Grid Clash Synchronization Protocol (GCSP)

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Contents

1 Introduction

The **Grid Clash Synchronization Protocol (GCSP)** is a lightweight, UDP-based communication protocol designed to support *real-time distributed interactive systems* operating under uncertainty, packet loss, and variable network delay. Similar to clinical monitoring systems that must deliver timely, reliable physiological data despite noise and intermittent sensor dropout, GCSP is engineered to maintain **state consistency, low latency, and resilience** during multi-user interactions on a shared grid-based environment.

GCSP enables multiple clients to acquire cells, receive authoritative snapshots, and maintain a consistent replicated state—without relying on heavy, connection-oriented transports such as TCP. The protocol explicitly targets scenarios where the timeliness of updates is more critical than perfect reliability, and where modest packet loss is acceptable. As in medical telemetry, **delayed information may become clinically irrelevant**, thus GCSP prioritizes *freshness* of data over full reliability, using redundancy and event-level acknowledgments to ensure essential operations succeed even under adverse conditions.

1.1 Purpose of the Protocol

Traditional transport mechanisms (e.g., TCP) introduce head-of-line blocking, retransmission delays, and strict ordering guarantees that degrade responsiveness during real-time interaction. Such characteristics are incompatible with fast-paced, multi-client simulations. GCSP introduces a custom reliability model optimized for the following needs:

- **Real-time responsiveness** — Clients must see state updates within milliseconds, not seconds.
- **Partial reliability** — Only critical messages (EVENT actions) require reliable delivery.
- **High-frequency state dissemination** — The server must broadcast snapshots at a fixed tick rate (20 Hz).
- **Loss tolerance** — The simulation should remain functional even with 5–10% packet loss.
- **Low overhead** — Header format and packet structure must remain compact to avoid exceeding MTU or increasing congestion.

GCSP is therefore not intended to replace TCP or RTP, but rather to fill a specific design niche comparable to “clinical real-time telemetry”: high-frequency monitoring where information is perishable and the latest values matter most.

1.2 Use Case Summary

The target application of GCSP is a *competitive grid acquisition game* in which each client attempts to claim cells on a 20×20 grid. The server maintains the authoritative state, processes client actions, and broadcasts snapshot updates at a stable 20 Hz refresh rate. Key requirements include:

- **Authoritative consistency:** Only the server decides final cell ownership.
- **Fast conflict resolution:** When multiple players claim the same cell, the first valid event wins.
- **Continuous state synchronization:** Clients always receive up-to-date grid states.
- **Measurement capability:** The protocol must support detailed performance logging (latency, jitter, retries).

This mirrors medical systems where multiple monitoring devices report readings, but only a central controller aggregates, validates, and synchronizes state across the network.

1.3 Assumptions

GCSP operates under a realistic set of conditions reflected in typical LAN and WLAN environments:

1. **Maximum packet size ≤ 1500 bytes**, respecting standard Ethernet MTU.
2. **Packet loss may reach 5–10%**, especially on congested wireless links.
3. **No global clock synchronization**; client timestamps are used relative to server receipt.
4. **Network delay may fluctuate ±20 ms** under minor load, higher under congestion.
5. **Clients may disconnect abruptly** without sending a shutdown message.
6. **Reordering is possible**, since UDP provides no ordering guarantees.

These assumptions justify design decisions such as redundant snapshot broadcasting and idempotent event handling.

1.4 System Constraints

GCSP must adhere to the following constraints:

- **Uses UDP exclusively.**
  The protocol cannot depend on stream semantics or guaranteed delivery.
- **Server tick frequency fixed at 20 Hz.**
  Higher frequencies risk bandwidth congestion; lower rates degrade responsiveness.
- **Limited per-message payload size.**
  Header must remain compact; payloads must avoid fragmentation.
- **Clients cannot depend on persistent state.**
  They must re-join gracefully after disconnects.
- **Server must scale to multiple clients without degrading tick rate.**
  CPU time for snapshot generation < 50 ms per interval.

2 Protocol Architecture

The Grid Clash Synchronization Protocol (GCSP) follows a **central-authority distributed architecture**

2.1.1 Architectural Entities

2.1.2 Server

The server corresponds to a *central medical supervisor*, maintaining the authoritative state of the environment and providing consistent updates to all clients.

- **Server Responsibilities**
- Maintain the global grid (20×20) representing owned/unowned cells.
- Assign unique player identifiers upon client joining.
- Validate and apply EVENT messages (e.g., ACQUIRE_REQUEST).
- Ensure **idempotent** processing of events to avoid double-application.
- Broadcast authoritative snapshots at a fixed rate (20 Hz).
- Send ACK responses to confirm event receipt.
- Detect and remove inactive clients using timeout-based heartbeats.
- Log all relevant metrics (latency, jitter, snapshot count) for evaluation.

2.1.3 Clients

Clients act like remote medical sensors in a clinical network—collecting user actions, sending them reliably, and receiving continuous updates from the server.

- **Client Responsibilities**
- Initiate a JOIN handshake and obtain a player ID.
- Maintain local replicated game state based on snapshots.
- Transmit EVENT messages (cell acquisition attempts) reliably.
- Handle retries for EVENT messages until acknowledged.
- Maintain pending-events queue.
- Log latency and jitter for performance evaluation.

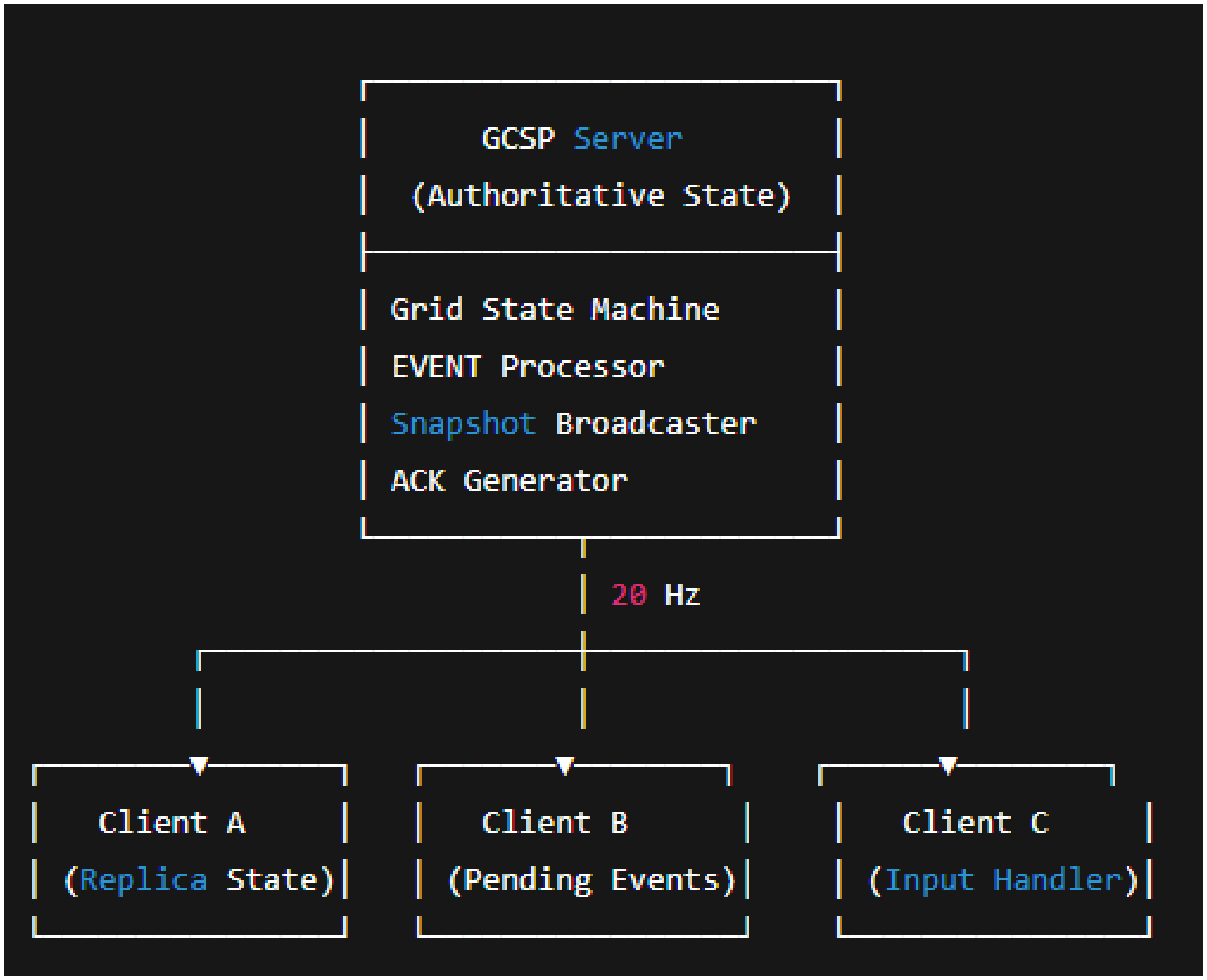
2.2 Communication Model

GCSP uses **UDP**, providing:

- Connectionless transport
- No delivery guarantees
- No ordering guarantees
- No retransmission at the transport layer

Therefore, the protocol enforces **application-layer reliability** only where needed (EVENT messages).
SNAPSHOT messages remain **fire-and-forget**, providing “freshness-first” information flow.

2.3 System Overview Diagram



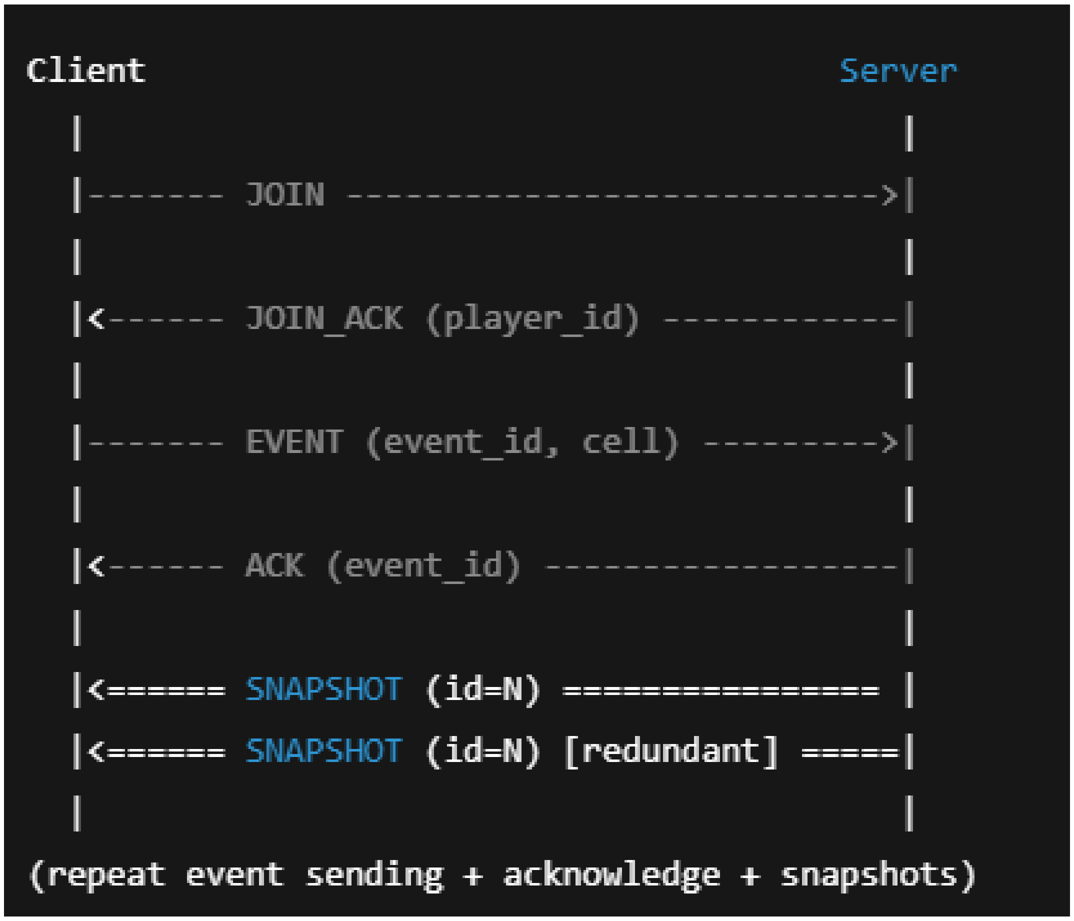
```
                    ┌──────────────────────────┐
                    │      GCSP Server         │
                    │  (Authoritative State)   │
                    ├──────────────────────────┤
                    │ Grid State Machine       │
                    │ EVENT Processor          │
                    │ Snapshot Broadcaster     │
                    │ ACK Generator            │
                    └────────────┬─────────────┘
                                 │ 20 Hz
             ┌───────────────────┼───────────────────┐
             │                   │                   │
  ┌──────────▼──────┐  ┌─────────▼────────┐  ┌───────▼──────────┐
  │    Client A     │  │    Client B      │  │    Client C      │
  │ (Replica State) │  │ (Pending Events) │  │ (Input Handler)  │
  └─────────────────┘  └──────────────────┘  └──────────────────┘
```

2.4 Protocol Flow Overview

GCSP operates through three concurrent flows:

1. **Session Establishment Flow**
   Client requests to join → server responds with JOIN_ACK.
2. **Reliable Event Flow**
   CLIENT → EVENT → SERVER
   SERVER → EVENT_ACK → CLIENT
   Retries occur until EVENT_ACK is received.
3. **Snapshot Synchronization Flow**
   SERVER → SNAPSHOT → CLIENTS
   Broadcast every 50 ms (20 Hz), sent twice for redundancy.

2.5 Detailed Sequence Diagram



```
Client                                    Server
  |                                          |
  |------- JOIN --------------------------->|
  |                                          |
  |<------ JOIN_ACK (player_id) ------------|
  |                                          |
  |------- EVENT (event_id, cell) --------->|
  |                                          |
  |<------ ACK (event_id) ------------------|
  |                                          |
  |<====== SNAPSHOT (id=N) ================ |
  |<====== SNAPSHOT (id=N) [redundant] =====|
  |                                          |
(repeat event sending + acknowledge + snapshots)
```

2.6 Finite-State Machine

2.6.1 Client

State 0 — DISCONNECTED

- No communication established.
- Waiting for user input to start session.

State 1 — JOIN_SENT

- Client sends JOIN request.
- Awaiting JOIN_ACK.
- Timeout → resend JOIN.

State 2 — ACTIVE

- Client has player ID.
- Maintains snapshot-replicated state.
- Sends EVENT messages when user interacts.
- Retries pending events until ACKed.

State 3 — WAITING_FOR_ACK

- After sending an EVENT.
- If timeout: resend EVENT unless retries exhausted.

State 4 — TERMINATED

- User quits, or server timeout removes client.
- Cleanup occurs.

2.6.2 Server

State 0 — IDLE

- Server running with no connected clients.

State 1 — ACTIVE

- Clients joined.
- Receiving EVENT messages.
- Broadcasting SNAPSHOT packets every 50 ms.

State 2 — TIMEOUT_PROCESSING

- Detects clients with no communication for 5 seconds.
- Removes them safely.

State 3 — SHUTDOWN

- Server terminates by operator.

2.7 Thread Architecture

The server uses **three concurrent threads**, analogous to separate clinical monitoring subsystems:

1. **Receiver Thread**
    - Reads JOIN and EVENT messages
    - Applies game logic
    - Sends ACKs
2. **Snapshot Broadcaster Thread**
    - Broadcasts snapshots at fixed frequency
    - Implements redundancy (2 sends)
3. **Client Cleanup Thread**
    - Removes inactive clients
    - Preserves player_id history for reconnection

3 Message Formats

GCSP defines a compact packet structure optimized for low-latency real-time synchronization.
All fields use **big-endian (network byte order)** to ensure consistent cross-platform interpretation.

Each message consists of:

1. **Fixed-length GCSP header (28 bytes)**
2. **Variable-length payload**, depending on message type.

3.1 GCSP Header

The header precedes **all** GCSP packets (JOIN, JOIN_ACK, EVENT, ACK, SNAPSHOT).

3.1.1 GCSP Header Structure (28 bytes)

FIELD NAME	SIZE (BYTES)	OFFSET	DESCRIPTION
PROTOCOL_ID	4	0–3	Always b'GCSP', identifies the protocol
VERSION	1	4	Protocol version, currently 1
MSG_TYPE	1	5	Message type enum (JOIN=0, ACK=4, SNAPSHOT=2, ...)
SNAPSHOT_ID	4	6–9	Monotonic ID, used for ordering snapshots
SEQ_NUM	4	10–13	Server-side packet counter (client sets to 0)
SERVER_TS_MS	8	14–21	Server timestamp (ms since epoch)
PAYLOAD_LEN	2	22–23	Length of payload in bytes
CHECKSUM	4	24–27	Reserved for future CRC validation

3.1.2 Struct Packing Format

The header is encoded using:

```
HEADER_FORMAT = "!4s B B I I Q H I"
```

Where:

- ! → network byte order
- 4s → protocol_id
- B → version
- B → msg_type
- I → snapshot_id
- I → seq_num
- Q → server_ts_ms
- H → payload_len
- I → checksum

3.2 EVENT Message Format

EVENT messages are **reliably delivered** using ACK and retransmissions.

FIELD	SIZE	OFFSET	DESCRIPTION
EVENT_TYPE	1 byte	0	EVENT type (ACQUIRE_REQUEST = 0)
EVENT_ID	4 bytes	1–4	Client-generated unique ID
ROW	1 byte	5	Grid row (0–19)
COL	1 byte	6	Grid column (0–19)
CLIENT_TS_MS	8 bytes	7–14	Client timestamp used for latency measurement

3.2.1 EVENT Struct Format

```
EVENT_FORMAT = "!B I B B Q"
```

3.3 ACK Format

ACK messages confirm successful EVENT processing.
They are **mandatory** for client reliability logic.

FIELD	SIZE	OFFSET	DESCRIPTION
ACK_TYPE	1 byte	0	ACK type (EVENT_ACK = 0)
EVENT_ID	4 bytes	1–4	ID of acknowledged event

3.3.1 ACK Struct Format

```
ACK_FORMAT = "!B I"
```

3.4 SNAPSHOT Format

SNAPSHOT messages are large, frequent, and **unreliable but redundant**.
They contain:

- Grid dimensions
- Player list (with fake positions for now)
- Full grid ownership (400 cells × 1B each)

3.4.1 SNAPSHOT Payload Structure

FIELD	SIZE	OFFSET	DESCRIPTION
N	1 byte	0	Grid dimension (20)
NUM_PLAYERS	1 byte	1	Active players
PLAYER ENTRIES	6 bytes × Nplayers	2–...	Each: (player_id, x_pos(float), y_pos(float))
GRID CELLS	N×N bytes	...	Ownership array: 0 = unowned, otherwise player_id

3.4.2 Per-Player Substructure

FIELD	SIZE	DESCRIPTION
PLAYER_ID	1 byte	Unique identifier
X	4 bytes	Fake normalized x position
Y	4 bytes	Fake normalized y position

3.4.3 SNAPSHOT Struct Format

```
payload = struct.pack("!B B", N, num_players)
payload += repeat(num_players × struct.pack("!B f f"))
payload += repeat(N*N × struct.pack("!B"))
```