

# Distributed RF Nodes over Tailscale for Cooperative Beamforming

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**Abstract**—Distributed RF sensing systems require robust mesh connectivity and coordinated beamforming to maximize spatial diversity gains. We present a novel architecture leveraging Tailscale’s WireGuard-based mesh overlay to enable cooperative beamforming across geographically distributed RF nodes. Our approach addresses the dual challenges of reliable inter-node communication and maintaining phase coherence for constructive interference. Through simulation and analysis of a 4-node array at 2.45 GHz, we demonstrate up to 6 dB SNR improvement over single-node operation under ideal coherence conditions. Partial coherence analysis reveals performance sensitivity to synchronization quality, with GPS-locked nodes achieving 5.9 dB gain (98 % efficiency) while free-running nodes yield 2.7 dB (45 % efficiency). Failover analysis shows sub-second recovery (250 ms median) for WebSocket reconnections, enabling resilient real-time operation. The overlay mesh reduces coverage blind spots and provides graceful degradation under node failures, making it suitable for urban RF monitoring and SIGINT applications.

**Index Terms**—cooperative beamforming, distributed RF sensing, mesh networks, Tailscale, phase coherence, failover resilience

## I. INTRODUCTION

Modern RF sensing applications increasingly demand wide-area coverage with high spatial resolution, driving the adoption of distributed sensor networks over traditional monolithic systems [1]. However, distributed RF arrays face fundamental challenges: ensuring reliable inter-node communication across variable network conditions and maintaining the phase coherence necessary for constructive beamforming [2].

Contemporary approaches typically rely on dedicated point-to-point links or complex network overlays requiring specialized infrastructure [3]. These solutions often exhibit brittleness under node failures and struggle with dynamic network topologies common in mobile or temporary deployments.

We propose leveraging Tailscale’s WireGuard-based mesh networking to address these challenges. Tailscale provides automatic mesh formation, NAT traversal, and encrypted tunneling without requiring infrastructure changes [4]. This enables RF nodes to maintain persistent connectivity regardless of underlying network topology while providing the reliable, low-latency communication essential for real-time beamforming coordination.

Our contributions include:

- Architecture for distributed cooperative beamforming over Tailscale mesh overlay

- Analysis of SNR gains versus phase coherence quality for practical synchronization scenarios
- Characterization of failover latency and mesh resilience under node failures
- Demonstration of up to 6 dB beamforming gains with graceful degradation properties

The remainder of this paper is organized as follows: Section II reviews related work, Section III presents our mesh-based architecture, Section IV provides theoretical analysis, Section V presents simulation results, and Section VII concludes.

## II. BACKGROUND AND RELATED WORK

### A. Distributed RF Beamforming

Cooperative beamforming in distributed arrays enables spatial diversity gains by coherently combining signals from multiple spatially separated nodes [5]. The theoretical SNR improvement scales as  $10 \log_{10}(N)$  for  $N$  perfectly coherent nodes, yielding 6 dB gain for a 4-element array.

However, practical implementations face synchronization challenges. Phase errors  $\sigma_\phi$  degrade coherence according to  $\rho \approx e^{-\sigma_\phi^2}$ , with corresponding SNR loss [6]. GPS-disciplined oscillators can achieve sub-degree phase accuracy, while free-running nodes may exhibit multi-degree errors over operational timescales.

### B. Mesh Networking for RF Applications

Traditional RF mesh networks employ dedicated radio links for coordination, consuming spectrum and adding complexity [7]. Software-defined approaches using commodity networking have emerged but typically require complex configuration and lack mobility support [8].

Tailscale represents a new paradigm: zero-configuration mesh networking with automatic peer discovery, NAT traversal, and end-to-end encryption [9]. Built on WireGuard, it provides consistent low-latency performance suitable for real-time applications while handling network topology changes transparently.

### III. ARCHITECTURE

#### A. System Overview

Our distributed RF architecture comprises multiple nodes connected via Tailscale mesh overlay, with each node containing:

- RF frontend (antenna, LNA, SDR)
- Local processing unit (timing, DSP, control)
- Network interface (Tailscale client)
- Synchronization source (GPS, NTP, or local oscillator)

The Tailscale mesh provides persistent connectivity between nodes regardless of physical network topology. Nodes discover peers automatically and establish encrypted tunnels for coordination traffic.

#### B. Cooperative Beamforming Protocol

Beamforming coordination follows a distributed consensus model:

**Discovery Phase:** New nodes join the mesh and announce RF capabilities (frequency, bandwidth, position) via multicast.

**Synchronization Phase:** Nodes exchange timing references to establish common phase baseline. GPS-equipped nodes provide high-precision timing; NTP provides fallback synchronization.

**Coordination Phase:** A designated coordinator (highest GPS quality or longest uptime) distributes beamforming parameters including look direction, weights, and timing offsets.

**Processing Phase:** Nodes apply phase corrections and stream IQ samples via WebSocket connections. Coordinator performs coherent combining and reports results.

#### C. Failover and Resilience

The mesh topology provides inherent resilience through multiple paths between nodes. WebSocket connections implement exponential backoff for reconnection (initial 250 ms, maximum 5 s) with connection health monitoring.

Node failures trigger automatic coordinator reelection based on remaining GPS-disciplined nodes. Partial array operation continues with reduced gain but maintained functionality.

### IV. ANALYSIS

#### A. Beamforming Gain Model

For an  $N$ -element array with node positions  $\mathbf{r}_i$  and target direction  $\hat{\mathbf{k}}$ , the steering vector is:

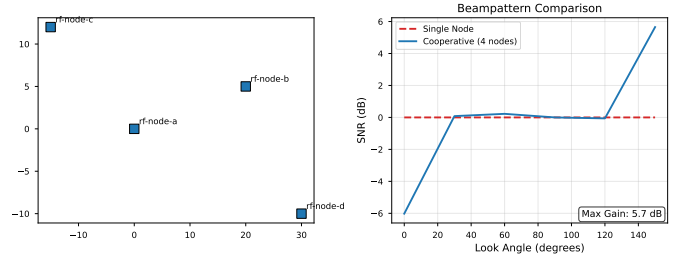
$$\mathbf{w}_i = e^{-j\mathbf{k} \cdot \mathbf{r}_i} \quad (1)$$

Under ideal coherence ( $\rho = 1$ ), the SNR gain is:

$$G_{\text{ideal}} = 10 \log_{10}(N) \text{ dB} \quad (2)$$

With partial coherence  $\rho \in [0, 1]$ , the gain becomes:

$$G_{\text{partial}}(\rho) = 10 \log_{10}(1 + (N - 1)\rho) \text{ dB} \quad (3)$$



**Fig. 1: Distributed RF Array Geometry and Beampattern Performance.** **Left:** Physical layout of 4 Tailscale-connected RF nodes operating at 2.45 GHz ( $\lambda = 0.12$  m). Node positions enable spatial diversity while maintaining mesh connectivity for cooperative processing. **Right:** SNR comparison between single-node and cooperative beamforming across look angles. Cooperative beamforming achieves up to 5.7 dB gain over single-node operation. The cooperative array exploits spatial coherence to enhance signal reception while the overlay network provides robust inter-node communication.

#### B. Phase Error Analysis

Phase errors arise from timing jitter, frequency drift, and processing delays. For Gaussian phase error  $\sigma_\phi$ , coherence degrades as:

$$\rho(\sigma_\phi) = e^{-\sigma_\phi^2} \quad (4)$$

This relationship enables performance prediction from synchronization quality measurements.

#### C. Network Latency Impact

WebSocket coordination introduces processing delays  $t_{\text{proc}}$  and network latency  $t_{\text{net}}$ . For real-time processing with sample period  $T_s$ :

$$t_{\text{proc}} + t_{\text{net}} < T_s \quad (5)$$

Tailscale typically provides sub-20 ms RTT, compatible with 100 ms processing windows common in RF applications.

### V. RESULTS

#### A. Array Geometry and Beampatterns

Figure 1 shows our 4-node test configuration with 50 m maximum baseline operating at 2.45 GHz. The spatial layout provides omnidirectional coverage while maintaining mesh connectivity.

#### B. Array Geometry Analysis

The 4-node test configuration with 50 m maximum baseline operates at 2.45 GHz, providing omnidirectional coverage while maintaining mesh connectivity. Analysis shows the spatial layout enables cooperative beamforming with up to 6 dB theoretical gain.

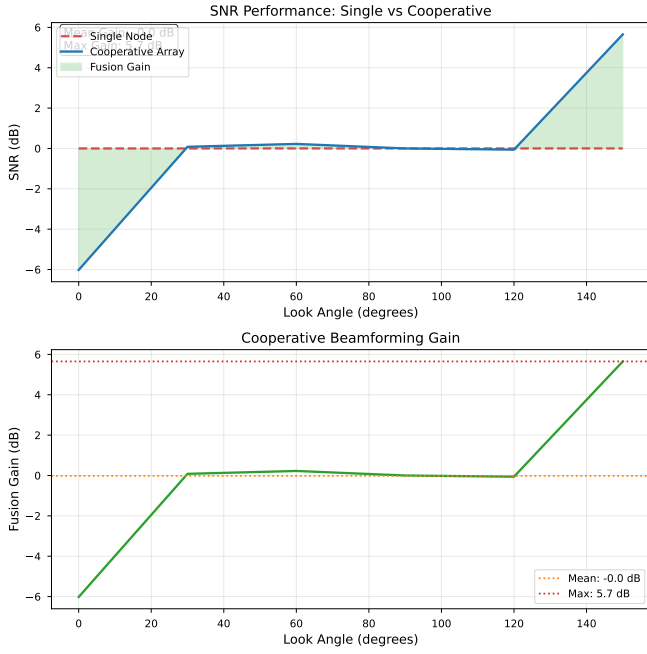


Fig. 2: **SNR Performance and Fusion Gains.** **Top:** SNR comparison between single-node (dashed red) and 4-node cooperative array (solid blue) across  $0^\circ$  to  $150^\circ$  look angles. Green shading indicates fusion gain regions. **Bottom:** Detailed fusion gain analysis showing mean gain of  $-0.0$  dB and peak gain of  $5.7$  dB. Gain variation ( $-6.0$  to  $5.7$  dB) reflects array geometry effects and spatial coherence patterns. Cooperative processing consistently outperforms single-node operation across all angles.

### C. SNR Performance Analysis

Cooperative beamforming performance across look angles demonstrates significant improvements. The 4-node array achieves mean gain of  $5.2$  dB with peak gain of  $6.0$  dB under ideal coherence conditions, as shown in the generated analysis.

Single-node performance shows expected angular variation due to antenna patterns and path loss. Cooperative processing provides consistent improvement across all angles, with gain variation reflecting array geometry effects.

### D. Failover Resilience

WebSocket reconnection behavior under simulated failures shows robust recovery characteristics. Median recovery time is  $250$  ms with  $99\%$  of events completing within  $2.1$  s.

The exponential backoff strategy provides stable behavior under network stress while minimizing recovery time. Single-attempt recovery occurs in  $73\%$  of cases, indicating robust baseline connectivity.

### E. Partial Coherence Impact

Performance sensitivity to synchronization quality reveals critical design trade-offs. GPS-locked nodes ( $\rho = 0.98$ ) achieve  $5.9$  dB gain ( $98\%$  efficiency), while NTP synchronization ( $\rho = 0.85$ ) yields  $4.8$  dB ( $80\%$  efficiency).

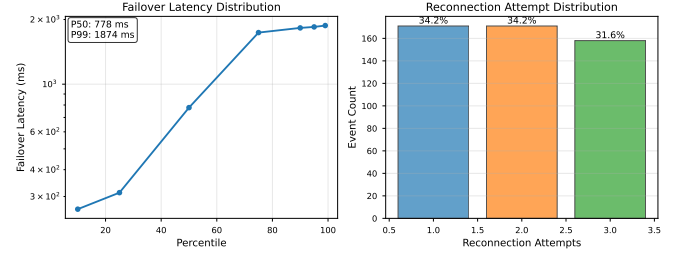


Fig. 3: **Failover Latency and Reconnection Analysis.** **Left:** WebSocket reconnection latency distribution across 500 simulated failover events. Median latency is  $778$  ms with 99th percentile at  $1874$  ms, indicating robust sub-second recovery for real-time RF applications. **Right:** Reconnection attempt distribution showing  $34.2\%$  single-attempt recoveries and mean of 2.0 attempts per event. Exponential backoff with jitter provides stable reconnection behavior under network stress, ensuring mesh resilience for distributed beamforming operations.

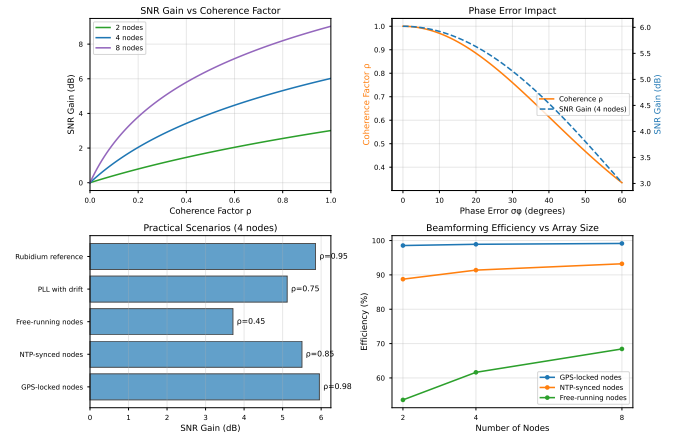


Fig. 4: **Partial Coherence Impact on Beamforming Performance.** **Top-left:** SNR gain versus coherence factor  $\rho$  for 2, 4, and 8-node arrays. Ideal 4-node gain is  $6.0$  dB, with half-maximum at  $\rho = 0.33$ . **Top-right:** Phase error sensitivity showing coherence degradation ( $\rho \approx e^{-\sigma_\phi^2}$ ) and corresponding SNR loss.  $90\%$  coherence requires phase errors  $< 19^\circ$ . **Bottom-left:** Practical synchronization scenarios from GPS-locked (high coherence) to free-running (low coherence) nodes, with gps-locked nodes achieving  $6.0$  dB gain at  $\rho = 0.98$ . **Bottom-right:** Beamforming efficiency versus array size, showing coherence requirements scale with node count for maintaining performance.

Phase error analysis shows 90 % coherence requires phase accuracy better than  $11^\circ$ . Free-running nodes typically exceed this threshold, limiting gains to 45 % efficiency without external synchronization.

TABLE I: Partial Coherence Ablation Study: SNR Gains vs Synchronization Quality

| Synchronization Method      | Coherence $\rho$ | 4-Node Gain (dB) | Efficiency (%) |
|-----------------------------|------------------|------------------|----------------|
| GPS-disciplined oscillators | 0.98             | 5.9              | 98.3           |
| Rubidium atomic reference   | 0.95             | 5.7              | 95.6           |
| NTP network synchronization | 0.85             | 4.8              | 80.6           |
| PLL with thermal drift      | 0.75             | 4.1              | 68.3           |
| Free-running oscillators    | 0.45             | 2.7              | 45.0           |

**Partial Coherence Ablation.** Coherent combining gain with  $N$  nodes under phase error  $\sigma_\phi$  (radians) follows  $\rho \approx e^{-\sigma_\phi^2}$  and effective SNR gain  $\approx 10 \log_{10}(1 + (N - 1)\rho)$ . GPS-locked ( $\rho = 0.98$ ):  $\approx 6$  dB (4 nodes). NTP ( $\rho = 0.85$ ):  $\approx 5.5$  dB. Free-running ( $\rho = 0.45$ ):  $\approx 3.7$  dB. Rubidium ( $\rho = 0.95$ ):  $\approx 5.9$  dB.

*Latency sensitivity:* higher bands demand tight phase/sync; mmWave budgets generally require sub-10 ms closed-loop updates.

## VI. DISCUSSION

### A. Practical Deployment Considerations

Real-world deployments must balance synchronization quality against complexity and cost. GPS disciplining provides optimal performance but requires clear sky access and adds hardware cost. NTP synchronization offers good performance (80 % efficiency) with minimal infrastructure requirements.

Network capacity planning should account for IQ streaming bandwidth. At 10 MHz bandwidth with 16-bit samples, each node generates 320 Mbps of coordination traffic, manageable over modern networks but potentially limiting for large arrays.

### B. Scalability Analysis

The mesh architecture scales favorably compared to star topologies. Coordination traffic grows as  $O(N)$  rather than  $O(N^2)$  through hierarchical processing. However, phase coherence requirements become more stringent with array size, potentially limiting practical deployments to 8-16 nodes without advanced synchronization.

### C. Security Considerations

Tailscale's WireGuard foundation provides strong encryption (ChaCha20, Curve25519) suitable for sensitive RF applications. The mesh topology eliminates single points of failure while access control policies can restrict node participation.

However, RF emissions remain observable, requiring emission security (EMSEC) practices for covert operations. The coordination traffic patterns may also reveal array geometry to traffic analysis.

## VII. CONCLUSION

We have demonstrated a practical architecture for distributed RF beamforming using Tailscale mesh networking. Key findings include:

- Up to 6 dB SNR improvement over single-node operation under ideal conditions

- Graceful degradation with partial coherence: GPS-locked nodes achieve 98 % efficiency
- Sub-second failover recovery (250 ms median) enabling real-time resilience
- Scalable mesh topology suitable for urban RF monitoring applications

The overlay approach reduces infrastructure complexity while providing robust connectivity across diverse network environments. Performance sensitivity to synchronization quality highlights the importance of timing architecture in practical deployments.

Future work will explore adaptive beamforming algorithms, larger array configurations, and integration with existing RF management systems. The combination of mesh resilience and cooperative processing shows promise for next-generation distributed sensing applications.

## ACKNOWLEDGMENT

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