# Why AI-enabled drone swarms need mesh ranging radios

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## Introduction

As the AI boom expands in full swing, innovative techniques to solve the demands for communication at higher-and-higher data rates must be developed. In data centers, this is already visible: the industry is moving toward high-radix Ethernet fabrics, optical interconnects, co-packaged optics, and carefully scheduled traffic because model training and distributed inference are increasingly network-bound. In heavy edge-compute networks where wired optical links are impractical, it will fall upon wireless link architectures to innovate.

> "The network is ultimately responsible for AI performance." **- NVIDIA**[1]

This exact bottleneck is arriving at the frontier of academia. Autonomous drones, robots, and sensor teams increasingly depend on local AI models, visual-inertial odometry, LiDAR mapping, collaborative SLAM, cooperative perception, and distributed planning. These systems do not merely exchange commands. They exchange features, descriptors, keyframes, map fragments, model outputs, poses, covariances, and health telemetry. A swarm is therefore not just a group of aircraft. It is a moving, wireless, compute cluster.

Beyond high datarate links, there are other constraining factors in the innovation of drone swarm technology. Scalability: how do you efficiently communicate in a network of hundreds of drones where each node begins to distort its many neighbors?

> ***The U.S. Department of Defense's Replicator initiative was built around the premise that thousands of attritable autonomous systems may need to be fielded quickly across domains.*** [3]

At the same time, the positioning assumptions behind many drone systems are breaking. GNSS denial and spoofing are becoming ever-present operational realities in contested and industrial environments.

> ***Open reporting on the Black Sea and Ukraine region describes persistent, dynamic GNSS interference campaigns that degrade navigation for aircraft, ships, and drones.*** [2]

In order for drone swarms to effectively coordinate, both local and relative positioning have to be accounted for, without GNSS. The state-of-the-art ranging solution lies in collaborative SLAM; however, it relies on high-throughput wireless links and fails catastrophically in degraded visual conditions.

The conventional response is to use UWB for ranging. This comes with several key limitations:

1. Each UWB radio comes as a detriment to cost and SWaP from hardware overhead in board area, antennas, power consumption, and integration complexity
2. UWB pulses introduce distortion into adjacent communication transceivers, creating RF coexistence problems that become significantly more severe with scaling
3. UWB suffers from significant latency constraints from scheduled polling cycles, to the point where reliable ranging begins to fail at 10+ UAVs

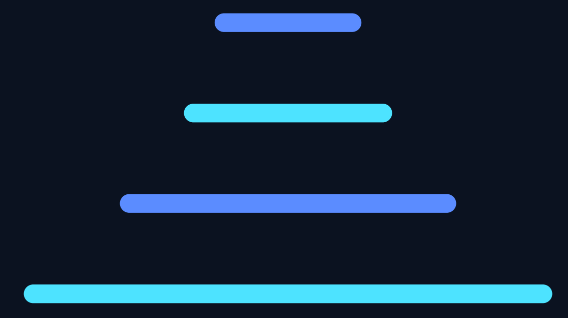
The key takeaway: UWB scales poorly.

**The Idea**

Integrated Sensing and Communications (ISAC) collapses this stack. Instead of carrying data on one radio and measuring range on another, the swarm radio itself becomes a source of range, timing, channel, and uncertainty measurements.

Integrating the range sensing layer into the communication layer is a novel way to eliminate these drawbacks. Simultaneously achieving sub-meter precision ranging and multi-Mbps throughput will be challenging; despite this, Centurion Tech has devised Phalanx, a RF hardware-to-protocol-level stack to subvert these challenges and solve this problem with a cross-domain solution. The time is now. Geopolitics is pushing the pace of AI and drone innovation to an explosive sprint. Centurion Tech Inc. will pioneer the radio technology that will serve as the crux of the incoming autonomy age.

**Figure 1. Wireless data demand is rising while autonomy adds local burst traffic.**



| Metric | Value | Relative scale |
|---|---|---|
| Global mobile data traffic, 2025 | 146 EB/month | |
| Total mobile network traffic incl. FWA, 2025 | 203 EB/month | |
| Global mobile data traffic, 2031 forecast | 328 EB/month | |
| Total mobile network traffic incl. FWA, 2031 forecast | 515 EB/month | |

Ericsson forecasts total mobile data traffic of 328 EB/month in 2031 and total mobile network traffic including fixed wireless access of 515 EB/month. The drone-swarm problem is smaller in absolute traffic, but harsher in latency, mobility, RF contention, and link volatility. [5]

Table 1: The macro trend is clear: wireless networks are being asked to carry more data, more intelligence, and more control-critical traffic.

# Why a Mesh Ranging Radio?

ISAC Radios offer several fundamental benefits compared to other sensing and communication stackups, especially when deployed at scale. Significant cost savings can be achieved by embedding sensing into the already-necessary high bandwidth communications layer without the need for additional UWB/ sensor hardware. This architecture can leverage lower latency by estimating propagation delay directly from modified data packets rather than running independent scheduled polling events. ISAC Radios can integrate seamlessly into the existing communications infrastructure, offering the same plug-and-play capability of modern WiFi modules. Perhaps most importantly, they can be scaled massively beyond 10+ drones without the throughput or latency constraints faced by other sensing and communication stacks, utilizing an integration-first approach to deploy them rapidly. For advanced users/researchers, ISAC Radios can expose key signal metrics unavailable in traditional radio, providing several rich DoFs for use in model-based estimators. These advantages are explained below and considered against the consequential challenges and additional costs associated with integrating sensing and communication.

## Current State-of-the-Art

| System | What it does well | What it costs | Where it breaks |
|---|---|---|---|
| RTK GNSS | Outdoor global position | Receiver, antenna, correction link or base station | GNSS-denied, indoors, urban canyons, jamming, spoofing |
| UWB ranging | Dedicated decimeter-class pairwise range | Extra radio, antenna, MAC schedule, integration path, comms interference | Scaling beyond 10+ UAVs, polling latency, jamming, Multipath Fading |
| Visual / LiDAR SLAM | Rich geometry and local odometry | Cameras/LiDAR, compute, features, keyframes | Data-rate limitations, Low texture, darkness, occulsion, poor overlap, repeated scenes |
| Collaborative SLAM | Shared map and pose-graph consistency | Compute, coordination, descriptors, keyframes, states | Data-rate limitations, Network delays, visual overlap, feature quality |
| MANET radio | Mesh peer-to-peer data transport | Mesh networking occurs at IP-layer, abstraction at cost of performance | Absent positional data, spoofing, jamming, Multipath Fading |
| ISAC radio | Scalable High-throughput mesh + low-latency precision RF ranging factors | Calibration, Complex PHY/ MAC design, estimator integration | HPM jamming, Multipath Fading |

Table 2: The current autonomy stack solves communication, ranging, and mapping separately. ISAC Radio collapses part of that stack by moving ranging into the radio already needed for high-throughput communication.

## Reduced Hardware Expenses

A dedicated UWB module sounds cheap and simple. But at swarm scale, the cost is not only the transceiver. It is the second antenna, placement constraints, RF coexistence, power, firmware integration, ranging scheduler, timestamp reconciliation, test process, and the fact that a separate localization radio cannot carry the high-throughput data that collaborative autonomy already needs.

A localization-native mesh radio asks a different question:

> If the swarm must already carry a high-throughput SDR/FPGA mesh radio, what is the marginal cost of making that radio emit range factors?

The answer is not zero. It requires calibrated timestamps, waveform design, pilot allocation, channel estimation, clock-skew correction, and multipath rejection. But the marginal cost may be far lower than the full system cost of a second ranging radio on every drone, especially when the network must scale beyond small demonstrations.

## Scalability

| Fleet size | All-pairs links | Implication for separate ranging | PoseLink approach |
|---|---|---|---|
| 10 drones | 45 links | Polling is manageable | Sparse range graph plus data packets |
| 20 drones | 190 links | Scheduling starts to dominate | Nearest-neighbor plus long-baseline edges |
| 50 drones | 1,225 links | All-pairs ranging becomes impractical | Estimator-driven graph scheduling |
| 100 drones | 4,950 links | Dedicated polling cycles do not scale | Clustered mesh, range-on-packet, adaptive pilots |

Table 3: The number of potential pairwise links grows as (N(N-1)/2). At 20+ drones, the MAC scheduler is as important as the range sensor.

A swarm does not need every drone to range every other drone every frame. It needs enough well-conditioned edges to estimate a stable relative frame, maintain collision-relevant local geometry, and prevent map/formation drift. That suggests a sparse, adaptive ranging graph:

$$L(N) = \frac{N(N-1)}{2}$$

but

$$L_{\text{scheduled}} \ll L(N)$$

The scheduler should select links by expected estimator value:

- near-neighbor links for collision avoidance and formation maintenance,

- long-baseline links to reduce global graph drift,
- anchor or leader links when a global frame is available,
- cross-cluster links to merge local maps,
- and degraded-vision links when visual SLAM confidence drops.

This is where ISAC becomes more than waveform design. The radio, estimator, and planner must be coupled.

## Speed of Deployment

A localization-native radio should be deployed like a modern mesh module, not like a custom research stack. The goal is a plug-in system with:

- power, RF, and compute interfaces,
- ROS 2 and MAVLink messages,
- calibrated factory delay parameters,
- timestamped range-factor outputs,
- optional raw CSI/CIR export for researchers,
- and a default scheduler that works before custom tuning.

The value is not that every customer writes their own estimator. The value is that the radio exports both packets and navigation factors in forms that autonomy stacks already understand.

## Support for Collaborative SLAM and Swarm Communication

Collaborative SLAM already proves the demand for high-bandwidth, low-latency drone-to-drone communication. $D^2$SLAM reports representative message sizes of 20.1 kB for complete stereo keyframes and 56.3 kB for complete omnidirectional keyframes at 5 Hz, along with compact keyframes and pose-graph updates. [4]

| D2SLAM traffic type | Size | Rate | Payload rate |
|---|---|---|---|
| Complete stereo keyframe | 20.1 kB | 5 Hz | 0.80 Mbps |
| Complete omni keyframe | 56.3 kB | 5 Hz | 2.25 Mbps |
| Compact stereo keyframe | 1.2 kB | 5 Hz | 0.048 Mbps |
| Compact omni keyframe | 4.8 kB | 5 Hz | 0.192 Mbps |
| Example VINS update | 3.5 kB | 5 Hz | 0.14 Mbps |
| Example PGO update | 81 kB | 1 Hz | 0.65 Mbps |
| RF range factor | 32-128 B | 10-50 Hz/link | kbps/link |

Table 4: Collaborative visual SLAM can be Mbps-class per active UAV. RF range factors are tiny by comparison, but can stabilize the same pose graph.

The radio therefore has two jobs:

1. carry the keyframes, descriptors, and state updates that collaborative autonomy already needs;
2. produce cheap RF range factors that keep the relative graph constrained when visual conditions degrade.

# Market Opportunity

## Multiple trends are converging.

| Trend | What changed | Why it matters for Phalanx |
|---|---|---|
| AI networking | AI infrastructure is increasingly network-bound; hyperscale vendors now optimize full-stack fabrics around AI traffic. [1] | Edge swarms will also need deterministic, high-rate local links for features, maps, and coordination. |
| Drone scale | Defense and commercial autonomy are moving from single platforms toward many attritable or cooperative systems. [3] | Hundreds of nodes cannot be treated as a small lab WLAN. |
| GNSS denial | Interference and spoofing are operational realities in contested regions. [2] | Relative, infrastructure-light localization becomes necessary. |
| Visual SLAM maturity | Collaborative SLAM can deliver strong relative localization, but depends on visual overlap, features, compute, and communication. [4] | RF range factors become a complementary sensor, not a replacement. |
| ISAC validation | Recent OFDM ISAC prototypes demonstrate real-time video, range/angle sensing, and radio SLAM. [7] | The concept is no longer purely theoretical. |
| SDR/FPGA edge compute | Compact SDRs, FPGAs, and Jetson-class compute make custom PHY-to-SLAM integration practical. | A cross-layer radio is now buildable on UAV-class hardware. |

Table 5: Phalanx sits at the intersection of AI networking, swarm autonomy, GNSS-denied operation, collaborative SLAM, and SDR/FPGA hardware.

## Centurion Tech will become the telecommunications powerhouse of the Autonomous era

# System Architecture

Centurion Tech’s ISAC Radio is a full-stack radio architecture, not only a waveform.

| RF/Analog | FPGA PHY | Ranging MAC | Jetson Estimator |
|---|---|---|---|
| bandwidth, LO, filters, antennas | markers, FFT, timestamps, CSI | TWR, DS-TWR, sparse graph | factor graph, SLAM, planning |

Table 6: Architecture separates nanosecond-sensitive PHY work from graph-level autonomy. The FPGA timestamps and extracts channel observables; the Jetson fuses them with VIO, LiDAR, and SLAM.

## Physical architecture

Each node contains:

- SDR RF front end appropriate to the operating band;
- stable oscillator, preferably TCXO or better;
- FPGA fabric for correlation, FFT/IFFT, timestamping, pilot extraction, and CSI/CIR output;
- antenna system designed for the airframe;
- Jetson Orin Nano or similar companion compute;
- calibration memory for RF-chain delay, antenna delay, and temperature compensation;
- ROS 2 / MAVLink / DDS integration;
- optional PPS, RTK, or wired sync input for anchor mode.

## Network architecture

The network operates in three layers.

1. Data layer. Normal mesh traffic: commands, telemetry, keyframes, descriptors, maps, and state updates.
2. Ranging layer. FTM-like TWR/DS-TWR exchanges embedded into normal packets or scheduled as mini-slots.
3. Estimator layer. Range factors, visual factors, inertial priors, loop closures, and optional anchors are fused into a shared swarm state.

| Message | Data payload | Localization payload |
|---|---|---|
| Poll | mesh header, optional data | TX marker timestamp ID |
| Response | ACK, routing, optional data | RX/TX timestamps, CIR quality, SNR |
| Follow-up | optional payload | DS-TWR correction or clock-skew update |
| Broadcast state | pose, velocity, covariance | range factors, NLOS flags, link quality |
| SLAM burst | keyframe, descriptors, loop closure | coincident RF link metrics and range priors |

Table 7: The same packet exchange can carry mesh payloads and ranging metadata.

# Cost and System Inversion

ISAC Radio is tailored to these conditions:

- high-throughput mesh networking;
- relative localization without GNSS;
- collaborative SLAM or cooperative perception traffic;
- low SWaP;
- rapid deployment;
- and scalable scheduling.

| Cost item | Mesh + UWB stack | ISAC stack | System-level implication |
|---|---|---|---|
| High-throughput data radio | Required | Required | No difference; swarm data still needs a mesh |
| Relative ranging radio | Separate UWB module | Embedded in mesh radio | Potential hardware and integration reduction |
| Antenna system | Separate or carefully co-located | Shared or integrated design | Lower SWaP and RF coexistence burden |
| Ranging schedule | Independent polling cycle | Merged with data/MAC schedule | Potential latency and airtime savings |
| Estimator interface | Range-only, often module-specific | Range, variance, CIR, phase, NLOS, CSI | Richer factors for SLAM and graph optimization |
| Regulatory path | UWB-specific constraints | Band-dependent non-UWB or licensed/authorized operation | Requires careful RF strategy either way |

Table 8: ISAC Radio's advantage is not cheaper silicon alone. It is the collapse of communication, timing, ranging, and estimator observability into one radio stack.

# Performance Targets and Baselines

## The central thesis

The radio will become the next navigation sensor. Drone swarms already require a high-throughput wireless mesh to exchange commands, features, keyframes, state updates, and map fragments. Centurion Tech's localization-native radio turns those same packets into calibrated range, channel, timing, and uncertainty measurements for swarm-level navigation.

A recent 5G-NR-aligned OFDM ISAC prototype reports real-time high-definition video transmission, range/angle sensing, and radio SLAM, with 0.3 m range RMSE, 2.3 degree angle RMSE, and 0.25 m radio-SLAM localization error in its real-world tests. [7] This is not the same as a small-drone mesh radio, but it shows that communication-centric OFDM ISAC can produce useful sensing observables while carrying real data.

Centurion Tech's target is not to beat every dedicated ranging technology on day one. The near-term target is system-level value:

- high-throughput mesh communication,
- sub-meter RF range factors in practical LoS conditions,
- decimeter-class targets under calibrated, favorable conditions,
- robust covariance and NLOS detection,
- sparse graph localization,
- and fusion with visual/LiDAR SLAM.

# Conclusion

ISAC radios are ambitious because they force more meaning into the same spectrum. A localization-native radio must communicate, range, estimate channel quality, support swarm graph localization, and cooperate with visual/LiDAR SLAM without collapsing under latency or calibration error. That is a difficult engineering problem, but it is aligned with the direction of the industry: AI workloads are becoming network-bound, wireless data traffic is rising, autonomy is moving to the edge, GNSS denial is operationally relevant, and collaborative SLAM already depends on robust communication.

Centurion Tech's position is that drone swarms will not be unlocked by communication or localization alone. They require the fusion of both. The winning radio will not simply move packets. It will expose the physical world: range, timing, channel structure, uncertainty, and graph value.

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