

NetSim Application Note

Drone MANET Communications in Contested Environments

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1 Background and Motivation

The use of drones in modern warfare has expanded rapidly over the past decade. Recent conflicts, including the Russia-Ukraine and the US-Iran wars, have demonstrated the military value of low-cost uncrewed aircraft for strike, surveillance, and deep-area denial missions. Individually piloted FPV attacks and drone reconnaissance platforms dominated the early phase of this shift; the current trajectory is toward coordinated formations and, ultimately, drone swarms of cooperating UAS that share sensing and targeting data, re-plan routes when members are lost, and saturate point-defence systems from multiple axes. Swarming depends on a persistent mesh datalink that tolerates node loss, electromagnetic interference, and a continuously changing topology.

This scenario models one such deployment. A mixed force of eight FPV strike drones, two ISR drones, and four high-altitude relay drones connects to a ground control station over an L-band ad-hoc mesh. The area of operations is a contested $5\text{ km} \times 5\text{ km}$ patch in which an adversary jammer targets the mesh frequency and an air-defence system engages low-altitude UAS. The remaining sections specify the PHY/MAC configuration, traffic model, mobility profiles, stress events, and the three experiments used to evaluate mesh performance under progressive stress.

2 Operational Setting

2.1 Mission Context

A drone strike and reconnaissance operation is conducted in a contested environment. The force comprises:

- **8 Strike UAS** (FPV attack drones) carrying out precision strikes against ground targets
- **2 ISR UAS** providing wide-area surveillance and target acquisition
- **4 Relay UAS** forming a multi-hop mesh backbone at altitude, extending communication range between strike/ISR drones and the GCS
- **1 Ground Control Station** (GCS) operated by a small team of drone operators
- **1 Air-defence system** (short-range, capable of engaging low-altitude UAS) operated by the adversary
- **1 Jammer** operated by the adversary, targeting the drone mesh frequency in the operating area

2.2 Geographic Scale

Parameter	Value
Simulation area	$5000\text{ m} \times 5000\text{ m}$
Drone operating altitude	100–500 m AGL
GCS position	Ground level at area edge

3 Network Architecture

The scenario uses a single communication domain.

Domain	Freq. Band	Protocol/MAC	Purpose
Drone MANET Mesh	L-band (1350–1400 MHz)	DTDMA / AODV	UAS-to-GCS



Figure 1: Network topology and initial node deployment. 8 Strike, 2 ISR, and 4 Relay drones form a multi-hop DTDMA mesh (L-band, AODV routing). Lines show primary mesh links. The shaded circle marks the jammer’s 750 m effective radius, which covers Strike-1, Strike-2, ISR-1, and Relay-2.

3.1 DTDMA Mesh Parameters

All 14 drones and the GCS form a single DTDMA mesh on L-band.

Parameter	Value
Node count	14 UAS + 1 GCS
UAS roles	8 Strike (FPV attack), 2 ISR, 4 Relay
Node type	WirelessNode (NetSim MANET library)
MAC protocol	DTDMA
Network type	AD-HOC
Lower frequency	1350 MHz
Upper frequency	1400 MHz
Bandwidth	5 MHz
Hop channels (C)	$\lfloor (1400 - 1350)/5 \rfloor = 10$
Frequency hopping	ON (one hop per slot, slow FH)
TX power	20 W (default)
Receiver sensitivity	-101 dBm
Modulation	16QAM (4 bits/symbol)
Coding rate	3/4
Symbol rate	4000 kBd
Antenna	Omnidirectional, 1 dBi gain
Antenna height	0 m
Pathloss model	Range-based (fixed cutoff)
Communication range	1500 m
Routing protocol	AODV (reactive, suits mobile UAS)
Frame duration	1 s
Slot duration	2 ms
Guard interval	100 μ s
Slot allocation	Round robin
Channel capacity	12 Mbps (aggregate)
BER model	SINR-BER table lookup
Jammer support	Enabled on jammer node (native DTDMA feature)
Buffer size	8 MB per node

3.2 PHY Rate

The PHY parameters are based on published specifications of fielded tactical MANET radios operating in L-band (Silvus SC4400, Persistent Systems MPU5, L3Harris ANW2). At 5 MHz channel bandwidth, a symbol rate of 4000 kBd fits within the Nyquist limit with standard root-raised-cosine filtering. With 16QAM modulation and rate-3/4 coding, the aggregate channel capacity is 12 Mbps.

Multi-hop forwarding amplifies the effective load: each packet consumes a DTDMA slot at every relay hop. With an average path length of 3–5 hops across 15 nodes, the usable per-flow throughput is roughly $12/\bar{h} \approx 2\text{--}4$ Mbps aggregate, where \bar{h} is the mean hop count weighted by traffic volume.

4 Traffic Patterns

Four application flows model the operational traffic. All UAS-originated flows terminate at the GCS; the C2 flow originates at the GCS and terminates at the strike drones.

Flow	Type	Source	Dest	Transport	Rate	Pkt Size
C2 Commands	CBR	GCS	Each Strike UAS	UDP	64 kbps \times 8	120 B
FPV Video	Video	Each Strike UAS	GCS	UDP	64 kbps \times 8	1400 B
PLI	CBR	Each UAS (all 14)	GCS	UDP	16 kbps \times 14	200 B
ISR Imagery	Video	Each ISR UAS	GCS	UDP	128 kbps \times 2	1400 B

Aggregate offered load: \sim 0.5 Mbps downlink (C2) and \sim 1.0 Mbps uplink (0.5 Mbps FPV + 0.26 Mbps ISR + 0.224 Mbps PLI). With an average path length of 3–5 hops on the uplink, the effective channel load is \sim 3–5 Mbps, well below the 12 Mbps aggregate capacity.

4.1 Flow Descriptions

C2 Commands

High-priority, low-bandwidth command and control stream. The GCS sends joystick/waypoint updates to each of the 8 Strike UAS at 64 kbps (0.5 Mbps aggregate). Latency requirement: $<$ 200 ms end-to-end. Loss tolerance: $<$ 1%.

FPV Video

First-person-view surveillance video from each Strike UAS camera. 64 kbps per stream (0.5 Mbps aggregate) corresponds to low-bitrate H.265 encoding at QVGA/CIF resolution. The flow traverses the MANET mesh from Strike UAS to GCS. Jitter tolerance: $<$ 30 ms.

PLI (Position Location Information)

Periodic position/status reports from all 14 UAS nodes to the GCS at 1-second intervals. Low bandwidth (16 kbps per node, 224 kbps aggregate). Loss-tolerant but must arrive within 5 seconds for situational awareness. Modeled as CBR with 200 B UDP datagrams (PLI payload plus headers) at 10 packets/s.

ISR Imagery

Wide-area surveillance video from each of the two ISR drones to the GCS. 128 kbps per stream (0.26 Mbps aggregate) corresponds to low-bitrate H.265 encoding of wider field-of-view surveillance video, at roughly twice the FPV rate reflecting the higher target resolution needed for ISR. UDP, 1400 B packets. Latency tolerance 1 s (operational viewing, not real-time control).

5 Stress Conditions

The scenario includes two stress events to test network resilience. Figure 2 shows their timing within the 70-second simulation window.

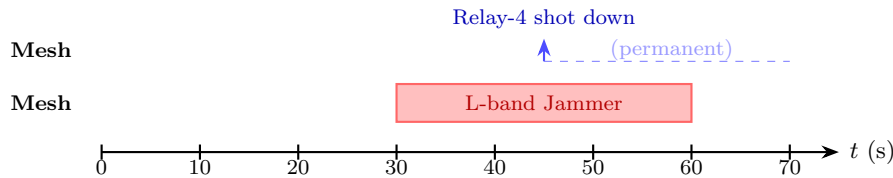


Figure 2: Stress event timeline. Both events affect the drone MANET mesh.

5.1 Event 1: L-band Jammer Activation ($t = 30$ s to $t = 60$ s)

A jammer activates at coordinates (2200, 2500), targeting the 1350–1400 MHz drone mesh band. Drones within 750 m of the jammer experience a 20 dB increase in noise floor, degrading SINR

and causing packet loss on the mesh. At the initial node positions, the jammer zone covers Strike-1, Strike-2, ISR-1, and Relay-2, disrupting both forward C2/FPV flows and the central relay backbone link. Additional strike drones may transit the zone during ingress.

NetSim implementation: Use DTDMA’s native jammer support. Set `JAMMER=true` on the jammer node with `RANGE=Fixed` and `DISTANCE=750` (meters). DTDMA calculates interference power based on frequency overlap and adds it to the noise floor when computing SINR for affected receivers.

5.2 Event 2: Relay UAS Shoot-down (t = 45s)

One of the four Relay UAS nodes (Relay-4) is engaged and destroyed by adversary air-defence fire at $t = 45$ s and drops from the network. Relay-4 serves as the primary link between the GCS and the relay backbone, so its loss forces AODV to discover alternative routes through Relay-1 or other relay nodes. From the mesh’s perspective the kinetic kill manifests as an abrupt, permanent disappearance of the node: no graceful shutdown, no prior SINR degradation, and no chance of recovery within the simulated window.

NetSim implementation: The failure cause is kinetic rather than electronic, but at the network layer both are modelled as an instantaneous node drop. Use file-based mobility to translate Relay-4 out of the simulation area at $t = 45$ s (e.g., to (50000, 50000, 0)), so that the node leaves the 1500 m neighbourhood of every peer at the same instant.

6 Experiment Design

The following three experiments progressively increase the stress level to isolate the impact of each failure mode.

Exp.	Name	Configuration
1	Baseline (uncontested)	No jamming, no failures. Establishes best-case throughput, latency, and PDR under nominal mobility.
2	Mesh under jamming	L-band jammer active (t=30–60s). Measures C2/FPV disruption for drones near the jammer.
3	Jamming + relay shoot-down	Exp. 2 conditions plus Relay-4 shoot-down at t=45s. Tests AODV re-routing under simultaneous electronic and kinetic stress.

6.1 Metrics to Collect

For each experiment, collect:

- **Per-flow:** Throughput (Mbps), end-to-end delay (μ s), jitter (μ s), packet delivery ratio (%)
- **Per-link:** Packets transmitted/errored/collided, SINR (from radio measurement logs)
- **Routing:** AODV RREQ/RREP/RERR counts, route convergence time after Relay-4 shoot-down

6.2 Simulation Parameters

Parameter	Value
Simulation time	70 seconds
Seed values	12345678 / 23456789 (repeat with 2 additional seeds)
Packet trace	Enabled
Event trace	Enabled (filtered to routing events)
Confidence	4 runs per experiment, report 95% CI
Total runs	3 experiments \times 4 seeds = 12 simulation runs

7 NetSim Implementation Mapping

7.1 Simulation Structure

The scenario runs as a single NetSim simulation using the MANET (DTDMA) library. All 14 UAS, the GCS, and the jammer node are configured in one `Configuration.netsim` file.

7.2 NetSim Module Mapping

Scenario Element	NetSim Module	Notes
Drone mesh nodes	DTDMA library, WirelessNode	Slot/frame config
AODV routing	AODV DLL (built-in)	Reactive routing
C2 traffic (64 kbps)	CBR application	UDP, high priority
FPV video (64 kbps)	Video application	UDP
PLI (16 kbps)	CBR application	UDP, periodic, all 14 UAS
ISR imagery (128 kbps)	Video application	UDP, ISR drones only
UAS mobility	File-based mobility	CSV: time, id, x, y, z
Node loss (shoot-down)	File-based mobility	Move node out of simulation area
Jammer	DTDMA native jammer	JAMMER=true; fixed or pathloss-based range
Frequency hopping	DTDMA native	ON by default; random hop per slot

8 Assumptions

The following modeling assumptions apply across all three experiments.

1. **Perfect time synchronization.** All DTDMA nodes share a common clock. No clock drift or synchronization error is modeled. The $100\ \mu\text{s}$ guard interval absorbs minor timing offsets that would arise in practice.
2. **Range-based path loss.** A node can communicate with any other node within 1500 m; beyond that distance, the signal is fully attenuated. This hard cutoff replaces continuous path loss modeling and forces multi-hop routing across the 5 km area. No terrain or obstacle modeling is applied.
3. **Fixed TX power.** All nodes transmit at 20 W. There is no adaptive power control or interference mitigation beyond frequency hopping.

4. **No retransmission.** DTDMA does not implement MAC-layer ARQ. All flows use UDP, so there is no transport-layer retransmission either. A packet lost to interference or collision is permanently lost.
5. **Homogeneous radio parameters.** All UAS share identical radio settings (modulation, coding rate, antenna gain). The only distinction between drone roles is position and mobility profile.
6. **Stationary jammer.** The adversary jammer remains at a fixed position for the duration of the simulation.

9 Node Inventory and IP Plan

Figure 1 shows the initial node positions and mesh topology. The table below lists all nodes with their IP addresses and coordinates.

ID	Name	Role	IP Address	Position (x,y,z)
1	Strike-1	Strike UAS	10.1.0.2	(2250, 3000, 150)
2	Strike-2	Strike UAS	10.1.0.3	(2750, 2750, 120)
3	Strike-3	Strike UAS	10.1.0.4	(3250, 3250, 150)
4	Strike-4	Strike UAS	10.1.0.5	(3750, 2750, 130)
5	Strike-5	Strike UAS	10.1.0.6	(1750, 3250, 140)
6	Strike-6	Strike UAS	10.1.0.7	(4000, 3250, 160)
7	Strike-7	Strike UAS	10.1.0.8	(1250, 3500, 135)
8	Strike-8	Strike UAS	10.1.0.9	(4250, 3000, 145)
9	ISR-1	ISR UAS	10.1.0.10	(1750, 2500, 300)
10	ISR-2	ISR UAS	10.1.0.11	(3500, 2250, 280)
11	Relay-1	Relay UAS	10.1.0.12	(1250, 1750, 450)
12	Relay-2	Relay UAS	10.1.0.13	(2000, 2000, 400)
13	Relay-3	Relay UAS	10.1.0.14	(2750, 1750, 420)
14	Relay-4	Relay UAS	10.1.0.15	(1750, 1250, 430)
15	GCS	Ground Ctrl	10.1.0.16	(750, 1000, 3)

10 Mobility Profiles

All UAS use file-based mobility (CSV format: Time(ms), DeviceID, X(m), Y(m), Z(m)). The GCS is stationary at (750, 1000, 3) for the entire simulation.

10.1 Baseline Mobility Model

The baseline uses a waypoint-based trajectory for every UAS. Mobility is divided into three classes by drone role.

10.1.1 Strike UAS (8 drones)

Each strike drone follows a three-phase flight profile.

Phase	Time interval	Speed	Altitude	Trajectory
Ingress	$t = 0-30$ s	30–40 m/s	120–160 m	Linear approach
Loiter	$t = 30-70$ s	10–15 m/s	100–150 m	Racetrack, $r = 300$ m
Egress	$t = 70-100$ s	30–40 m/s	120–160 m	Linear return

The eight strikes are split into two approach groups:

- **Western group** (Strike-1, Strike-2, Strike-5, Strike-7): approach from the northwest toward the center of operations ($\approx 2500, 2500$).
- **Eastern group** (Strike-3, Strike-4, Strike-6, Strike-8): approach from the northeast toward the same area.

During ingress, each drone covers 900–1200 m in 30 s. During loiter, strikes orbit over their assigned sector. During egress, they retrace toward their starting positions. The phase transitions at $t = 30$ s and $t = 70$ s force AODV route re-discoveries as optimal next-hops change.

10.1.2 ISR UAS (2 drones)

Continuous racetrack orbit for the full 100 s.

Drone	Orbit center	Radius	Speed	Altitude
ISR-1	(1750, 2500)	300 m	15 m/s	300 m
ISR-2	(3500, 2250)	300 m	15 m/s	280 m

ISR-1 covers the western half of the area; ISR-2 covers the eastern half. The 300 m orbit radius is sized so that each ISR remains within 1500 m of its assigned relay nodes throughout the orbit. At 15 m/s, the orbit period is approximately $2\pi \times 300/15 \approx 126$ s, so each ISR drone completes roughly 80% of an orbit during the 100 s simulation.

10.1.3 Relay UAS (4 drones)

Continuous racetrack orbit for the full 100 s at high altitude.

Drone	Orbit center	Radius	Speed	Altitude
Relay-1	(1250, 1750)	150 m	18 m/s	450 m
Relay-2	(2000, 2000)	150 m	18 m/s	400 m
Relay-3	(2750, 1750)	150 m	18 m/s	420 m
Relay-4	(1750, 1250)	150 m	15 m/s	430 m

Adjacent relay orbit centers are spaced 750–800 m apart. With orbit radii of 150 m, the worst-case separation between two adjacent relays is approximately $800 + 150 + 150 = 1100$ m. This is within the 1500 m communication range with 400 m margin, so relay-to-relay backbone links remain connected at all times regardless of orbital phase.

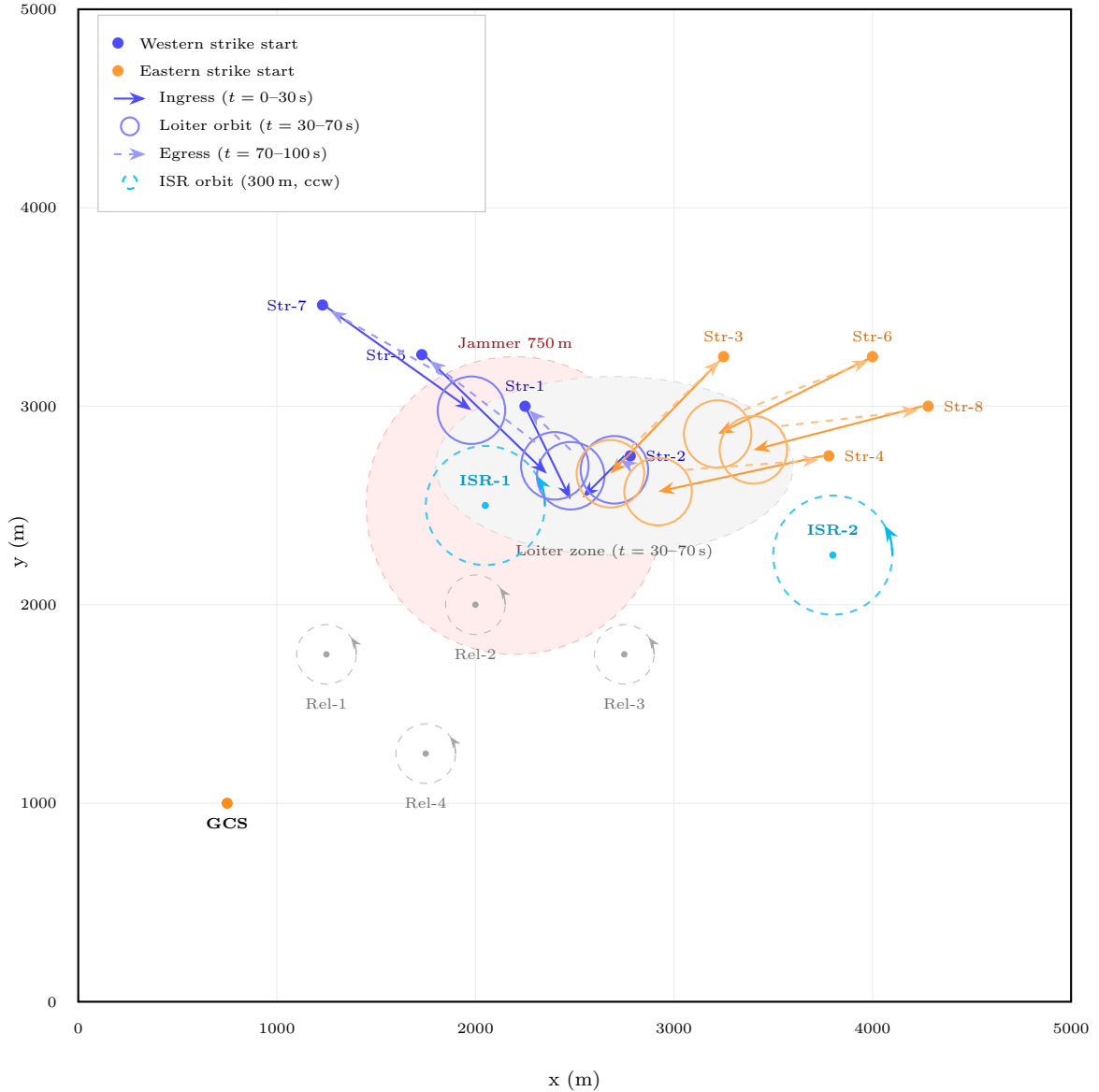


Figure 3: Mobility trajectories. Western strikes (blue) ingress from the northwest; eastern strikes (orange) from the northeast. Each strike drone (filled dot) follows a solid ingress arrow into the loiter zone, orbits at $r = 170$ m for $t = 30-70$ s, then egresses (dashed) back to its start. ISR drones orbit ccw at $r = 300$ m (cyan), relays at $r = 150$ m (gray). The GCS is stationary. Per-node tabulated coordinates are listed in Appendix A.

10.2 Link Connectivity Under Baseline Mobility

The relay backbone provides the primary multi-hop path between forward drones and the GCS. The following connectivity properties hold under baseline mobility:

With the 1500 m range-based pathloss model, connectivity is binary: two nodes either have a link (distance ≤ 1500 m) or they do not. Table 1 lists the shortest AODV path from each drone to the GCS at the initial positions.

Drone	Shortest path to GCS	Key distances	Hops
Str-1	→ Rel-2 → Rel-4 → GCS	1031 m, 791 m, 1031 m	3
Str-2	→ Rel-2 → Rel-4 → GCS	1061 m, 791 m, 1031 m	3
Str-5	→ Rel-2 → Rel-4 → GCS	1275 m, 791 m, 1031 m	3
Str-7	→ ISR-1 → Rel-1 → GCS	1118 m, 901 m, 982 m	3
Str-3	→ ISR-2 → Rel-3 → Rel-2 → Rel-4 → GCS		5
Str-4	→ Rel-3 → Rel-2 → Rel-4 → GCS	1414 m, 791 m, ...	4
Str-6	→ ISR-2 → Rel-3 → Rel-2 → Rel-4 → GCS		5
Str-8	→ ISR-2 → Rel-3 → Rel-2 → Rel-4 → GCS		5
ISR-1	→ Rel-1 → GCS	901 m, 982 m	2
ISR-2	→ Rel-3 → Rel-2 → Rel-4 → GCS		4

Table 1: Shortest AODV paths from each drone to the GCS at initial positions, with per-hop distances and total hop count.

Key observations:

Relay backbone: All adjacent relay pairs are ~ 800 m apart (worst case with 150 m orbits: $1100 \text{ m} < 1500 \text{ m}$). The backbone never partitions.

Western strikes (Str-1, 2, 5): Within direct range of Relay-2 (1031–1275 m). These take 3 hops to GCS.

Eastern strikes (Str-3, 6, 8): Cannot reach any relay directly (>1500 m). Must route through ISR-2, adding one hop. These take 5 hops to GCS.

Outer strikes (Str-7, Str-4): Str-7 reaches ISR-1 at 1118 m (3 hops). Str-4 reaches Relay-3 at 1414 m (4 hops).

GCS: Can reach Relay-4 (1031 m) and Relay-1 (982 m) only. Cannot reach Relay-2 (1562 m), ISR, or any strike directly.

The asymmetry between western (3 hops) and eastern (5 hops) sides is a direct consequence of the GCS position and the range cutoff. Eastern strikes should exhibit higher latency and lower PDR even in the baseline.

10.2.1 Forwarding Role of ISR Drones

The path table shows that ISR-2 acts as a forwarding hop for the four eastern strike drones (Strike-3, 4, 6, 8), since none of them are within 1500 m of any relay node. ISR-1 also serves as the next hop for Strike-7. Therefore the ISR drones are not pure traffic sources; they also relay strike-to-GCS traffic in the same manner as the relay drones.

This is reasonable operationally: MALE/HALE-class ISR platforms (Predator/Reaper family, Heron, Bayraktar TB2) routinely double as comms relays, since they orbit at higher altitude than strike drones and have line-of-sight to a wider set of nodes.

The cost is that ISR uplink (own PLI and 500 kbps imagery) competes with forwarded strike traffic for the ISR’s own DTDMA slots. With round-robin allocation each device gets an equal share, so heavy forwarding through an ISR can throttle its own imagery flow. This is captured in the experiments and reported per-flow.

10.3 Predicted Mobility Effects

With range-based pathloss, link state is binary: a node either has a link or it does not. There is no gradual SINR degradation from distance. This makes link breaks abrupt and AODV reconvergence the dominant performance factor.

Ingress ($t = 0\text{--}30\text{ s}$)

Strike drones move toward the center of operations at 30–40 m/s. Western strikes close on Relay-2; some that start near the 1500 m boundary (e.g., Str-5 at 1275 m) move well within range, improving link margin. Eastern strikes approach ISR-2, entering or stabilizing links. AODV discovers initial routes during this phase. Expect 2–4 RREQ/RREP exchanges per strike as routes form.

Loiter ($t = 30\text{--}70\text{ s}$)

Strikes orbit at 300 m radius, 10–15 m/s. Relay and ISR drones continue their own orbits. All links from the hop table above remain within 1500 m (orbit radii are small relative to link margins). Routes should be stable. This is the steady-state measurement window for the baseline.

Egress ($t = 70\text{--}100\text{ s}$)

Strikes return toward starting positions at 30–40 m/s. Links begin to stretch. Str-7 (returning toward 1250, 3500) moves away from ISR-1; at ISR-1’s worst orbital position, separation can exceed 1500 m, causing a link break. Similarly, Str-6 and Str-8 may lose their link to ISR-2. AODV will issue RERR and attempt re-routing through adjacent strike drones (e.g., Str-7 \rightarrow Str-5 \rightarrow ISR-1). Expect 1–3 route reconvergences per outer strike during egress.

Doppler is not a concern at these speeds. At L-band (1375 MHz) and 40 m/s, the maximum Doppler shift is approximately $f_d = v/\lambda \approx 183\text{ Hz}$, well within the coherence bandwidth of the 5 MHz channel.

10.4 Mobility in Stress Scenarios

Experiments 2 and 3 use the same mobility profiles as the baseline. The only difference is the addition of stress events:

- **Exp. 2 (Jamming):** The jammer at (2200, 2500) adds 20 dB to the noise floor of nodes within 750 m. Although the range-based model still considers these links “up” (distance < 1500 m), the elevated noise floor degrades SINR and increases packet error rate. Affected nodes (Strike-1, Strike-2, ISR-1, Relay-2) will see C2 and FPV packet loss spike during $t = 30\text{--}60\text{ s}$. AODV may re-route western strike traffic through Relay-1 instead of the jammed Relay-2, increasing hop count by one.
- **Exp. 3 (Jamming + Relay-4 shoot-down):** Same as Exp. 2, but at $t = 45\text{ s}$ Relay-4 is destroyed by adversary fire and drops off the network. The GCS loses its primary first-hop link and must use Relay-1 as the sole entry point to the backbone. All traffic concentrates on the path GCS \rightarrow Relay-1 \rightarrow Relay-2 $\rightarrow \dots$. Combined with jamming on Relay-2, the central backbone is under simultaneous capacity and interference stress. Eastern strike traffic now traverses 6 hops (vs. 5 in baseline).

11 Simulation Results

All three experiments were run in NetSim Pro v15.0 with the configuration described above (round-robin DTDMA slot allocation, four application flows, 70 s simulated time, seed pair (12345678, 23456789)).

11.1 Experiment 1: Baseline (no jamming, no failure)

Representative per-flow results, grouped by hop count to the GCS:

Tier	Representative flow	PDR	Delay	Hops
1 (GCS neighbours)	PLI Relay-1 → GCS	90.0%	5.72 s	1
	PLI Relay-2 → GCS	47.7%	19.71 s	2
2 (ISR / west strikes)	FPV Strike-1 → GCS	90.0%	5.76 s	3
	PLI ISR-1 → GCS	90.0%	5.73 s	2
	ISR-1 imagery → GCS	90.0%	5.73 s	2
3 (east strikes)	FPV Strike-8 → GCS	37.8%	24.16 s	5
	ISR-2 imagery → GCS	37.8%	24.08 s	4
Downlink	C2 GCS → Strike-1	3.5%	21.69 s	3
	C2 GCS → Strike-6	11.2%	29.12 s	5

Link layer totals: 93,738 data packets transmitted, 9,202 control, zero errored, zero collided, zero buffer drops.

Key observations:

- **East-west asymmetry confirmed.** Western strikes (fewer hops via relay backbone) achieve $\approx 90\%$, while eastern strikes (longer paths via ISR-2) operate at $\approx 35\text{--}38\%$. This matches the hop-count-based performance trend described in Section 10.2.
- **ISR multi-hop forwarding works.** ISR-2's own imagery delivers at $\approx 37.8\%$, which is consistent with the eastern strike flows it supports. ISR-1 (shorter path, no forwarding burden) achieves $\approx 90\%$.
- **C2 downlink remains the bottleneck.** All C2 flows originate from the GCS, which has limited slot allocation and lies on longer downlink paths. Delivery remains low ($\approx 3\text{--}11\%$) with delays around 21–29 s.
- **Negligible PHY errors and no collisions.** The DTDMA channel (12 Mbps) comfortably supports the offered load, resulting in minimal PHY errors (only 1 observed) and no collisions. Performance is primarily limited by hop count and slot allocation rather than channel capacity.

11.2 Experiment 2: Jamming ($t = 30\text{--}60$ s)

The jammer node at (2200, 2500) joins at $t = 30$ s with `JAMMER=True` and leaves at $t = 60$ s. It raises the noise floor of Strike-1, Strike-2, ISR-1, and Relay-2 (all within 750 m), degrading SINR on their links.

Metric	Exp 1 (Baseline)		Exp 2 (Jamming)	
	PDR	Delay	PDR	Delay
<i>Jammed nodes (within 750 m of jammer)</i>				
FPV Strike-1 → GCS	90.0%	5.76 s	88.1%	5.66 s
PLI Strike-1 → GCS	90.0%	5.75 s	88.1%	5.65 s
FPV Strike-2 → GCS	35.5%	25.51 s	35.5%	25.51 s
PLI ISR-1 → GCS	90.0%	5.73 s	90.4%	5.62 s
ISR-1 imagery → GCS	90.0%	5.73 s	90.4%	5.62 s
PLI Relay-2 → GCS	47.7%	19.71 s	47.7%	19.71 s
<i>Non-jammed nodes</i>				
FPV Strike-8 → GCS	37.8%	24.16 s	37.8%	24.16 s
PLI Relay-1 → GCS	90.0%	5.72 s	90.4%	5.61 s
PLI Relay-3 → GCS	37.9%	23.93 s	37.9%	23.93 s
C2 GCS → Strike-1	3.5%	21.69 s	3.5%	21.69 s
C2 GCS → Strike-6	11.2%	29.12 s	10.6%	28.24 s
<i>Link-level summary</i>				
Data packets transmitted		59,111		58,636
Control packets		9,320		9,320
Errored (PHY)		1		263
Collided / Buffer drops		0		0

Key observations:

- **Jammer leads to PHY errors.** The jammer leads to 263 PHY errors, concentrated on links within its coverage region during the active period.
- **Jammed nodes show a moderate PDR drop.** Strike-1 FPV drops 90.0% → 88.1%, PLI Strike-1 drops 90.0% → 88.1%, while ISR-1 imagery shows a slight increase (90.0% → 90.4%). Other jammed links such as FPV Strike-2 and PLI Relay-2 remain unchanged in PDR but experience interference. The jammed links remain “up” from AODV’s perspective (distance <1500 m), so routes are not recomputed; only SINR-driven errors cause the degradation.
- **Non-jammed nodes show negligible change.** Strike-8 remains unchanged at 37.8%, and Relay-1 shows a slight increase (90.0% → 90.4%). Similarly, Relay-3 and C2 links show no change or very minor variation. This confirms that the jamming impact is spatially localized.
- **AODV control overhead remains unchanged** (9,320 vs 9,320). No route-discovery activity is triggered, since jamming introduces packet errors rather than link failures.
- **Jamming slightly reduces delay.** Since errored packets are dropped early instead of being queued, the average delay of successfully delivered packets reduces slightly (for example, FPV Strike-1: 5.76 s → 5.66 s, PLI Strike-1: 5.75 s → 5.65 s).

11.3 Experiment 3: Jamming + Relay-4 Shoot-down

Experiment 3 adds a Relay-4 shoot-down at $t = 45$ s, modelled by relocating Relay-4 to (50000, 50000, 0) via the mobility file so the node leaves every peer’s 1500 m neighbourhood in a single step. The adversary engages Relay-4 on top of the Exp 2 jamming: one relay is destroyed kinetically while Relay-2 is still being jammed electronically. Relay-4 is one of the GCS’s two first-hop relay neighbours, so its loss forces all downlink traffic to enter the backbone through Relay-1.

Metric	Exp 1 Baseline	Exp 2 Jamming	Exp 3 Jam + Shoot-down
<i>Jammed nodes</i>			
FPV Strike-1 → GCS (PDR)	90.0%	88.1%	82.5%
PLI ISR-1 → GCS (PDR)	90.0%	90.4%	84.8%
ISR-1 imagery → GCS (PDR)	90.0%	90.4%	84.8%
<i>Multi-hop (east) nodes</i>			
FPV Strike-3 → GCS (PDR)	37.8%	37.8%	27.6%
FPV Strike-8 → GCS (PDR)	37.8%	37.8%	27.0%
PLI Relay-3 → GCS (PDR)	37.9%	37.9%	27.7%
ISR-2 imagery → GCS (PDR)	37.8%	37.8%	29.6%
<i>Backbone / gateway nodes</i>			
PLI Relay-1 → GCS (PDR)	90.0%	90.4%	84.9%
PLI Relay-2 → GCS (PDR)	47.7%	47.7%	29.7%
PLI Relay-4 → GCS (PDR)	47.7%	47.7%	29.7%
<i>Link-level summary</i>			
Data packets transmitted	59,111	58,636	55,152
Control packets	9,320	9,320	27,095
Errored (PHY)	1	263	390
Buffer drops	0	0	0

Key observations:

- **Progressive degradation across experiments.** FPV PDR for Strike-1 reduces from 90.0% → 88.1% → 82.5%, while ISR-1 imagery remains stable under jamming (90.0% → 90.4%) and then drops to 84.8% after the shoot-down. This shows that jamming causes mild degradation, whereas the kinetic loss has a stronger impact.
- **Shoot-down drives routing overhead.** AODV control packets remain unchanged between Exp 1 and Exp 2 (9,320), confirming no route changes under jamming. However, they increase significantly to 27,095 in Exp 3 due to route rediscovery after Relay-4 is lost.
- **Relay-dependent and multi-hop flows degrade the most.** Nodes that rely on longer paths or relay forwarding show a sharp drop in performance. For example, FPV Strike-2 drops from 35.5% → 35.5% → 27.0%, and similar trends are observed across other multi-hop FPV and PLI flows.
- **Backbone congestion increases after the loss.** Once Relay-4 is lost, traffic is forced through fewer available relays, increasing congestion and reducing delivery efficiency across the network.
- **Delay reduces due to early packet drops.** In Exp 3, many packets are dropped early due to broken routes, and only successfully delivered packets are considered. This results in lower average delay (e.g., FPV Strike-8: 24.16 s → 15.17 s).
- **Buffer drops remain zero.** The network load remains within capacity limits, so no buffer overflows occur even under combined stress conditions.

11.4 Result Comparison Plots

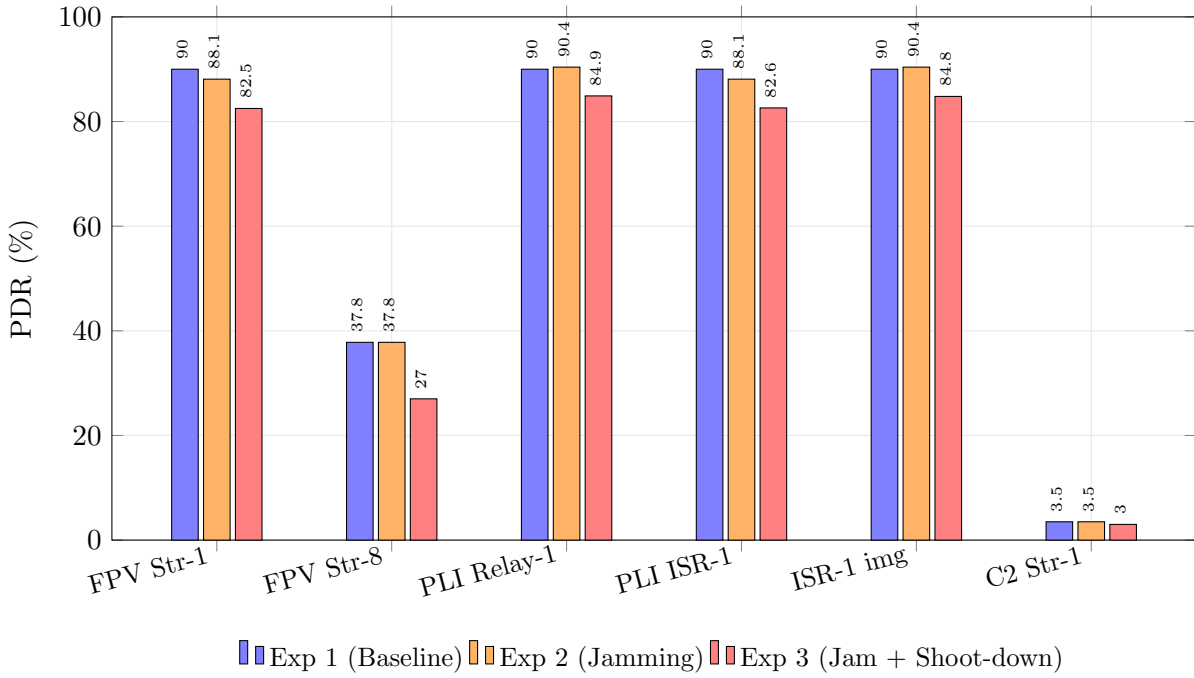


Figure 4: Packet delivery ratio across experiments for selected flows. Progressive degradation is visible for jammed nodes (FPV Str-1, ISR-1 PLI/imagery) and for backbone nodes (Relay-1 PLI). Far-east strikes (Str-8) are only mildly affected by jamming (outside the zone) but collapse further when Relay-4 is shot down. C2 remains uniformly low due to GCS-side slot saturation.

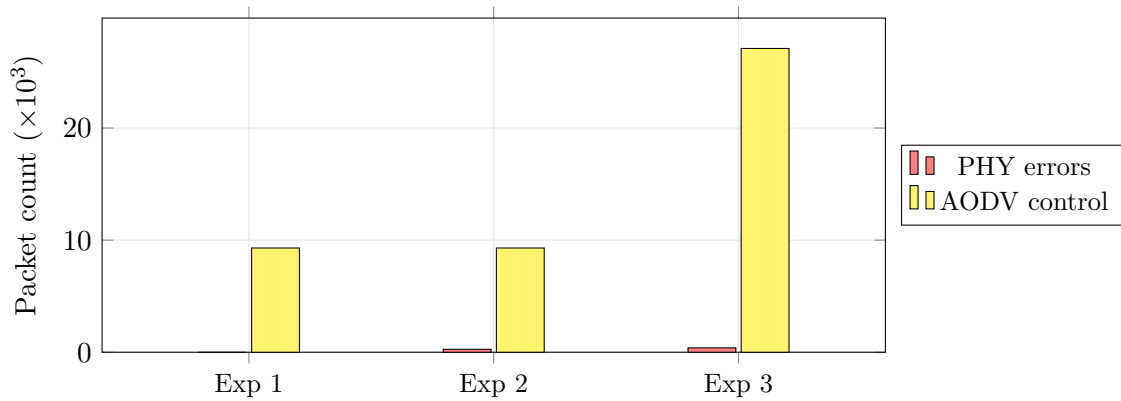


Figure 5: Packet-level outcomes across experiments (thousands). Exp 2 and Exp 3 show PHY errors introduced by the jammer. Exp 3 additionally shows an approximately 3× increase in AODV control packets as the Relay-4 shoot-down triggers route rediscovery and network reconvergence.

A Mobility Profile

The tables below list every waypoint loaded from the `mobility.csv` support file (`Time(s)`, `DeviceID`, `X`, `Y`, `Z`) for the 14 mobile UAS. The GCS (ID 15) is stationary at (750, 1000, 3). `Z` is constant for each UAS and is reported in the sub-heading; only the time-varying (x, y) values are listed. All coordinates are in metres; values are rounded to the nearest metre for display.

Strike-1 (z = 150 m)

t (s)	x (m)	y (m)
0	2250	3000
5	2292	2917
10	2333	2833
15	2375	2750
20	2417	2667
25	2458	2583
30	2500	2500
35	2794	2560
40	2776	2617
45	2748	2669
50	2709	2715
55	2662	2752
60	2609	2780
65	2551	2796
70	2491	2800
75	2451	2833
80	2411	2867
85	2371	2900
90	2330	2933
95	2290	2967
100	2250	3000

Strike-3 (z = 150 m)

t (s)	x (m)	y (m)
0	3250	3250
5	3144	3144
10	3038	3038
15	2932	2932
20	2826	2826
25	2720	2720
30	2614	2614
35	2908	2673
40	2890	2730
45	2861	2783
50	2823	2829
55	2776	2866
60	2722	2893
65	2665	2909
70	2605	2913
75	2712	2970
80	2820	3026
85	2927	3082
90	3035	3138
95	3142	3194
100	3250	3250

Strike-2 (z = 120 m)

t (s)	x (m)	y (m)
0	2750	2750
5	2708	2708
10	2667	2667
15	2625	2625
20	2583	2583
25	2542	2542
30	2500	2500
35	2794	2560
40	2776	2617
45	2748	2669
50	2709	2715
55	2662	2752
60	2609	2780
65	2551	2796
70	2491	2800
75	2534	2792
80	2577	2783
85	2621	2775
90	2664	2767
95	2707	2758
100	2750	2750

Strike-4 (z = 130 m)

t (s)	x (m)	y (m)
0	3750	2750
5	3603	2721
10	3456	2691
15	3309	2662
20	3162	2632
25	3015	2603
30	2867	2574
35	3162	2633
40	3144	2690
45	3115	2743
50	3076	2789
55	3030	2826
60	2976	2853
65	2918	2869
70	2859	2873
75	3007	2853
80	3156	2832
85	3304	2812
90	3453	2791
95	3601	2771
100	3750	2750

Strike-5 (z = 140 m)

t (s)	x (m)	y (m)
0	1750	3250
5	1856	3144
10	1962	3038
15	2068	2932
20	2174	2826
25	2280	2720
30	2386	2614
35	2680	2673
40	2663	2730
45	2634	2783
50	2595	2829
55	2548	2866
60	2495	2893
65	2437	2909
70	2378	2913
75	2273	2970
80	2168	3026
85	2064	3082
90	1959	3138
95	1855	3194
100	1750	3250

Strike-8 (z = 145 m)

t (s)	x (m)	y (m)
0	4250	3000
5	4106	2959
10	3962	2918
15	3817	2876
20	3673	2835
25	3529	2794
30	3385	2753
35	3679	2812
40	3661	2870
45	3632	2922
50	3594	2968
55	3547	3005
60	3493	3032
65	3436	3048
70	3376	3053
75	3522	3044
80	3667	3035
85	3813	3026
90	3959	3018
95	4104	3009
100	4250	3000

Strike-6 (z = 160 m)

t (s)	x (m)	y (m)
0	4000	3250
5	3866	3183
10	3732	3116
15	3598	3049
20	3463	2982
25	3329	2915
30	3195	2848
35	3489	2907
40	3471	2964
45	3443	3017
50	3404	3063
55	3357	3100
60	3304	3127
65	3246	3143
70	3186	3147
75	3322	3164
80	3458	3182
85	3593	3199
90	3729	3216
95	3864	3233
100	4000	3250

ISR-1 (z = 300 m)

t (s)	x (m)	y (m)
0	2050	2500
5	2041	2574
10	2013	2644
15	1970	2704
20	1912	2752
25	1845	2785
30	1771	2799
35	1697	2795
40	1625	2773
45	1562	2733
50	1510	2680
55	1473	2614
60	1453	2542
65	1452	2468
70	1469	2395
75	1504	2329
80	1554	2273
85	1616	2232
90	1687	2207
95	1761	2200
100	1835	2212

Strike-7 (z = 135 m)

t (s)	x (m)	y (m)
0	1250	3500
5	1367	3406
10	1484	3313
15	1601	3219
20	1719	3125
25	1836	3031
30	1953	2938
35	2247	2997
40	2229	3055
45	2200	3107
50	2162	3153
55	2115	3190
60	2061	3217
65	2004	3233
70	1944	3238
75	1828	3281
80	1713	3325
85	1597	3369
90	1481	3413
95	1366	3456
100	1250	3500

ISR-2 (z = 280 m)

t (s)	x (m)	y (m)
0	3800	2250
5	3791	2324
10	3763	2394
15	3720	2454
20	3662	2502
25	3595	2535
30	3521	2549
35	3447	2545
40	3375	2523
45	3312	2483
50	3260	2430
55	3223	2364
60	3203	2292
65	3202	2218
70	3219	2145
75	3254	2079
80	3304	2023
85	3366	1982
90	3437	1957
95	3511	1950
100	3585	1962

Relay-1 (z = 450 m)

t (s)	x (m)	y (m)
0	1400	1750
5	1374	1835
10	1304	1890
15	1216	1896
20	1139	1851
25	1102	1771
30	1115	1684
35	1176	1619
40	1263	1601
45	1345	1634
50	1394	1708
55	1393	1797
60	1341	1869
65	1258	1900
70	1172	1878
75	1113	1812
80	1102	1724
85	1143	1645
90	1221	1603
95	1309	1612
100	1377	1670

Relay-3 (z = 420 m)

t (s)	x (m)	y (m)
0	2900	1750
5	2874	1835
10	2804	1890
15	2716	1896
20	2639	1851
25	2602	1771
30	2615	1684
35	2676	1619
40	2763	1601
45	2845	1634
50	2894	1708
55	2893	1797
60	2841	1869
65	2758	1900
70	2672	1878
75	2613	1812
80	2602	1724
85	2643	1645
90	2721	1603
95	2809	1612
100	2877	1670

Relay-2 (z = 400 m)

t (s)	x (m)	y (m)
0	2150	2000
5	2124	2085
10	2054	2140
15	1966	2146
20	1889	2101
25	1852	2021
30	1865	1934
35	1926	1869
40	2013	1851
45	2095	1884
50	2144	1958
55	2143	2047
60	2091	2119
65	2008	2150
70	1922	2128
75	1863	2062
80	1852	1974
85	1893	1895
90	1971	1853
95	2059	1862
100	2127	1920

Relay-4 (z = 430 m)

t (s)	x (m)	y (m)
0	1900	1250
5	1882	1322
10	1831	1376
15	1761	1400
20	1688	1386
25	1630	1340
30	1602	1271
35	1610	1197
40	1652	1136
45	1718	1103
50	1793	1106
55	1856	1144
60	1894	1208
65	1896	1282
70	1863	1349
75	1802	1391
80	1728	1398
85	1660	1370
90	1613	1312
95	1600	1239
100	1624	1168