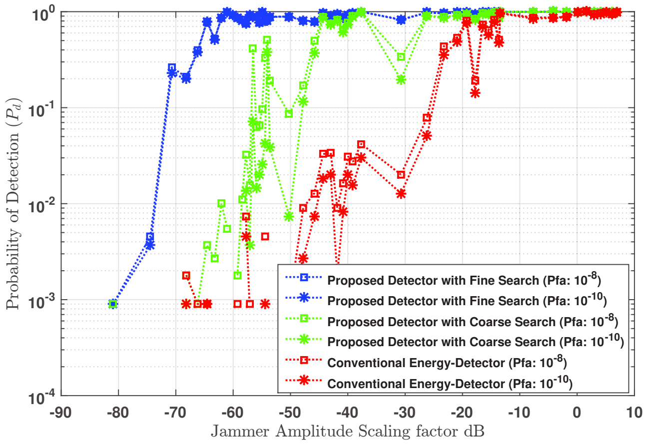

Fig. 3. Probability of Detection vs Signal Strength

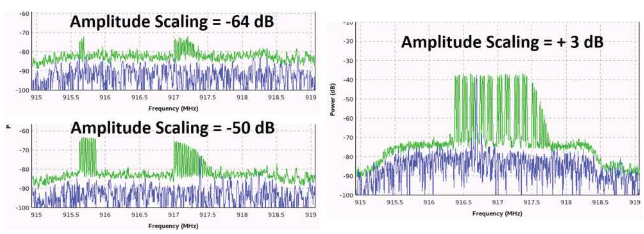

Fig. 4. SNR at different Jammer Scaling level

V. Conclusion and Future Work

In this work, we have presented a novel design (hardware and signal processing software) to develop a low cost, portable RFI detection and localization device that significantly outperforms the state-of-the-art devices in market. In this preliminary work, we have prototyped the device, implemented the parallel detection technique constituting of FRFT and kurtosis and presented OTA experimental results to prove the superiority of the proposed detection technique. The low SWaC of the proposed device will enable first responders and other users to carry it with ease during their mission. The proposed device will alert them of RFI in their channel enabling them to take preventive action thereby improving efficiency and safety. In future, we will implement the localization scheme, develop a mobile application for users to interface with the device and miniaturize the final product into much smaller form-factor.

VI. Acknowledgements

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