Debris Sensing Based on LEO Constellation: an Intersatellite Channel Parameter Estimation Approach

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Outline

Introduction: motivation of debris sensing

- **Low earth orbit (LEO) satellite constellations**, like StarLink and OneWeb, are key enablers in the space-aided next-generation communication systems [1, 2]. **Debris is threatening** for the security and robustness of the constellation systems. Detecting debris and estimating its trajectory is central to avoiding and creating additional debris
- One tricky issue is **a large number** of **tiny debris** from collisions, e.g., the hyper-velocity LEO collision events (Iridium 33 and Cosmos 2251) resulted in **thousands of** untrackable objects **less than 10 cm** in diameter [3].
- They are too small to be detected using ground-based radars (GBRs) and optical measurements, where the typical $500 - 1000$ km detection distance of LEO debris. Hence, **space-based measurements are needed** for detecting small debris.

Introduction: the twofold sensing system

A stand-alone debris detection system is costly and unrealistic:

- the **large quantity** of debris;
- the debris **around the satellite orbits** is more threatening.

We consider debris detection to be a twofold system:

i) The existing LEO constellations additionally conduct bistatic opportunistic sensing without extra resources of the **inter-satellite links (ISL)**, and it serves as preliminary localization.

ii) Specific threatening debris will be further refined using monostatic setups.

This paper introduces the first step, i.e., the intersatellite links (ISL) based opportunistic sensing.

System model: the architecture of sensing system

A typical hardware architecture of the integrated sensing and communication (ISAC) satellite system is in Fig. 1.

- ISLs are established between satellites. Without other scatterers in space, the NLoS path offers information about the debris.
- Any satellite can be Tx/ Rx based on the protocol, the identified Rx receives signals from the adjacent Tx satellites and acts as the data fusion center.

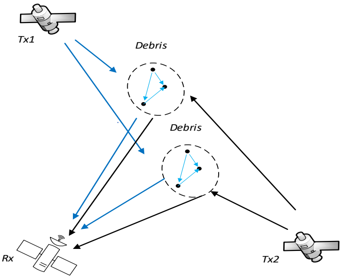

Figure: An ISAC satellite system: M Tx satellites, one Rx satellite, and $L \geq 1$ debris clusters.

- Clustering paths are similar in the amplitude, range, and angular domains of channel impulse response (CIR).

System model: signal model

- Let $l_K \geq 1$ denote the number of paths for the lth cluster ($l \in [1, L]$) and h_{l_c} denote the path corresponding to the centroid of the lth cluster, the channel of the l_kth ($l_k \in [1, l_K]$) debris as

$$h_{l,l_k}(t) = h_{l_c}(t)\Delta h_{l,l_k} = h_{l_c}(t)(1 + \Delta\alpha_{l_k})e^{j\Delta\varphi_{l_k}}, \quad (1)$$

where $\Delta\alpha_{l_k}$ and $\Delta\varphi_{l_k}$ follow $N(0, \sigma_1^2)$ and $N(0, \sigma_2^2)$.

- The baseband equivalent signal model of $h_{l_c}(p)$ is

$$h_{l_c}(p) = \alpha_{l_c} \underbrace{e^{-j2\pi f_s p \tau_{l_c}}}_{range} \underbrace{e^{j2\pi \frac{f_c}{f_s} \frac{v_{l_c}^{\text{tx}} + v_{l_c}}{c} p}}_{Range-Doppler-coupling}, \quad (2)$$

- The NLoS ISL is the superposition of individual components as

$$h_{\text{NLoS}}(p) = \sum_{l=1}^{L} \sum_{l_k=1}^{l_K} h_{l,l_k}(p) + z(p) = \sum_{l=1}^{L} h_l(p) + z(p), \quad (3)$$

where $z(p)$ follows $N(0, \sigma_0^2)$.

System model: signal model

The second exponential term in (2) $e^{j2\pi \frac{f_c}{f_s} \frac{v_{l_c}^{\text{tx}} + v_{l_c}}{c} p}$ shows the range-Doppler coupling:

i) Since the constellation and debris are moving fast, the range-Doppler coupling effect can impact the accuracy of distance estimation [4, 5], where most of the radar scenarios are ignored.

ii) One example in the simulation part shows that the relative velocity of debris is 5 km/s and the error in delay estimation is about 2.6 km.

iii) In the preliminary localization, we pursue the estimation of approximate delay. Additional addresses can be done using waveform design and multiple frames of data in the twofold system.

Methodology: parameter estimation of the NLoS ISLs 1/5

We convert the debris sensing to parameter estimation of the non-line-of-sight (NLoS) ISLs.

- There are various high-resolution channel parameter estimation algorithms, where the iterative expectation maximization (EM) using MLE is popular.
- The space alternative generation EM (SAGE) is an acceleration structure of EM [6, 7], where parameter subsets are alternatively estimated in each iteration until convergence.
- In this paper, we model the spatial dense-distributed debris to be clustered and propose a nested expectation (E)-based SAGE (SAGE^2) algorithm for the cluster-based channel model, where parameters of the centric path in each cluster are estimated, and other multipaths are statistically represented, hence estimating fewer paths and reducing the iterations.

Methodology: parameter estimation of the NLoS ISLs 2/5

- Let $\mathbf{h}_{\text{NLoS}} = [h_{\text{NLoS}}(1), h_{\text{NLoS}}(2), \ldots, h_{\text{NLoS}}(P)]^T$. The received signal consists of the multipaths from L clusters, following the concept of EM, this incomplete data $\mathbf{h}_{\text{NLoS}} \in \mathbb{C}^{P\times 1}$ can be decomposed into L complete data $\mathbf{h}_l \in \mathbb{C}^{P\times 1}$ as

$$\mathbf{h}_{\text{NLoS}} = \sum_{l=1}^{L} \mathbf{h}_l = \sum_{l=1}^{L} (\sum_{l_k=1}^{l_K} \mathbf{h}_{l,l_k} + \beta_l \mathbf{z}) = \sum_{l=1}^{L} (\sum_{l_k=1}^{l_K} \mathbf{h}_{l_c} \odot \Delta \mathbf{h}_{l,l_k} + \beta_l \mathbf{z}), \tag{4}$$

  $\sum_{l=1}^{L} \beta_l = 1$ to satisfy the conservation of noise variance between complete data and incomplete data.
- The SAGE works when the incomplete data is independent and resolvable. However, the paths within the cluster are correlated and are not necessarily resolvable.

- $$\mathbf{h}_l = \sum_{l_k=1}^{l_K} \mathbf{h}_{l_c} \odot \Delta\mathbf{h}_{l,l_k} + \beta_l \mathbf{z} = l_K \mathbf{h}_{l_c} \odot \left[\frac{1}{l_K} \sum_{l=1}^{L} \Delta\mathbf{h}_{l,l_k} \right] \tag{5}$$
  $$\mathbf{h}_l \approx l_K \mathbf{h}_{l_c} \odot \mathbb{E}\left[\Delta\mathbf{h}_{l,l_k}\right] + \beta_l \mathbf{z},$$
  where the sum is replaced by the expectation $\mathbb{E}(\cdot)$, under the assumption of a large number of paths within a cluster.
- $$\mathbb{E}\left[\Delta\mathbf{h}_{l,l_k}\right] = \mathbb{E}[\underbrace{e^{j\Delta\varphi_{l_k}}}_{f(\Delta\varphi_{l_k})} + \underbrace{\Delta\alpha_{l_k} e^{j\Delta\varphi_{l_k}}}_{g(\Delta\varphi_{l_k})}] = \mathbb{E}\left[f(\Delta\varphi_{l_k})\right] + \mathbb{E}\left[g(\Delta\varphi_{l_k})\right], \tag{6}$$
  where $\mathbb{E}_{f(\Delta\varphi_{l_k})} = e^{-\frac{1}{2}\sigma_2^2}$; $\Delta\alpha_{l_k}$ and $\Delta\varphi_{l_k}$ are independent and follow the normal distribution, $\mathbb{E}_{g(\Delta\varphi_{l_k})} = \mathbb{E}_{\Delta\alpha_{l_k}} \mathbb{E}_{e^{j\Delta\varphi_{l_k}}} = 0$.

- $$\mathbf{h}_{l_c} \approx \alpha_{l_c}\mathbf{a}(\tau_{l_c}), \tag{7}$$

  with $\mathbf{a}(\tau_l) \in \mathbb{C}^{P\times 1} = [e^{-j2\pi f_s 1\tau_{l_c}}\, e^{-j2\pi f_s 2\tau_{l_c}} \cdots e^{-j2\pi f_s P\tau_{l_c}}]^T$.
- Substituting (7) and (6) into (5), we can characterize the channel of the lth cluster as

  $$\mathbf{h}_l = l_k' l_K \alpha_{l_c}\mathbf{a}(\tau_{l_c}) + \beta_l \mathbf{z} = l_k' \tilde{\mathbf{h}}_l + \beta_l \mathbf{z}, \tag{8}$$

  where $l_k' = e^{-\frac{1}{2}\sigma_2^2}$ and $\tilde{\mathbf{h}}_l = l_K \alpha_{l_c}\mathbf{a}(\tau_{l_c})$, the parameters to be estimated are $\boldsymbol{\theta}_l = [\tau_{l_c}, \alpha_{l_c}, l_K]$.

- While the MLE of $\boldsymbol{\theta}_l$ for the complete data is $\arg\max_{\boldsymbol{\theta}_l}\{\mathbf{h}_l(\boldsymbol{\theta}_l)\}$, the quantity $\mathbf{h}_l$ is not observable. However, the conditional expectation $\mathbb{E}[\mathbf{h}_l(\boldsymbol{\theta}_l)|\mathbf{H}_{\text{NLoS}}(\hat{\boldsymbol{\theta}}_l), \hat{\boldsymbol{\theta}}_l]$, has the same dependence on $\boldsymbol{\theta}_l$ as the original MLE function, hence it is used to estimate $\hat{\mathbf{h}}_l$.
- E-step: With an initialization $\boldsymbol{\theta}_l^{(0)}$ and following [8], closed-form expression of $\mathbb{E}[\mathbf{h}_l(\boldsymbol{\theta}_l)|\mathbf{H}_{\text{NLoS}}(\hat{\boldsymbol{\theta}}_l), \boldsymbol{\theta}_l]$ is,

$$\hat{\mathbf{h}}_l^{(i)} = l'_k\tilde{\mathbf{h}}_l(\boldsymbol{\theta}_l^{(i-1)}) + \beta_l\left(\mathbf{h}_{\text{NLoS}} - \sum_{l=1}^{L} l'_k\tilde{\mathbf{h}}_l(\boldsymbol{\theta}_l^{(i-1)})\right). \tag{9}$$

- M-step: Obtaining the parameters as

$$\boldsymbol{\theta}_l^{(i)} = \arg\min_{\boldsymbol{\theta}_l} \frac{\left(\hat{\mathbf{h}}_l^{(i)} - l'_k\tilde{\mathbf{h}}_l(\boldsymbol{\theta}_l)\right)\left(\hat{\mathbf{h}}_l^{(i)} - l'_k\tilde{\mathbf{h}}_l(\boldsymbol{\theta}_l)\right)^H}{\beta_l\sigma_0^2} \tag{10}$$

Methodology: simulation and discussion 1/2

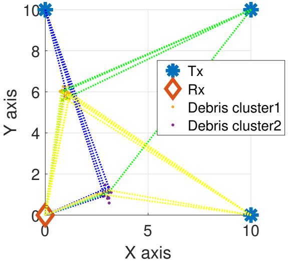

Figure: Simulation scenario: 1 Rx (data fusion center) and 3 adjacent Txs to sense debris in a region of $1000 \times 1000\ km^2$, with two debris clusters are considered.

Table: Simulation configurations

Configurations	Values
Simu range [km^2]	1000^2
f_c [GHz]	14 GHz
f_s [MHz]	1
P	7001
EIRP [dBW]	34
G_r [dB]	30
SNR [dB]	40
Tx velocity	$[0, -3]]\ km/s$
Debris velocity	$[5, 0]\ km/s$
NO. of debris	25/ 15

Methodology: simulation and discussion 2/2

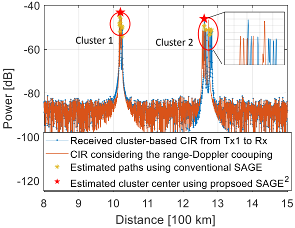

Figure: Cluster-based CIRs: the estimated paths of cluster centroid using the proposed SAGE^2 are denoted as red stars, and estimated paths using conventional SAGE are denoted as yellow dots.

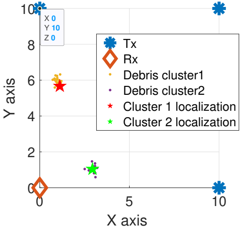

Figure: Positioning result of the cluster center, where the cluster centroid is estimated directly, while the conventional SAGE algorithm requires further clustering algorithms for scatterer localization.

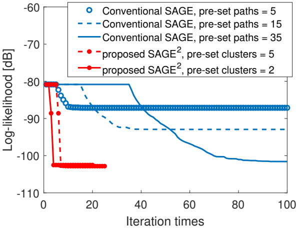

Figure: Comparison of iteration times: the incorrect number of paths in SAGE will lead to local optima, in the proposed SAGE^2, the prior information on the number of clusters is much easier to obtain and converges fast.

Conclusion

- This work proposes an opportunistic debris-sensing approach based on channel parameter estimation using the ISLs in LEO constellations.
- In this approach, the debris is modeled as clusters and the proposed SAGE^2 method is used to estimate the parameters of the cluster-based channel and localize the centroid of the debris cluster based on the estimated delay information among different Tx-debris-Rx links.
- The SAGE^2 is tested using a stochastic channel model with multiple clusters, as well as the convergence comparison with the conventional SAGE algorithm.
- The results show that the proposed approach works well in debris center localization with fewer iterations for convergence.
- Dedicated mechanisms can further use the output of the proposed method for further identification and accurate tracking of threatening debris.

Thanks for listening!

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