Wide-Area Spectrum Cartography

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***Abstract*—This paper describes U.S. spectrum management measurement challenges and a potential scalable solution using satellite-based observations. Specifically, we investigate the radio frequency passive imaging technique of synthetic aperture source localization (SASL), which combines elements of aperture synthesis (*cf.* synthetic aperture radar) and time and frequency difference of arrival. We simulate the use of low-cost software-defined radio receivers and low-gain antennas at a common small-satellite altitude of 550 km to implement a SASL approach. Preliminary results demonstrate resolution of emitters with sufficient spatial and spectral detail to provide useful statistical spectrum quantification information to U.S. policymakers and technology developers.**

I. Introduction

The National Telecommunications and Information Administration (NTIA) Institute for Telecommunication Sciences (ITS) conducts, *inter alia*, research projects in pursuit of both understanding current U.S. spectrum usage and informing NTIA Office of Spectrum Management (OSM) feasibility studies regarding future bands that may support sharing between federal and commercial systems. A current example is NTIA's Spectrum Quantification, Validation, and Characterization (SQVC) project, which analyzes aggregate usage of the Citizens Broadband Radio Service (CBRS) band (3550 MHz–3700 MHz) at census-block spatial resolution, with 10 MHz channel resolution [1]. In the SQVC project, CBRS data is provided to ITS by CBRS Spectrum Access System administrators on a quarterly basis, which while highly useful for understanding trends in the CBRS band, is narrowly applicable to that band and spectrum sharing architecture. Another source of spectrum occupancy data for NTIA is produced by ITS-developed spectrum sensing hardware and algorithms, which are invaluable for continuous measurements of (*i.e.*, "monitoring") spectrum occupancy in particular areas and examining detailed characteristics of weak or infrequent signals [2], [3]. However, networks of such sensors, even when composed of low-cost software-defined radios (SDR), are cost-prohibitive when scaled up to measure nationwide spectrum usage.

The need to understand nationwide aggregate spectrum usage in arbitrary bands, the reluctance of spectrum users to volunteer their spectrum usage data, and the limitations of data sources such as those described above, are the motivation for this paper. The proliferation of and access to small satellites invite us to ask if these platforms could be used to measure the spectrum in a manner analogous to how earth observation satellites provide information to meteorologists: by making periodic sparsely-sampled measurements, and synthesizing them into a data product such as a map, which is continually revised as new data are collected.

II. Spectrum Management Requirements

To inform policymakers on spectrum usage, data with spatial resolution comparable to a census block are required, as in the SQVC project. Census tracts are geographic regions that average about $4\,000$ inhabitants, with a minimum of $1\,200$ and maximum of $8\,000$, while census blocks are subdivisions of census tracts, which have a mean area of $1.2\,\mathrm{km}^2$. Although census blocks are complex polygons in reality, we suggest that an average spatial resolution of not less than $1\,000 \times 1\,000\,\mathrm{m}$ is a reasonable goal. This fixed resolution will oversample in large census blocks where there may be no emitters, and undersample in densely populated regions where there could be hundreds of emitters within each resolved "pixel"; higher-resolution sampling in urban regions can be accomplished with ground-based sensor networks.

From diffraction theory it is known that a small satellite in low Earth orbit (LEO) at, *e.g.*, $550\,\mathrm{km}$ altitude cannot reasonably host a large enough antenna for this angular resolution of $0.1°$, when only performing received signal strength (power) measurements. For example, a $5\,\mathrm{m}$ aperture would achieve this resolution only when $f > 40\,\mathrm{GHz}$; typical low-gain antennas would provide spatial resolution on the order of an entire state or region. Approaches involving some level of signal processing, such as direction of arrival (triangulation), time/frequency difference of arrival (TDOA/FDOA), and interferometry all present challenges, such as requiring numerous sensors, requiring *a priori* signal information, or producing ambiguous results in dense emitter environments, respectively.

Synthetic aperture source localization (SASL), a back-propagation method recently developed by Waddington [4], combines concepts of synthetic aperture radar (SAR) and TDOA/FDOA, and was developed for localization of ground-based linear frequency-modulated (LFM) high-frequency signals using receivers on aircraft. In this paper, we investigate the applicability of SASL using SDRs at greater altitudes and velocities, *i.e.*, small satellites. SASL is agnostic of center frequency f_0, but received signal bandwidth determines cross-track spatial (range) resolution, just as in synthetic aperture radar. For example, to characterize the $7.125\,\mathrm{GHz}$–$8.5\,\mathrm{GHz}$ frequency range, while system noise is a function of the receiver bandwidth (likely $50\,\mathrm{MHz}$–$100\,\mathrm{MHz}$, scanning across the $1.375\,\mathrm{GHz}$ band), cross-track spatial resolution depends on the bandwidth of the received signals.

III. Modeling Parameters

SASL requires two synchronized receivers, so we fix one (γ_1) on the ground $10\,\mathrm{km}$ from the center of a $2 \times 2\,\mathrm{km}$ region of interest (ROI), and the other (γ_2) on a small satellite at $550\,\mathrm{km}$ altitude with a velocity of $7.585\,\mathrm{km/s}$. In the simulation, we move γ_2 through a path approximately 200 km long, overflying the ROI. Using the start-stop approximation (*cf.* SAR), we collect $N_f = 60\,000$ "fast time" samples at each of the $N_s = 99$ "slow time" steps, recognizing that phase and Doppler corrections are necessary due to the satellite's motion. The receivers have parameters compatible with low-cost SDRs, with a sampling rate of $f_s = 25$ MS/s, resulting in $T_f = N_f/f_s = 2.4$ ms per acquisition. If mapping a wide band, the SDR can be stepped through a set of frequencies to capture N_f samples per N_s step per f_0.

Following Waddington [4] for simplicity, we place a 3×3 grid of transmitters with a pitch of 900 m in the ROI. The transmitters are in the 900 MHz industrial, scientific, and medical (ISM) band, overlap in frequency, and produce LFM signals with chirp rates between 1×10^{11} Hz/s and 1×10^{12} Hz/s, chirp bandwidths from 8 MHz to 16 MHz, and duty cycles between 0.1 % and 2 %. The start times of the chirps are randomized within each receiver's N_s receive windows so there is no synchronization among transmitters nor between transmitter and receiver pairs. The ISM band and signal bandwidths were selected to align with future experimental measurements.

To focus on demonstrating the utility of SASL imaging for resolving ground-based emitters, we employ simplified antenna patterns: omnidirectional antennas on transmit and γ_1, and a low-gain antenna on γ_2. The RF channel is modeled as free-space path loss and propagation delay.

IV. Results

Simulation results with signals overlapping in frequency and time do not show categorical differences from cases where the signals do not overlap in frequency or time. While we have randomized the start times of the chirps completely in most simulations, which is the most realistic, Fig. 1 shows an example acquisition by γ_1 of N_f samples at $N_s = 1$ where the chirps began in the first 20 % of the receive window, in order to demonstrate a challenging dense emitter environment. The same plot for γ_2 shows the chirps arriving at the end of the receive window, due to the time delay to LEO.

Fig. 2 is a processed SASL image of the ROI. The transmitters are clearly resolved, with artifacts ranging from non-existent to distracting. The majority of the artifacts are a blur in the cross-range direction, which is understood [4]. Regardless, resolution of the point sources is on the order of 100 m.

V. Conclusion

SASL has the potential to serve as a data-generation technique to provide new and useful maps of spectrum utilization. Future work includes adding additional realism to the model, such as directional transmitters, multipath, receiver position and angle uncertainty, investigation of other waveforms, and characterization of spatial resolution and dynamic range from an image processing perspective.

Acknowledgement

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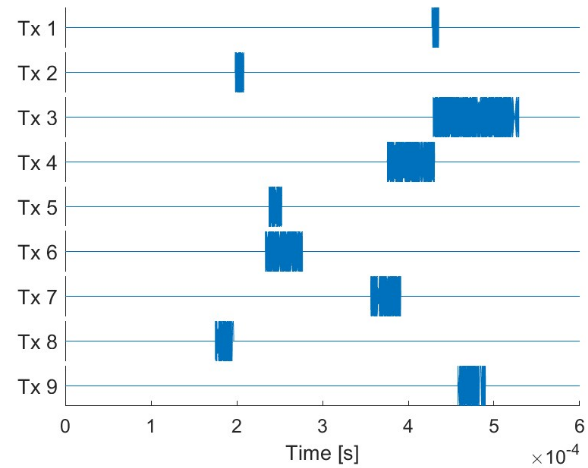

Fig. 1. Example of signals received at γ_1 at $N_s = 1$, with start times randomized in the first 20 % of the 2.4 ms receive window.

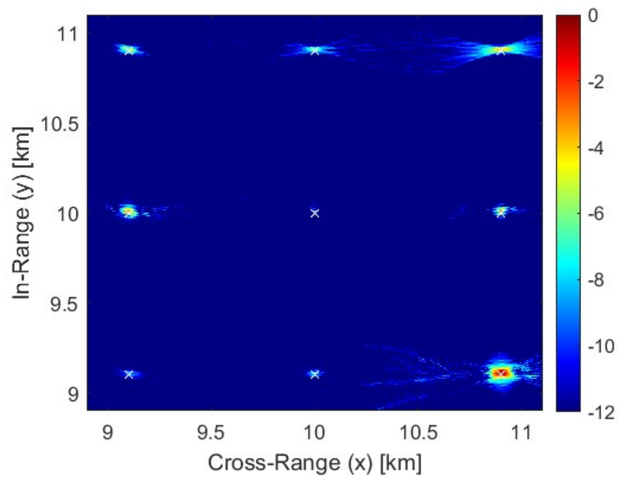

Fig. 2. SASL image resolving 9 transmitters separated by 900 m in range and cross-range. The color scale is in decibels normalized to the peak received signal.

References

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