A Novel Joint Phase Processing Algorithm for MIMO Sensor Imaging

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CSEM is developing a generic MIMO Sensor Imager (MIMOSI) for various sensing applications based on RF mmWave radar technology. Towards this end, we have designed a new joint phase processing algorithm that performs as well as the optimal Doppler FFT for linear phase signals, while overcoming its limitations for nonlinear phase signals arising in a variety of sensing applications.

CSEM develops a generic MIMO Sensor Imager based on RF mmWave radar technology, aiming at covering various sensing applications such as vital signs monitoring, presence detection, see through walls, etc. The approach is to process the phase of the received radar signal across several transmissions to capture the "motion pattern" of subjects and extract relevant information. Phase processing is widely adopted, e.g., in traditional radar Doppler signal processing, to detect moving targets and estimate their velocity (via Doppler FFT). These methods are, however, limited to linear phases (targets moving with a constant radial velocity towards/away from the radar). In the MIMOSI applications, the phase patterns are not linear, which requires new algorithms for joint phase processing under nonlinear priors.

Our numerical simulations show that our new algorithm has almost the same performance as Doppler FFT for linear phases and is able to reliably processes phase at Signal to Noise Ratios (SNRs) that are orders of magnitude lower than the working SNR of per-sample phase processing methods currently in use and described in the literature. As a result, with the new algorithm, we can work with very low signal powers or cover wider ranges.

Joint phase processing extracts the phase signal $\boldsymbol{\phi} = (\phi[1], \ldots, \phi[T])$ from the received signal $\boldsymbol{r} = (r[1], \ldots, r[T])$, while taking into account the ambiguity of the mapping from $\phi[n]$ to $r[n]$, namely, adding any integer multiple of 2π to $\phi[n]$ yields the same signal $r[n]$. This implies that we need additional structure on the phase signal to be able to recover it. [1] shows that the minimal necessary and sufficient condition for the unique recovery of $\boldsymbol{\phi}$ is given by

$$C: \max_{n \in [T]} |\phi[n] - \phi[n-1]| \leq \pi.$$

Based on this condition, we proposed in [1] a simple per-sample phase recovery algorithm adopted in almost all publicly available real-time demos (especially for vital signs). This algorithm yields a consistent estimation of $\boldsymbol{\phi}$ at large SNRs when $\boldsymbol{\phi}$ fulfils condition C. Although it does not incur any computational delay, it has several crucial drawbacks:

- It is good for high-SNR scenarios (typically larger than 3 dB) such as live demos but not for practical scenarios where SNR can be very low due to low transmit power, low radar cross section of subjects, or their large distance from radar.
- Meeting condition C typically requires increasing the sampling rate of the signal, thus, using short (low energy) Chirp signals in FMCW radar with lower per-sample SNR.
- This method cannot incorporate the joint structure of the phase signal $\boldsymbol{\phi}$ such as its periodicity, slow variation, etc.

This motivated us to design a new joint phase processing algorithm, which computes the Likelihood Ratio (LR) function of the received signal $r[n]$ in Gaussian noise and constructs the Generalized Likelihood Ratio (GLR) function by computing the maximum of LR with respect to the unknown signal amplitudes. This corresponds to maximizing the following metric

$$\sum_{n \in [T]} g(\phi_r[n] - \phi[n]), \ \boldsymbol{\phi} \in \Phi, \qquad (1)$$

where $\phi_r[n] = \angle r[n]$, where Φ is the space of all valid phase vectors used as a regularization for joint phase processing, and where g is a positive function of period 2π defined by

$$g(x) = \begin{cases} \sin^2(x), & |x| \leq \frac{\pi}{2}, \\ 1, & \frac{\pi}{2} < |x| \leq \pi, \end{cases} \qquad (2)$$

over its single period $x \in [-\pi, \pi]$. Depending on our design of the signal transmission in MIMOSI (tuned for specific application), we adopt a suitable convex constraint set Φ that allows us to impose on $\boldsymbol{\phi}$ conditions such as total variation or sparsity in the FFT domain to model its smoothness and periodicity. Unfortunately, even with a convex constraint set Φ, the optimization (2) remains nonconvex.

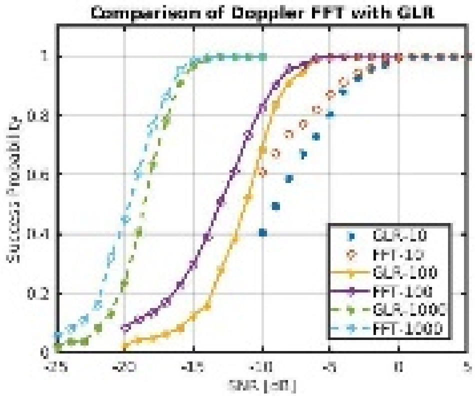

Figure 1: Comparison of Doppler FFT and GLR for different SNR.

Figure 1 illustrates the simulated Doppler FFT with the proposed GLR method for different values of SNR and signal dimensions. In this ideal scenario, phase signal changes linearly and the Doppler FFT is known to be the optimal processing algorithm. Our proposed method has a comparable performance and yields only a minor loss in SNR, especially for large signal dimensions. Also, it processes the phase at very low SNRs (as low as $-10 \log T$), which is almost impossible with the previously adopted per-sample phase processing methods.

Our goal is to extend and use this method for non-linear phase patterns, while keeping efficiency in solving the non-convex optimization problem (2) for the large-dimensional scenarios ($T \sim 10^3 - 10^5$) we may encounter in a variety of sensing applications.

[1] S. Haghighatshoar, J. R. Farserotu, P. Dallemagne, "Generic MIMO Sensor Imager: Theoretical Study, Options, and Recommendations", April 2020.