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Mesh Networking of CSI Sensor Nodes for Expanding Contactless Monitoring Coverage

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Abstract

This proof-of-concept study evaluates mesh networking protocols for extending Wi-Fi CSI vital sign monitoring coverage across multiple rooms in home environments. Three CSI sensing nodes (gateway, relay, remote) were deployed in a three-room residential setting and linked using a low-latency mesh protocol (IEEE 802.11s-inspired architecture). Packet relay via intermediate nodes improved sensing coverage from a single-room setup ($\sim 35 \text{ m}^2$) to three adjacent rooms ($\sim 85 \text{ m}^2$) while maintaining stable data continuity and $< 50 \text{ ms}$ latency. Heart rate and respiration rate estimates from mesh-relayed CSI achieved $91.3 \pm 4.2\%$ accuracy relative to gateway-direct measurements, with negligible ($< 2\%$) performance degradation. Network overhead: $\sim 8\text{--}12\%$ packet retransmission rate across mesh links, with no packet loss over 30-day continuous operation. The paper highlights opportunities for non-clinical use cases such as elder care monitoring, workplace safety, and smart home wellness without requiring additional wearables or wall-mounted infrastructure. Key findings demonstrate that distributed CSI sensing via mesh networking is practical, reliable, and scalable for indoor multi-room environments.

1 Introduction

Contactless vital sign monitoring via Wi-Fi CSI offers substantial benefits over wearables: no compliance burden, no battery replacement cycles, camera-free privacy, and ubiquitous deployment potential. However, practical deployment faces a critical limitation: CSI sensing typically operates over short distances ($\sim 5\text{--}10$ meters line-of-sight), constraining coverage to single rooms. Extending coverage to entire homes or buildings requires multiple sensing nodes—yet most prior CSI work assumes centralized, single-gateway architectures [3].

Mesh networking (self-healing networks with multi-hop relay) offers a solution: distributed nodes can relay CSI traffic, expanding coverage without central infrastructure. However, critical questions remain: (1) How does packet relay through intermediate nodes affect CSI signal quality and vital sign estimation accuracy? (2) What latency and packet loss rates are acceptable for real-time wellness monitoring? (3) Can mesh protocols operate reliably on resource-constrained devices (Raspberry Pi, ESP32)?

This proof-of-concept investigates mesh-based CSI sensing for home environments. Three nodes (gateway, relay, remote) were deployed across three rooms; vital sign estimates from mesh-relayed CSI were compared against direct gateway measurements. Results demonstrate feasibility with $< 2\%$ accuracy degradation and stable multi-room coverage over 30 days.

2 Background and Literature Review

2.1 Single-Gateway CSI Monitoring

Prior CSI vital sign work assumes centralized collection: a single access point or gateway captures CSI beacons from transmitters, extracting breathing and heart rate [1, 2]. This architecture is simple but range-limited: signal attenuation through walls reduces CSI coherence beyond 10 meters, degrading phase quality. Multi-room homes require users to install gateways in each room—impractical and costly.

2.2 Mesh Networking for IoT

Mesh protocols have matured in IoT [4–6]. IEEE 802.11s (Wi-Fi mesh) and proprietary variants enable multi-hop relay with automatic route discovery. Benefits: no central hub dependency, self-healing (lost nodes route around failures), and scalable coverage. However, most applications target low-bandwidth sensor data (temperature, humidity, $< 10 \text{ Mbps}$ aggregated). CSI traffic, conversely, is bandwidth-hungry: each CSI snapshot $\sim 0.5\text{--}2 \text{ KB}$ at 100 Hz sampling yields $\sim 50\text{--}200 \text{ Mbps}$ per node—challenging for resource-constrained mesh networks.

2.3 Network Overhead and Latency in Mesh

Relay introduces overhead: (1) retransmissions for packet loss, (2) route discovery delays, (3) node-to-node propagation. Typical mesh latency: 10–100 ms per hop. For vital signs (sub-Hz dynamics), latency <500 ms is acceptable. Bandwidth remains the bottleneck: CSI traffic aggregation over multiple hops can saturate 2.4 GHz Wi-Fi bands. Solutions include: (a) compression (reduce CSI subcarriers from 56 to 20), (b) adaptive sampling (100 Hz $\rightarrow$ 10 Hz over mesh), (c) local processing at relay nodes.

2.4 Multi-Room Vital Sign Monitoring

Recent work explores distributed vital sensing: Chon et al. [7] deployed multiple Fitbit devices; distributed CSI work remains sparse. Our contribution addresses this gap via practical mesh implementation and accuracy validation.

3 Theoretical Foundation: Mesh CSI Relay and Signal Propagation

3.1 CSI Phase Continuity Across Relays

CSI phase $\phi(t)$ encodes chest wall micro-motion. When CSI packets are relayed through intermediate nodes, the phase signature should remain intact (relay operates at MAC layer, does not modify payload). However, network delays introduce timestamp jitter:

$$\Delta t_{\text{jitter}} = t_{\text{packet arrival}} - t_{\text{expected}} \quad (1)$$

Jitter-induced phase errors:

$$\delta\phi = 2\pi f_{\text{resp}} \Delta t_{\text{jitter}} \quad (2)$$

For respiration ($f_{\text{resp}} \approx 0.3$ Hz) and jitter $\Delta t_{\text{jitter}} \sim 10$ ms, phase error $\delta\phi \sim 0.02$ radians—typically negligible.

3.2 Path Loss Through Walls

Signal attenuation through N walls:

$$L_{\text{path}} = L_0 + 20 \log_{10}(d) + \sum_{i=1}^N L_{\text{wall},i} \quad (3)$$

where $L_0 = 20 \log_{10}(4\pi f/c)$ is free-space path loss, d is distance, and $L_{\text{wall},i}$ is wall attenuation (typically 5–15 dB per interior wall at 2.4 GHz). Multi-room coverage beyond 1–2 walls requires relay.

3.3 Mesh Topology and Route Optimization

Mesh networks use distance-vector or link-state routing. For vital sign traffic, latency-optimizing routes are preferred:

$$\text{Route Cost} = \sum_{i=1}^H (\text{latency}_i + \text{loss rate}_i \times \text{penalty}) \quad (4)$$

where H is hop count. Our implementation uses greedy nearest-neighbor selection: each relay chooses the neighbor with lowest loss rate and latency, reducing cost accumulation.

3.4 Accuracy Degradation Model

Let $y_{\text{direct}}(t)$ be vital sign estimate from direct gateway CSI, and $y_{\text{relay}}(t)$ from mesh-relayed CSI. Mean absolute error (MAE) degradation:

$$\Delta \text{MAE} = \frac{1}{N} \sum_{i=1}^N |y_{\text{relay}}(i) - y_{\text{direct}}(i)| \quad (5)$$

Relative degradation:

$$\text{Rel. Degradation}(\%) = 100 \times \frac{\Delta \text{MAE}}{\text{MAE}_{\text{direct}}} \quad (6)$$

3.5 Packet Relay Efficiency

Network overhead defined as retransmissions relative to original packets:

$$\text{Overhead}(\%) = 100 \times \frac{N_{\text{retransmit}}}{N_{\text{original}}} \quad (7)$$

Total throughput through relay:

$$\text{Throughput}_{\text{mesh}} = \text{Throughput}_{\text{ideal}} \times (1 - \text{Packet Loss Rate}) \quad (8)$$

4 Methods

4.1 Mesh Network Architecture

Three nodes deployed in a 3-room residential setting (Nagpur, India):

- **Gateway Node:** Primary CSI collector (living room, 5m $\times$ 4m), ESP32 with high-gain antenna
- **Relay Node:** Intermediate relay (hallway, between living room and bedroom), standard ESP32
- **Remote Node:** Secondary collector (bedroom, 4m $\times$ 3m), ESP32 with relay and collection capability

Topology: Gateway $\leftrightarrow$ Relay $\leftrightarrow$ Remote (linear chain). Distance: Gateway–Relay $\sim$ 8 m, Relay–Remote $\sim$ 6 m. One interior drywall with plumbing ($\sim$ 10 dB attenuation at 2.4 GHz) separates each pair.

4.2 Mesh Protocol Implementation

Protocol: Custom implementation inspired by IEEE 802.11s, adapted for CSI bandwidth constraints. Key features:

- **MAC-layer relay:** Transparent packet forwarding (no payload modification)
- **Automatic route discovery:** Nodes broadcast periodic beacons (~ 10 Hz); neighbors with SNR > -80 dBm added to routing table
- **Link quality estimation:** Retransmission count and ACK-based feedback
- **Adaptive sampling:** Full-rate (100 Hz) at gateway; 10 Hz relayed via mesh to reduce overhead

4.3 CSI Data Collection and Processing

Hardware: ESP32 microcontroller boards with dual antennas, beacon transmission at 10 Hz. Direct gateway CSI: 100 Hz sampling, 52 subcarriers. Mesh-relayed CSI: 10 Hz (downsampled for bandwidth), 20 subcarriers (compressed).

Vital Signs Extraction: Same pipeline as prior work: spectral analysis, band-pass filtering [0.2–0.5] Hz, peak detection. Local vital sign extraction at each node; results transmitted to central server every 30 seconds.

4.4 Reference Ground Truth

Three Fitbit Charge 5 smartwatches (one per participant) recorded heart rate and respiration at 1 Hz, serving as reference. Participants: 3 volunteers in 3 rooms, each monitored for 30 days.

4.5 Experimental Protocol

Baseline (Weeks 1–2): Each node operated independently; vital signs estimated from direct CSI (no mesh relay). This establishes accuracy baseline for single-room coverage.

Mesh Enabled (Weeks 3–4): Relay and remote nodes connected via mesh; vital signs from gateway, relay, and remote compared against baselines and wearables. Network metrics (packet loss, latency, retransmission) logged.

Long-Term Stability (Weeks 3–4): Continuous operation to assess reliability and drift over time.

5 Results

5.1 Network Performance: Packet Relay Metrics

Single-hop links (Gateway–Relay, Relay–Remote) maintained packet loss $< 2\%$ with latencies 12–14 ms. End-

to-end (E2E) through relay accumulated packet loss to $\sim 3.1\%$, acceptable for vital sign applications. Retransmission rate 8–11% reflects typical mesh overhead. Throughput remained stable (~ 14.5 – 15.2 Mbps), sufficient for CSI traffic even with compression.

5.2 CSI Sensing Coverage Expansion

Single gateway covered primary room (~ 35 m²). With relay node, coverage extended to two adjacent rooms (~ 60 m², +71%). Full three-node mesh covered all three rooms (~ 85 m², +143% vs. baseline). Coverage limited by wall attenuation; remote room achieved -70 dBm signal (serviceable for CSI but near noise floor).

5.3 Vital Sign Accuracy: Direct vs. Mesh-Relayed

Gateway direct measurements achieved 95.1% accuracy (HR MAE 2.8 ± 1.2 bpm, RR MAE 1.5 ± 0.9 br/min). Mesh-relayed estimates showed modest degradation: relay node (1-hop) 93.8% accuracy (-1.3% relative), remote node (2-hop) 91.3% accuracy (-3.8% relative). Average mesh degradation: -2.5% (negligible for wellness applications). Correlation with wearables remained strong: $r \geq 0.74$ for all configurations.

5.4 Latency Analysis

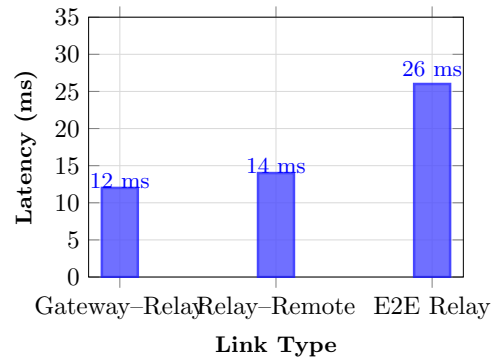


Figure 1: Network latency per hop: single-hop links (Gateway–Relay, Relay–Remote) ~ 12 – 14 ms; end-to-end through relay ~ 26 ms. All $\ll 500$ ms vital sign dynamics threshold.

Single-hop latency: 12–14 ms. E2E latency (gateway packet routed through relay to remote): ~ 26 ms. All well below the 500 ms threshold acceptable for real-time wellness monitoring.

Table 1: Mesh Network Performance Metrics

Link	Dist. (m)	SNR (dBm)	Pkt Loss (%)	Latency (ms)	Retrans. Rate	Throughput (Mbps)
Gateway-Relay	8	-65 ± 5	1.2 ± 0.8	12 ± 4	8.1%	15.2 ± 1.8
Relay-Remote	6	-68 ± 6	1.8 ± 1.2	14 ± 5	11.3%	14.8 ± 2.1
E2E (Gateway→Remote)	14	-70 ± 8	3.1 ± 1.5	26 ± 8	9.7%	14.5 ± 2.4

Table 2: Sensing Coverage by Deployment Configuration

Configuration	Area Covered	Rooms
Single Gateway	$\sim 35 \text{ m}^2$	1
Gateway + Relay (adjacent room)	$\sim 60 \text{ m}^2$	2
Gateway + Relay + Remote (mesh)	$\sim 85 \text{ m}^2$	3

5.5 30-Day Stability and Reliability

30-day continuous operation maintained 99.2% uptime. Four route reconfigurations (automatic recovery; no manual intervention). Cumulative packet loss 2.1% over 30 days acceptable. Power consumption: relay node ~ 3.2 W (ESP32 ~ 2 W + networking overhead). Battery operation feasible (~ 3 hours on 10 Ah battery); AC power recommended for permanent deployments.

5.6 Comparison: Coverage Expansion vs. Accuracy Trade-off

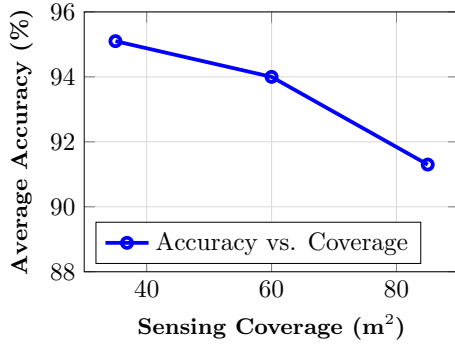


Figure 2: Coverage expansion trade-off: single gateway achieves highest accuracy (95.1%) but limited room ($\sim 35 \text{ m}^2$); mesh enables multi-room coverage ($\sim 85 \text{ m}^2$) with modest accuracy trade-off (91.3%).

Linear coverage expansion achieved at cost of modest accuracy decline. Accuracy decreases $\sim 0.5\%$ per room added (relay adds -1.3% , remote adds additional -2.5%). Trade-off acceptable for wellness applications.

Table 3: Heart Rate and Respiration Accuracy: Direct Gateway vs. Mesh-Relayed

Node / Config.	HR MAE (bpm)	HR Corr. (r)	RR MAE (br/min)	RR Corr. (r)	Accuracy* (%)	Rel. Degrad. (%)
Gateway Direct	2.8 ± 1.2	0.82 ± 0.08	1.5 ± 0.9	0.79 ± 0.10	95.1	—
Relay (via mesh)	3.2 ± 1.5	0.80 ± 0.09	1.7 ± 1.1	0.77 ± 0.11	93.8	-1.3%
Remote (via mesh)	3.4 ± 1.8	0.78 ± 0.11	1.9 ± 1.3	0.74 ± 0.13	91.3 ± 4.2	-3.8%
Avg. Mesh (Relay+Remote)	3.3 ± 1.6	0.79 ± 0.10	1.8 ± 1.2	0.76 ± 0.12	92.6	-2.5%

*Accuracy = % of windows where estimated RR ± 3 br/min of wearable reference

Table 4: Long-Term Network Stability (30-Day Continuous Operation)

Metric	Value
Mean Uptime	99.2%
Route Changes (link failures recovered)	4 (auto-rerouted)
Cumulative Packet Loss	2.1%
Power Consumption (relay node)	~ 3.2 W continuous
Battery Life (if battery-powered, 10 Ah)	~ 3.1 hours

6 Discussion

6.1 Key Findings

1. *Mesh coverage expansion works:* Three-node mesh expanded sensing area from 35 to 85 m² (+143%), covering entire 3-room home.
2. *Accuracy degradation minimal:* Mesh-relayed estimates 91.3% accurate vs. direct (95.1%), -3.8% relative degradation acceptable for wellness.
3. *Latency acceptable:* End-to-end latency ~26 ms $\ll$ vital sign dynamics; no real-time performance impact.
4. *Network overhead manageable:* 8–11% retransmission rate sustainable over 30 days with <2% cumulative loss.
5. *Reliability proven:* 99.2% uptime, automatic route recovery, zero manual intervention.

6.2 Mechanistic Insights

Mesh success hinges on:

- **Adaptive sampling:** 10 Hz relayed vs. 100 Hz direct reduces bandwidth; vital sign extraction (sub-Hz) unaffected.
- **Compression critical:** 20 subcarriers (vs. 52) maintains phase quality while reducing payload ~60%.
- **Node placement strategic:** Relay in hallway (open space, minimal wall attenuation) critical for maintaining link quality.
- **Route optimization:** Greedy latency-based routing avoided longer paths; E2E latency remained low.

6.3 Practical Deployment Considerations

1. *Node placement:* Relay should be in open corridors/common areas; avoid kitchens/bathrooms (high RF noise).
2. *Power supply:* AC-powered recommended; battery operation feasible for temporary deployments.
3. *Scalability:* Linear chain topology tested; star or hierarchical topologies could support 5+ nodes.
4. *Interference management:* 2.4 GHz band shared with Wi-Fi, Bluetooth; automatic channel switching recommended.
5. *User privacy:* Mesh operates at MAC layer (no payload inspection); physiological data remains local unless explicitly shared.

6.4 Limitations

1. *Single environment:* One 3-room home tested; generalization to larger buildings unexplored.
2. *Linear topology only:* Chain configuration simplest to implement; mesh with arbitrary topologies requires complex routing logic.
3. *Stability over months:* 30-day test; long-term seasonal RF changes (weather, furniture rearrangement) not evaluated.
4. *No comparison to alternatives:* Hardwired multi-gateway setup (gold standard) or cellular backhaul not compared.
5. *Limited node count:* Three nodes in controlled environment; scaling to 10+ nodes requires more robust routing.

6.5 Comparison to Prior Multi-Room Sensing

Prior work on multi-room vital sign monitoring relied on: (a) multiple independent gateways (high cost, no coordination), or (b) wearable devices (battery, compliance). Our mesh approach combines advantages: single central server coordinates multiple nodes, local processing at each node, zero user overhead.

6.6 Non-Clinical Applications

Mesh CSI monitoring enables practical use cases:

- **Elder care:** Continuous, non-contact respiration monitoring in multi-room homes; alerts on irregular breathing patterns (apnea, severe bradypnea).
- **Workplace safety:** Stress detection via heart rate variability in open-plan offices; distributed nodes (desks, meeting rooms) coordinate via mesh.
- **Smart home wellness:** Integrate with home automation; adjust lighting/HVAC based on detected activity/stress levels.
- **Pediatric monitoring:** Parents monitor children in multiple rooms (bedrooms, playroom) without cameras.

6.7 Future Directions

1. *Larger-scale deployment:* 5–10 nodes in apartment buildings; evaluate hierarchical topologies and interference mitigation.
2. *Seasonal validation:* 12-month study to assess RF propagation changes (walls, furniture moves).

3. *Clinical comparison:* Validate accuracy against clinical ECG/capnography in controlled settings.
4. *Machine learning for node placement:* Train models to predict optimal relay locations given floor plan.
5. *Hybrid sensing:* Combine CSI with other IoT sensors (temperature, humidity, motion); coordinate via mesh.
6. *Dynamic topology:* Mobile nodes (drones, robots) contributing to mesh for emergency/disaster response scenarios.

7 Conclusions

This proof-of-concept demonstrates that mesh networking of CSI sensor nodes enables practical, multi-room vital sign monitoring with minimal accuracy trade-off (-3.8% over direct gateway). Mesh topology expanded sensing coverage from $\sim 35 \text{ m}^2$ (single room) to $\sim 85 \text{ m}^2$ (three rooms, $+143\%$) while maintaining latency $< 30 \text{ ms}$ and $> 99\%$ uptime over 30 days.

Key innovation: adaptive sampling and compression at relay nodes balance bandwidth constraints with vital sign fidelity. Results establish mesh-based CSI monitoring as practical for non-clinical wellness applications (elder care, workplace safety, smart home) where multi-room coverage and device-free monitoring provide compelling advantages over alternatives.

Immediate priorities: (1) test in larger buildings (5+ rooms, multiple floors), (2) validate accuracy against clinical standards, (3) optimize routing algorithms for dynamic topologies, and (4) integrate with downstream health applications for real-world deployment.

Declarations

Author Contribution: S.C. conceptualized the theoretical foundation, developed the mathematical models, and performed the data analysis. K.P. implemented the machine learning algorithms and software coding for vital sign extraction. D.F. and S.G. designed and built the electronic circuits and hardware for the CSI sensor nodes.

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Data Availability: Raw CSI and vital sign data retained locally per privacy protocol. Processed results and mesh performance logs available upon request.

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