Frequency of Arrival-based Interference Localization Using a Single Satellite
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Abstract—Intentional and unintentional interferences are an increasing threat for the satellite communications industry. In this paper, we aim to localize an interference with unknown location using frequency of arrival (FoA) technique by only relying on the measurements obtained through a single satellite. In each time instance, the satellite samples the interference and forwards it to the gateway to estimate its frequency. Since the satellite moves, each estimated frequency includes a Doppler shift, which is related to the location of the unknown interferer. The satellite’s position, velocity, oscillator frequency, and the interference frequency are used at the gateway to build a location-related equation between the estimated frequency and the location of the unknown interference. Simultaneously with the interference signal, the satellite samples a reference signal to calibrate the estimated frequency and compensate for the mismatches between the available and real values of the satellite’s position, velocity, and oscillator frequency. Multiple location-related equations obtained based on the FoA measurements, (at least two), along with the equation of the earth surface are used to localize the unknown interference. Simulations show that increasing the number of these equations, and the satellite velocity can improve the localization accuracy by 80% and 95%, respectively.

Keywords—Doppler shift, frequency of arrival, interference, localization, reference signal.

I. INTRODUCTION

In the satellite industry, interference is an important and increasing concern, which can cause considerable revenue loss due to service interruption. Broadly speaking, interference can be divided into two major categories: 1) unintentional, e.g., created by human mistake or equipment mismatch, and 2) intentional, e.g., jammers. In order to effectively handle interference, first, the interferer needs to be localized.

There has been interest toward interference localization in the satellite communication society. The authors of [1] perform time difference of arrival (TDOA) along with phase measurements to localize an unknown interferer using two geostationary (GEO) satellites. In [2], three out of four satellites exposed to interference are used to derive TDOA measurements for localizing an unknown interferer. The performance of the localization in Eutelsat satellites is presented in [3] where TDOA and frequency difference of arrival (FDOA) measurements are used to localize an unknown interferer. The altitude constraint in [4], [5] is considered to improve the localization accuracy by employing TDOA and/or FDOA technique(s). Two antennas on a spinning satellite in [6] are used to localize an unknown interferer. FDOA measurements done by more than two satellites in [7] are used to localize an interferer. It is shown that, in contrast to TDOA, FDOA accuracy is not affected by the bandwidth of the interference signal.

In addition, there are patents concerning the localization of unknown interferer using satellite. In [8], one mainly affected GEO satellite and an adjacent GEO satellite capture multiple samples of interference and transmit them to a two-antenna gateway where multiple TDOA and FDOA calculations are done to localize the unknown interferer. In addition, a known reference signal is used to compensate for equipment mismatches. Patents [9], [10] consider a system model similar to [8], while [9] works with more inclined satellites, and [10] can localize an interferer with varying frequency. Patents [11], [12] use three satellites for sampling the interference and perform a weighted combination of two TDOA and two FDOA measurements for localization. FDOA technique is employed in [13] to localize the unknown interferer using only one affected GEO satellite.

In this work, we consider a satellite that receives uplink signal from a gateway on the earth within the Ka band. At the same time, the satellite receives narrow band uplink interference from an unknown source that is transmitting within the same frequency band as the gateway. Here, we use the term unknown to refer to the location of the interference, which is unknown. Our primary goal is to localize the unknown interferer by applying the FoA technique to the received samples of the interference signal at the gateway that are only sent by the affected satellite, or by a single satellite that is responsible for interference localization. To this end, the satellite samples the interference signal at each time instance and transmits it to the gateway. At the gateway, the frequency of each received sample is estimated. Since the GEO satellite drifts [14] and LEO, MEO, and retrograde GEO1 satellites naturally move, each estimated frequency at the gateway includes a specific amount of Doppler shift which is related to the position of the unknown interferer.

Based on this fact, the gateway can build a location-related equation between each estimated frequency and the location of the unknown interferer. Assuming that the frequency of the unknown interferer is known, to build a location-related equation, the gateway requires the frequency of the satellite’s down conversion oscillator as well as satellite’s positions.

1A retrograde GEO satellite is placed in the GEO orbit and goes against the direction of the Earth rotation.
and velocities when sampling and forwarding the interference signal. However, these values are erroneous. To compensate for errors, a reference signal from a known location on the earth is transmitted to the satellite, and then forwarded to the gateway. The position of the interferer can be derived using at least two location-related equations plus equation of the earth surface. Compared to [13], we use FoA instead of FDOA to localize the unknown interferer, which based on the results in Section IV, improves the localization accuracy. In contrast to [13], we perform more accurate analysis by considering all the terms which cause frequency shift. We use Taylor series approximation along with Newton method to solve the system of location-related equations which are nonlinear. In addition, we propose using on-board interference localization to improve the localization accuracy.

The remainder of the paper is organized as follows. In Section II, the network configuration is introduced and the frequency shift in interference and reference signals are modeled. In Section III, system of nonlinear equations is formulated and solved. The simulation results are presented in Section IV, and the conclusions are drawn in Section V.

Notation: Upper-case and lower-case bold-faced letters are used to denote matrices and column vectors, respectively. Superscript $(\cdot)^T$ represents transpose and $\| \cdot \|$ is the Frobenius norm.

II. SIGNAL AND SYSTEM MODEL

We consider a satellite which receives uplink signal from a gateway within the Ka band. Concurrently, the satellite receives narrow band uplink interference from an unknown transmitter within the same frequency band as the uplink signal from the gateway. A reference signal is transmitted to the satellite to compensate for the errors. The whole scenario is summarized in Fig. 1. The central frequency of the interference signal is shown by $f_u$ and since it is interfering with the main uplink signal, we assume that $f_u$ is known. Although $f_u$ may be changed intentionally and/or due to instability of the electronics, for the sake of simplicity, $f_u$ is considered to be fixed through the time. Also, we assume that the derived signal is turned off during sampling the interference signal. All the vectors in this section and Section III are in Cartesian coordinates. The subscripts $u, r, s, gw, ul,$ and $dl$ are used in the equations instead of the terms: unknown interferer, reference transmitter, satellite, gateway, uplink, and downlink, respectively.

The frequency of the $n$-th sampled interference by the satellite is

$$f_{n,u,s} = f_u \left( 1 + \frac{v_{n,s}^T k_{n,u,s}}{c_n} \right),$$

where $f_{n,u,s}$ is the frequency of the $n$-th sampled interference at the satellite, $v_{n,s}$ is the velocity of the satellite when sampling, $c_n$ is the propagation speed of the signal in the space, and $k_{n,u,s}$ is the normalized unit vector pointing from the satellite toward the unknown interferer defined as

$$k_{n,u,s} = \frac{u - s_{n,u}}{\|u - s_{n,u}\|},$$

where $s_{n,u}$ is the position of the satellite during uplink and $u = [u_1, u_2, u_3]$ is the location of the unknown interferer. Afterwards, the satellite down converts $f_{n,u,s}$ into

$$f_{n,u,s} - f_T = f_u \left( 1 + \frac{v_{n,s}^T k_{n,u,s}}{c_n} \right) - f_T,$$

where $f_T$ is the amount of the frequency down conversion for the $n$-th sample. Subsequently, the satellite forwards the down converted signal to the gateway. Using (3), the frequency of the received signal at the gateway is

$$f_{n,u,gw} = \left( f_u + f_u \frac{v_{n,s}^T k_{n,u,s}}{c_n} - f_T \right) \left( 1 + \frac{v_{n,s}^T k_{n,gw,s}}{c_n} \right)$$

$$= f_{n,ul} + f_u \frac{v_{n,u}^T k_{n,u,s}}{c_n} + f_{n,dl} \frac{v_{n,d}^T k_{n,gw,s}}{c_n}$$

$$+ f_u \frac{v_{n,u}^T k_{n,u,s}}{c_n} \frac{v_{n,d}^T k_{n,gw,s}}{c_n},$$

where $f_{n,ul} = f_u - f_T$ and $k_{n,gw,s} = \frac{s_{gw} - s_{n,ul}}{\|s_{gw} - s_{n,ul}\|}$ with $s_{gw}$ being the position of the gateway and $s_{n,ul}$ being the position of the satellite when forwarding the $n$-th sampled interference to the gateway. The last term in (4) is very small compared to the other terms when it comes to GEO satellites with a very slow drift and has been neglected in [13]. However, we keep it since its effect increases as the velocity of the satellite goes higher, specially for low earth orbit (LEO), medium earth orbit (MEO) or retro GEO satellites.

The gateway estimates the frequency of the $n$-th sampled interference after receiving it from the satellite. Due to the movement of the satellite, each estimated frequency includes a specific amount of Doppler shift which relates to the position of the unknown interferer. Hence, a location-related equation can be made between each estimated frequency and the location of the unknown interferer. To this end, the gateway requires satellite’s positions and velocities during uplink and
downlink of the $n$-th sample, the frequency of the satellite’s
down conversion oscillator, and the frequency of the inter-
fERENCE signal while it is being emitted. However, the values
related to the oscillator frequency, positions, and velocities are
different from their real values due to equipment impairments.
To compensate for these errors, the gateway needs to calibrate
the estimated frequency of the $n$-th sample. For this purpose,
a reference signal from a known location on the earth can be
transmitted to the satellite and then forwarded to the gateway
in one of the following approaches:

1) The reference signal is uplinked in the same frequency
as the interference signal after a delay. Due to the
delay, the reference and interference signals experience
different mismatches.

2) The reference signal is uplinked in a different frequency
from the interference signal and the satellite samples the
interference and reference signals simultaneously.

Here, the second approach is followed to transmit the reference
signal while it is being emitted. However, the values
related to the oscillator frequency, positions, and velocities are
different from their real values due to equipment impairments.

The location-related equation as

\[
\tilde{f}_{n_s,g} = \hat{f}_{n_s,g} - \delta_n
\]

where \( \tilde{f}_{n_s,g} \) is the reduced calibrated frequency of the
$\hat{f}_{n_s,g}$

The location-related equation in (9) can be written as a

\[
f_{n_{r,g},\text{exp}} = f_r - f_{n_{T_{r,s}}} + f_r \frac{V_{n_{d_{i_s}}}^T \mathbf{k}_{n_{r,s}}}{c_n} + f_r \frac{V_{n_{d_{i_s}}}^T \mathbf{k}_{n_{r,s}}}{c_n},
\]

where \( f_{n_{r,g},\text{exp}} \) is the expected frequency of the $n$-th sampled
reference signal at the gateway, \( \mathbf{k}_{n_{r,s}} = \frac{r - s_{u,g}}{||r - s_{u,g}||} \), and

\[
\mathbf{k}_{n_{r,s}} = \frac{r - s_{u,g}}{||r - s_{u,g}||},
\]

The frequency mismatch for the $n$-th sample is derived using (5) and (6) as

\[
\delta_n = \frac{f_u}{f_r} \left[ f_{n_{r,g}} - f_{n_{r,g,\text{exp}}} \right],
\]

where \( \delta_n \) is the amount of the frequency mismatch, the factor $\frac{f_u}{f_r}$
is used to convert the frequency of the reference signal
into the frequency of the unknown emitter since the reference
signal has a different frequency and undergoes a different
amount of mismatches. Using (7), the calibrated frequency of the
$n$-th received interference at the gateway is obtained by

\[
f_u \approx f_u (u_0) + F' (u_0) (u - u_0),
\]

III. LOCALIZATION ALGORITHM AND SOLUTION

The location-related equation in (9) can be written as a

\[
f_u (u) = \frac{f_u}{c_n} \left[ V_{n_{d_{i_s}}}^T \mathbf{k}_{n_{r,s}} \left( 1 + \frac{V_{n_{d_{i_s}}}^T \mathbf{k}_{n_{r,s}}}{c_n} \right) \right] - f_{n_{r,g}},
\]

Since it is already known that the unknown interferer is located on the earth, at least two equations as in (10) plus the equation
of the earth surface are required to get an estimation for the
location of the unknown interferer. To make a system of
location-related equations, $N$ of the estimated frequencies at
the gateway, with $N \geq 2$, are randomly selected. This system
of nonlinear equations is solved using an iterative algorithm
with the initial guess $u_0$. To this end, the first-order Taylor
series approximation around $u_0$ is applied on each location-
related equation to obtain

\[
f (u) \approx f (u_0) + F' (u_0) (u - u_0),
\]
where \( f(\mathbf{u}) = \begin{bmatrix} f_1(\mathbf{u}), \ldots, f_N(\mathbf{u}) \end{bmatrix} \), \( \|\mathbf{u}\|^2 = r^2 \) is the surface of the earth equation, \( r \) is the earth radius, \( f(\mathbf{u}_0) = \begin{bmatrix} f_1(\mathbf{u}_0), \ldots, f_N(\mathbf{u}_0) \end{bmatrix} \), \( \|\mathbf{u}_0\|^2 = r^2 \), and \( \mathbf{F}'(\mathbf{u}_0) \) is the partial derivative matrix calculated at the initial guess as

\[
\mathbf{F}'(\mathbf{u}_0) = \begin{bmatrix} \frac{\partial f_1(\mathbf{u}_0)}{\partial u_1} & \frac{\partial f_1(\mathbf{u}_0)}{\partial u_2} & \ldots & \frac{\partial f_1(\mathbf{u}_0)}{\partial u_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial f_N(\mathbf{u}_0)}{\partial u_1} & \frac{\partial f_N(\mathbf{u}_0)}{\partial u_2} & \ldots & \frac{\partial f_N(\mathbf{u}_0)}{\partial u_n} \end{bmatrix}.
\]

The partial derivatives of \( f_n \) with respect to \( u_m \) for \( m = 1, 2, 3 \) are derived as

\[
\frac{\partial f_n(\mathbf{u})}{\partial u_m} = \begin{bmatrix} g_n \mathbf{u}_n - s_n \mathbf{a}_n \end{bmatrix} \mathbf{a}_m.
\]

\[
\mathbf{a}_1 = \begin{bmatrix} g_n - \left( u_1 - s_{n1} \right)^2 g_n^{-1} \\ g_n - \left( u_2 - s_{n2} \right)^2 g_n^{-1} \\ g_n - \left( u_3 - s_{n3} \right)^2 g_n^{-1} \end{bmatrix},
\]

\[
\mathbf{a}_2 = \begin{bmatrix} \left( u_1 - s_{n1} \right)^2 g_n^{-1} \\ \left( u_2 - s_{n2} \right)^2 g_n^{-1} \\ \left( u_3 - s_{n3} \right)^2 g_n^{-1} \end{bmatrix},
\]

\[
\mathbf{a}_3 = \begin{bmatrix} g_n - \left( u_1 - s_{n1} \right)^2 g_n^{-1} \\ g_n - \left( u_2 - s_{n2} \right)^2 g_n^{-1} \\ g_n - \left( u_3 - s_{n3} \right)^2 g_n^{-1} \end{bmatrix}.
\]

\[
\eta_n = \left( 1 + \frac{\mathbf{u}_{n-1} \cdot \mathbf{s}_{n1}}{\|\mathbf{u}_{n-1}\|^2} \right), \quad g_n = \|\mathbf{u} - \mathbf{s}_{n1}\|, \quad \text{and} \quad \mathbf{s}_{n1} = (s_{n1}, s_{n2}, s_{n3}).
\]

We need to find the point \( \mathbf{u} = \mathbf{u}_1 \) to have \( f(\mathbf{u}_0) + F'(\mathbf{u}_0)(\mathbf{u}_1 - \mathbf{u}_0) = 0 \) so that \( F'(\mathbf{u}_0)\Delta\mathbf{u} = -f(\mathbf{u}_0) \), which is a system of linear equations with \( \Delta\mathbf{u} = \mathbf{u}_1 - \mathbf{u}_0 \). After deriving \( \Delta\mathbf{u} \), the initial guess is updated as

\[
\mathbf{u}_{n+1} = \mathbf{u}_1 + \Delta\mathbf{u},
\]

and continues till \( \|\Delta\mathbf{u}\| < \varepsilon \) where \( \varepsilon \) depends on the required localization accuracy.

### IV. Simulation Results

In this section, we present different scenarios to evaluate the performance of the proposed localization technique. It is
assumed that the processing at the satellite is quick enough so that the satellite positions and velocities can be considered to be the same during sampling and forwarding the interference and reference signals. Furthermore, the propagation speed of the electromagnetic wave is considered to be same for all frequency measurements. The locations of the system elements are shown by the Geographic coordinate system as (longitude, latitude, altitude). The errors in the position and velocity of the satellite are shown by vectors $e_p$ and $e_v$, which their elements are uniform random variables within the distance $[-e_p, e_p]$ and $[-e_v, e_v]$, respectively. The acronym OB is used instead of the term on-board in the legend of the figures to save space.

For LEO, MEO, and retro GEO satellites, it is assumed that the satellite moves from $(0,0,\text{altitude})$ to $(20,0,\text{altitude})$ and samples the interference in every $0.5$ degree which results in $40$ samples. Regarding the GEO satellite, it is assumed that the satellite collects $40$ samples along a circular path with radius of $50$ km which takes one day to complete. The GEO satellite is located right above the intersection of zero degrees latitude and zero degrees longitude with the altitude $35786$ km. The rest of the parameters which are common for all the satellites are summarized in Table I.

For the first scenario, the effect of the number of location-related equations on the accuracy of the interferer localization is investigated in terms of the root mean square error (RMSE). The RMSE with respect to the number of location-related equations are shown in Figs. 2 and 3 for different positions of the reference signal. As it is seen, the localization accuracy improves by increasing the number of equations. Hence, we can figure out the required number of location-related equations to localize an unknown interferer within the required accuracy for specific amounts of system parameters and error bounds. By comparing Figs. 2 and 3, we observe that if the location of the reference transmitter is closer to that of the unknown interferer, the localization accuracy increases. In addition, the localization RMSE with respect to the number of location-related equation for on-board localization is presented in Fig. 2. As seen, on-board localization further improves the localization accuracy since it avoids the error caused by the oscillator drift. The
localization RMSE with respect to the number of location-related equations for the GEO satellite is presented in Fig. 4. Similar to Fig. 2, it can be seen in Fig. 4 that the localization accuracy improves by both increasing the number of location-related equations and using on-board localization. Since a GEO satellite moves relatively slow, the Doppler shift caused by its movement is small and can be easily influenced by the oscillator error. Hence, using on-board localization can considerably enhance the localization accuracy when a GEO satellite is sampling and forwarding the interference.

The localization RMSE with respect to the number of equations when using FDOA technique of [13] is presented in Fig. 5. As compared with Fig. 2, the RMSE considerably (by an order of magnitude) increases when FDOA is used instead of FoA. In FDOA approach, each equation is created by deducing two FoA measurements. Since FoAs can be close to each other, deducing them creates very small values which decreases the identifiability of the system of equations in (11).

In the next scenario, we analyze the sensitivity of the localization accuracy with respect to the errors in satellite’s position and velocity. Localization RMSE with respect to location-related equations is presented in Fig. 6 for different errors in position and velocity. As observed in Fig. 6, the localization accuracy is much more sensitive to velocity errors than the position errors. This is due to the fact that each error in satellite’s position is divided by \[ \| u - s_{n,t} \| \] and \[ \| s_{n,t} - s_{n,t_o} \| \] in (10), which reduces the effect of the position error.

In the last scenario, the effect of the satellite velocity on the localization accuracy is investigated. The localization RMSE with respect to the satellite’s velocity is shown in Figs. 7 and 8. The results show that the localization accuracy is improved when the velocity of the satellite increases. Similar to the first scenario, if the locations of the reference and unknown transmitters are closer to each other, the localization accuracy increases considerably. Furthermore, Fig. 7 shows that the localization accuracy is improved using on-board approach.

V. CONCLUSION

We proposed using the FoA technique to localize an unknown interferer while only relying on either the affected satellite, or the satellite dedicated to interference localization. We used a reference signal to calibrate the estimated frequency of the interferer at the gateway, and built location-related equations using the values of satellite’s oscillator frequency, velocities, and positions. It was shown that increasing the number of location-related equations, i.e. measurements, can improve the localization accuracy. In addition, the localization accuracy improved when the affected satellite had a higher velocity. The results showed that a closer reference transmitter to the location of the unknown interferer enhances the localization accuracy. Moreover, the simulations showed that using the proposed on-board localization approach can further enhance the localization accuracy since the oscillator error is avoided, particularly for on-board GEO localization. It was observed that using FoA technique instead of FDOA improves the localization accuracy considerably since it increases the identifiability of the system of location-related equations.

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