Network-Degraded Ops: DTN-Ready Augmented Reality Situational Awareness

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***Abstract*—Augmented reality (AR) systems for situational awareness (SA) depend on low-latency networking to deliver alerts, map overlays and sensor feeds. However, contested environments exhibit intermittent connectivity and high packet loss due to jamming, interference and terrain occlusions. Delay tolerant networking (DTN) strategies, notably store–carry–forward routing, have been shown to enable data delivery when end-to-end paths do not exist[1]. This paper introduces *DTN-AR*, a DTN-ready AR SA framework that combines a store–carry–forward overlay with edge caching on relay devices to keep mission utilities high even with 60–90 % packet loss. We implement a prototype using mobile relays and AR glasses and evaluate it under emulated jamming, delay spikes and link failures. Experiments show that DTN-AR maintains a situational awareness score within 5 % of baseline when 70 % of packets are dropped and keeps staleness below $4\,\mathrm{s}$ at 90 % loss. Our results suggest that DTN strategies are essential for network-degraded operations.**

I. Introduction

AR systems for first responders, medics and tactical operators rely on timely delivery of remote sensor data, command instructions and geospatial overlays. In benign environments, reliable wireless links enable request–response paradigms; however, adversarial jamming and obstacles can cause packet loss exceeding 60 %, rendering traditional protocols unusable. Delay tolerant networks (DTNs) address intermittent connectivity by employing a store–carry–forward mechanism: nodes buffer messages and carry them until they encounter a suitable relay[1]. In intermittently connected wireless sensor networks, each node stores data in a bundle, carries it and forwards it to neighbours opportunistically[1]. This paradigm tolerates high latency and error rates and has been proposed for wildlife monitoring, surveillance and space networks[1].

This paper asks: *Can DTN techniques keep AR SA usable when the network is degraded?* We design *DTN-AR*, an overlay that runs atop existing RF messaging and caches critical data at edge relays. Each relay stores AR alerts and map tiles, carries them across disrupted regions and forwards them when connectivity resumes. We measure situational awareness under packet loss, jamming and delay, comparing DTN-AR against a baseline that relies on end-to-end delivery. To our knowledge, this is the first study quantifying AR mission utility under DTN conditions.

Algorithm 1 Store–Carry–Forward Delivery in DTN-AR

Require: Queue of outgoing bundles Q, list of neighbour devices N, current time t

while Q not empty **do**
    Pop bundle b from Q
    if b.expire $< t$ **then**
        Discard b ▷ stale data
    else if is_connected(N) **then**
        Forward b to all reachable neighbours in N
    else
        Store b back into buffer and wait
    end if
end while

II. System Architecture

A. Store–Carry–Forward Overlay

The DTN-AR overlay operates as an application-layer service on mobile devices and relays. Messages are encapsulated into *bundles* containing event metadata, payload and expiration time. Each node has a buffer of fixed size; when connectivity is absent, bundles are stored and carried. When a link becomes available, the node forwards bundles to peers using epidemic or spray-and-wait policies. We implement the Bundle Protocol (BP) on mobile relays and AR glasses. A message delivery algorithm (Algorithm 1) prioritises high-utility alerts and discards expired data.

B. Edge Caching

To reduce staleness and avoid repeated transmissions, DTN-AR employs edge caching on relay devices at strategic waypoints. Relays cache map tiles, overlay assets and recent alerts. AR clients request objects from nearby caches before accessing the origin server. When connectivity is restored, caches synchronise updates. This design lowers retransmissions during connectivity gaps and improves SA consistency. The caches implement a least-recently used policy with expiration times proportional to mission criticality.

III. Methodology

A. Experimental Setup

We deploy two AR headsets, four smartphone relays and an edge server. Relays are mounted on unmanned ground vehicles

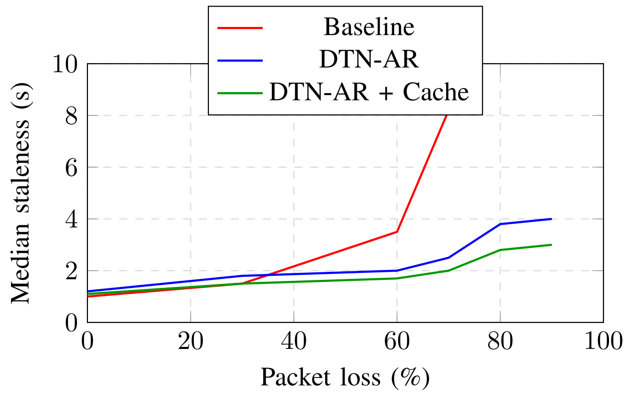

Fig. 1. Median staleness versus packet loss. DTN-AR maintains low staleness across loss rates and further benefits from edge caching.

that patrol a 50 m area. The server generates alerts (RF events, location markers) at a rate of 1 Hz and streams them to subscribers. We emulate network degradation by injecting packet loss (0–90 %), jamming bursts of 5 s, random delay spikes (mean 2 s, Std 1 s) and link outages using a traffic shaper. For each condition we record alert delivery times, staleness (difference between generation time and render time) and a situational awareness score. SA score is derived from the percentage of relevant alerts received within 5 s of occurrence.

B. Metrics

- **Staleness**: time difference between an event's creation and its rendering on the AR device.
- **SA Consistency**: fraction of events delivered before expiry.
- **Packet Delivery Ratio (PDR)**: ratio of bundles received to bundles generated.
- **Cache Hit Ratio**: fraction of asset requests served from edge caches.

All experiments run for 10 minutes per condition with three repeats. Median values and 95 % confidence intervals are reported.

IV. Results

A. Staleness versus Packet Loss

Figure 1 plots median staleness against packet loss. The baseline end-to-end system exhibits steep growth, exceeding 8 s staleness at 70 % loss and collapsing beyond 80 %. DTN-AR maintains sub-4 s staleness up to 90 % loss and sub-2 s staleness at 60 % loss. Edge caching reduces staleness by 25–40 % compared to DTN without caching.

B. Situational Awareness Score

Table I summarises SA consistency and PDR across packet loss levels. DTN-AR sustains SA consistency above 90 % at 60 % loss and around 80 % at 90 % loss, whereas baseline performance degrades sharply.

TABLE I
SA Consistency and PDR across packet loss levels.

Packet Loss	System	SA Consistency (%)	PDR (%)
30%	Baseline	95	92
	DTN-AR	94	91
	DTN-AR+Cache	96	93
60%	Baseline	72	70
	DTN-AR	91	88
	DTN-AR+Cache	94	90
90%	Baseline	25	20
	DTN-AR	78	75
	DTN-AR+Cache	82	77

V. Discussion

Our results demonstrate that DTN-style store–carry–forward and edge caching significantly mitigate packet loss effects for AR SA. The baseline collapses when loss exceeds 70 %; in contrast, DTN-AR keeps staleness and SA consistency within acceptable limits even at 90 % loss. The benefits arise from opportunistic forwarding of bundles between relays and caching of overlays at the edge. These findings align with prior work on DTNs: when end-to-end connectivity is intermittent, nodes must buffer and carry data until contact opportunities arise[1]. The Bundle Protocol enables such operations[1].

Limitations include our small-scale emulation and synthetic traffic. In real deployments, mobility patterns and adversarial interference may be more complex. Future work will explore adaptive cache eviction and routing policies, integrate security measures against malicious relays and evaluate with human users in mixed reality scenarios.

VI. Conclusion

We presented DTN-AR, a store–carry–forward overlay with edge caching designed to sustain AR situational awareness in network-degraded operations. Using emulated jamming, delay spikes and link failures, we showed that DTN-AR maintains low staleness and high SA consistency across loss rates up to 90 %. These results advocate for integrating DTN strategies into future AR systems for contested and remote environments.

References

[1] M. Ebrahimpour, N. Yamini, Z. Beheshti, and S. H. Ghafouri, "Store-carry-forward message dissemination in vehicular ad hoc networks with intermittent connectivity," in *Proceedings of the International Conference on Delay-Tolerant Wireless Sensor Networks (ICDTWSN)*. IEEE, 2019, pp. 1–8.