Simple Self-Repairing Beamforming Algorithm for Faulty Low-Resolution Phase Shifters

Student 30630711: Alexander Li
Monash University ECSE
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Abstract

1 Introduction

Phased array antennas are critical components in modern communication and radar systems, offering dynamic beam steering and spatial filtering through controlled phase shifts at individual antenna elements. However, as systems scale up in complexity and element count, ensuring reliability in the presence of hardware faults becomes a major concern, particularly in cost- and power-constrained environments where low-resolution phase shifters are used.

Recent work has focused on improving the robustness of phased arrays under failure conditions. Munsif and Ullah [1] investigated the impact of faulty phase shifters in conformal array geometries and demonstrated that failures in central phase shifters degrade the beam pattern more severely than those on the edges. They modeled failures as complete deviations to random phase states and employed multi-objective particle swarm optimization (MOPSO) to compensate using the remaining functional elements. Other studies have considered total or random failure modes and applied global optimization techniques—such as particle swarm optimization (PSO) and genetic algorithms—to reconfigure the array [CITE].

In contrast to existing models of complete or random failure, this paper introduces a new fault paradigm specific to low-resolution phase shifters: partial digital failures in which individual bits become stuck due to fragile diode malfunctions. Such partial faults result in a constrained set of achievable output phases per element, depending on which bits remain operable. This nuanced failure mode, though realistic in hardware implementations, has not been addressed in prior literature.

We propose a Simple Self-Repairing Beamforming Algorithm that operates offline, prior to deployment, once the positions and failure modes of the affected phase shifters are known. Rather than globally optimizing over the entire array, we locally adjust the remaining functional bits of the affected phase shifters to produce an output phase as close as possible to the desired ideal phase. By preserving the working hardware and adapting only the control logic, this approach offers a lightweight and hardware-efficient solution for restoring the beam pattern without requiring component replacement or real-time recalibration.

The proposed method is validated through numerical simulations that demonstrate its ability to recover beamforming performance under a variety of partial fault configurations. This contribution opens new pathways for robust beamforming in constrained, low-resolution systems with known pre-mission hardware defects.

2 Problem and Solution Formulation

2.1 System Model with Phase Shifter Quantisation

We consider a uniform linear array (ULA) consisting of $N = 8$ isotropic antenna elements arranged along the x-axis with half-wavelength spacing $d = \lambda/2$. Each element is equipped with a 4-bit digital phase shifter, allowing for $2^4 = 16$ discrete phase states uniformly distributed over the interval $[0, 2\pi)$. The ideal phase shift resolution is thus $\Delta\phi = \frac{2\pi}{16} = \frac{\pi}{8}$.

Let θ denote the angle of departure (or arrival) measured from broadside, and let the desired beam steering direction be θ_0. The ideal progressive phase shift across elements is given by:

$$\phi_n^{\text{ideal}} = -kdn \sin\theta_0 = -\pi n \sin\theta_0, \quad n = 0, 1, \ldots, N-1$$

where $k = \frac{2\pi}{\lambda}$ is the wavenumber. The ideal array factor can be expressed as:

$$AF_{\text{ideal}}(\theta) = \sum_{n=0}^{N-1} w_n e^{j(\phi_n^{\text{ideal}} + kdn \sin\theta)}$$

where w_n is the complex excitation weight, assumed to be uniform and of unit magnitude for all elements (i.e., $w_n = 1$).

Each ideal phase ϕ_n^{ideal} must be quantized to the nearest representable value given the 4-bit resolution. The set of quantized phase values is:

$$\mathcal{Q} = \left\{0, \frac{\pi}{8}, \frac{2\pi}{8}, \ldots, \frac{15\pi}{8}\right\}$$

We represent each 4-bit phase setting as a binary word $[b_3\, b_2\, b_1\, b_0]$, with b_3 as the most significant bit (MSB). The actual quantized phase applied to the n-th element is:

$$\phi_n = \frac{2\pi}{16} \cdot \sum_{i=0}^{3} b_i^{(n)} \cdot 2^i$$

2.2 Fault Model

We consider two types of hardware faults in the digital phase shifters:

- MSB Failures: In this common failure mode, one or more of the most significant bits (e.g., b_3, b_2) are stuck at either 0 or 1 due to diode malfunction. This constrains the phase shifter to a subset of possible output values.
- Random Bit Failures: A more general fault model in which any subset of bits (not necessarily contiguous or most significant) may be stuck, and the failure pattern is randomly assigned across the array.

Given the fault state, each element n has a constrained set of achievable phase values:

$$\mathcal{Q}_n^{\text{faulty}} \subseteq \mathcal{Q}$$

The beamforming task is then to select, for each element, the best achievable phase $\phi_n \in \mathcal{Q}_n^{\text{faulty}}$ that approximates ϕ_n^{ideal}, subject to the constraints of the faulty bits.

The resulting (fault-aware) array factor becomes:

$$AF_{\text{faulty}}(\theta) = \sum_{n=0}^{N-1} e^{j(\phi_n + kdn \sin\theta)}, \quad \phi_n \in \mathcal{Q}_n^{\text{faulty}}$$

The goal of the proposed self-repair algorithm is to minimize the distortion in the radiation pattern due to these bit-level constraints, by selecting the optimal phase from each element's feasible set. This is done offline assuming the failure state of each element is known during hardware inspection.

2.3 Pattern Recovery Algorithm

3 Simulation of Radiation Pattern Recovery

4 Limitations

5 Conclusion

References