Optimizing Quality of Experience for Long-Range UAS Video Streaming

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Motivation

- UAS Systems are seeing rapid growing interest in long-range distances (e.g., exceeding Visual Line of Sight (VLOS)).
  - Regulations are beginning to support long-distance UAS flights globally.
- Many UAS applications involve recording and streaming video.
  - Critical quality requirements.
  - Locations are determined by mission requirements, not optimal connectivity.
- Our focus: addressing the challenges for UAS video streaming at long-range distances.
  - Design a new video streaming algorithm to address the challenges of long-range UAS flight networks, and achieve good performance.

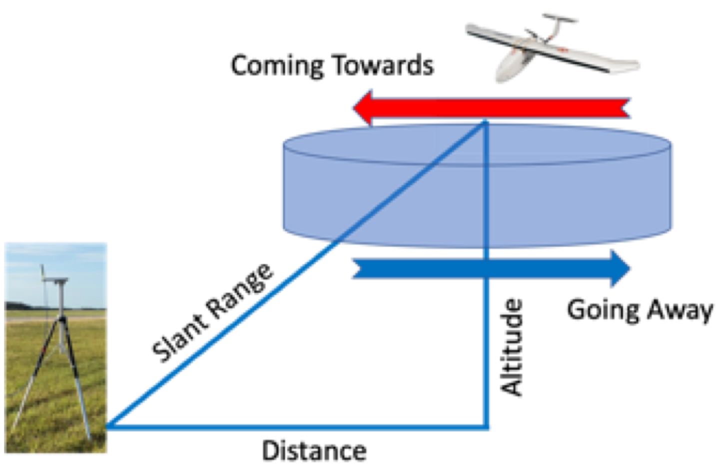
UAS networking requires different approaches than traditional Internet.

Contributions

- Real-world measurement of fixed wing UAS flights at long-range distances.
  - Long dropouts (and periods of poor throughput).
  - Performance depends on flight path (especially orientation).
- Design Proteus, the first system for video streaming in long-range UAS settings.
  - Control theoretic approach combines 'terminal cost' with model predictive control, optimized based on the UAS flight path.
- Proteus significantly improves performance compared to a state-of-the-art video streaming algorithm.
  - Reduced rebuffering ratio from 14.33% to 1.57% at the furthest distance, while maintaining other metrics comparable.

Motivating measurements

- Fixed-wing UAS flight tests.
  - Faster and longer endurance than multirotor.
- Circular orbits with distances 0.5 to 4.5 miles from the Ground Control Station (GCS) – beyond VLOS (with special approval).
- Tested with tactical radios (S-band and point-to-point).
- Omnidirectional antennas on the UAS for dynamic flight.



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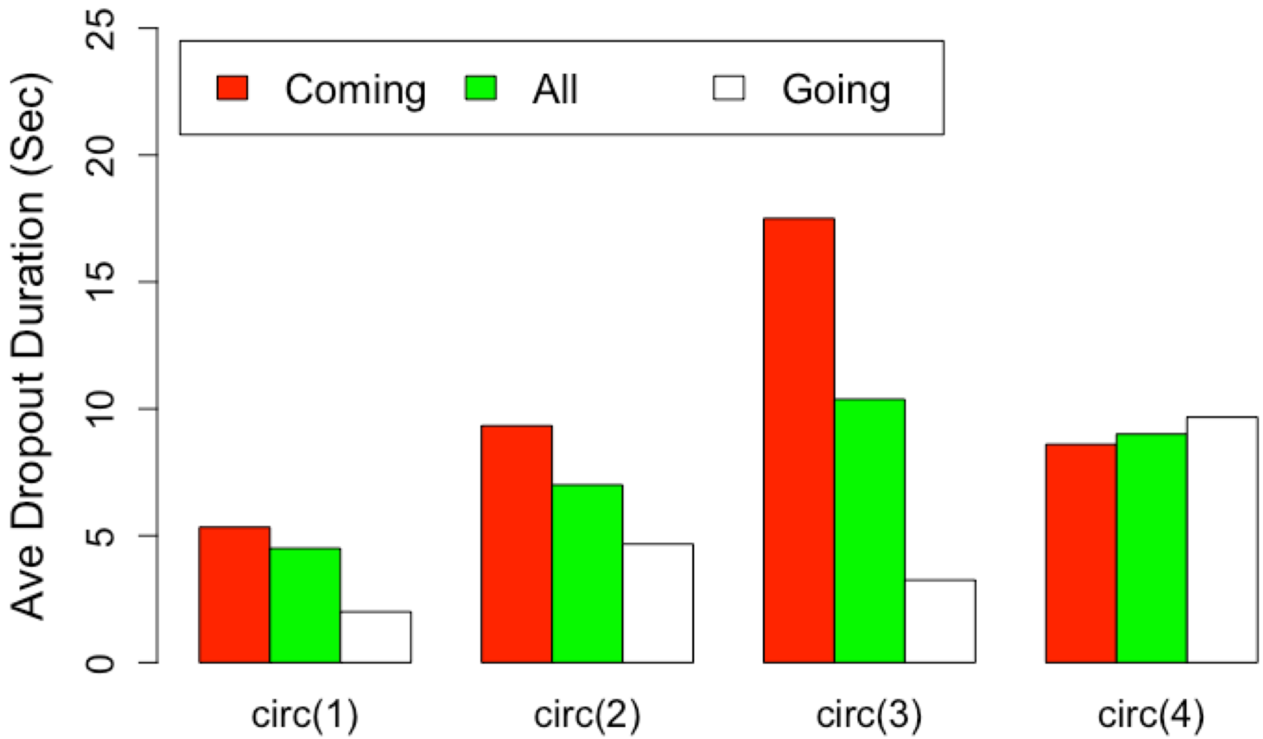
Flight measurement observations

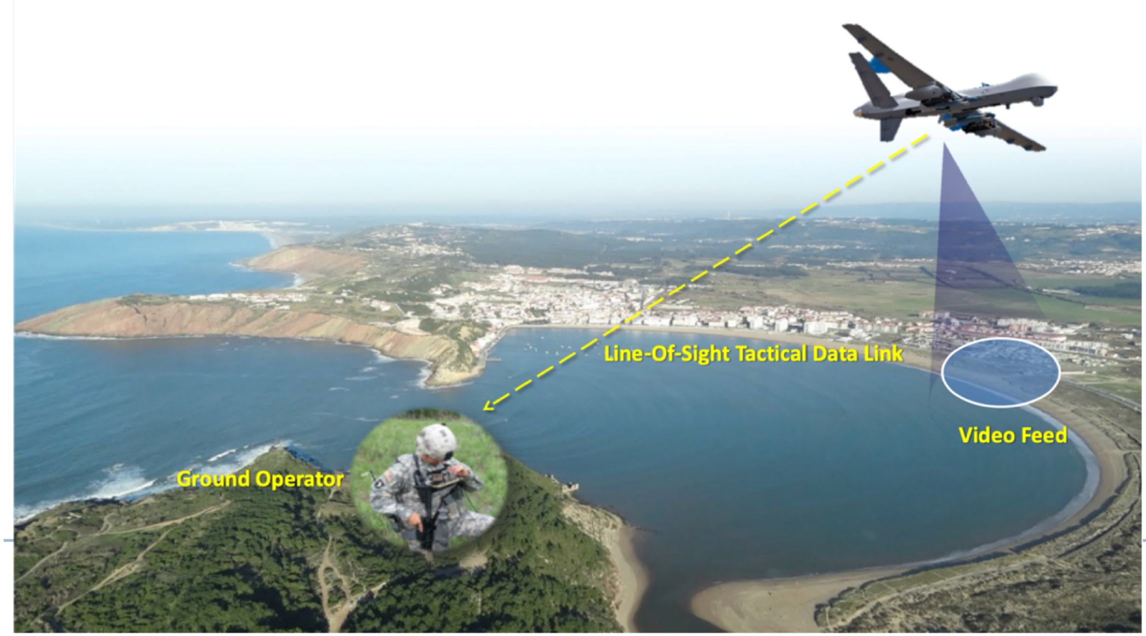
- Dropouts are common in UAS settings.
- Dropout duration increases with distance.
- *Coming towards* the GCS orientation experiences more dropouts.



Average dropout duration shows video streaming with delay of tens of seconds should be possible.

Proteus design rationale

- Optimize for long-range UAS flight.
  - Increase usable range to edge of connectivity, where dropouts are common.
- Focus on near real-time video streaming (< tens of seconds delays).
  - Minor delays are acceptable in many situations, and allow extension of mission range to previously inoperable areas (e.g., disaster response or military to safely rescue and guide personnel).
- Adaptive Bit Rate (ABR) algorithms are applicable to our scenario.



State-of-the-art ABR does not work well for UAS settings

- Existing ABR algorithms focus on traditional Internet, not UAS flight.
- Example: MPC [Yin, SIGCOMM 2015]
  - Look-ahead window in which the bitrate over the next few chunks is selected.
  - Uses a combination of future throughput prediction and buffer occupancy to select chunk bitrates, and optimizes decisions based on predicted QoE.
- MPC emulation tests show very high rebuffering with UAS flight traces.
  - Median rebuffering ratio over 15% with a practical predictor at roughly 4 miles.
  - Even with a perfect Oracle predictor, rebuffering is still an issue.
    - Over 5% at roughly 4 miles, and over 10% for the most challenging flight trace.
  - Rebuffering due to the greedy nature of ABR algorithms.
    - Not accounting for long dropout periods, UAS flight network variability

Proteus – a new algorithm for UAS video streaming

- Proteus overcomes of the challenges of MPC by:
  - Explicitly considering UAS networking dropouts.
  - Incorporating flight path knowledge and its interplay with throughput.
- Handling dropouts:
  - We create a new optimization metric for each look-ahead window.
  - Proteus compensates for the greedy nature of MPC by explicitly incentivizing video left in the buffer when selecting bit rates.
- Integrated into the Proteus algorithm via a **"terminal cost."**

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Terminal cost with Proteus

- Proteus implements a new reward equation, with terminal cost.
  - Quality of Experience (QoE) is a widely used scoring system, based on video bitrate, video quality smoothness, and rebuffering/delay time.
  - Proteus adds a **terminal cost** term, $\gamma \cdot \epsilon(b)$, that carefully considers the amount of video in the buffer at the end of the window.

$$QoE_b = QoE(i, i + W - 1) + \gamma \cdot \epsilon(b)$$

Our new QoE equation to optimize for UAS flight:

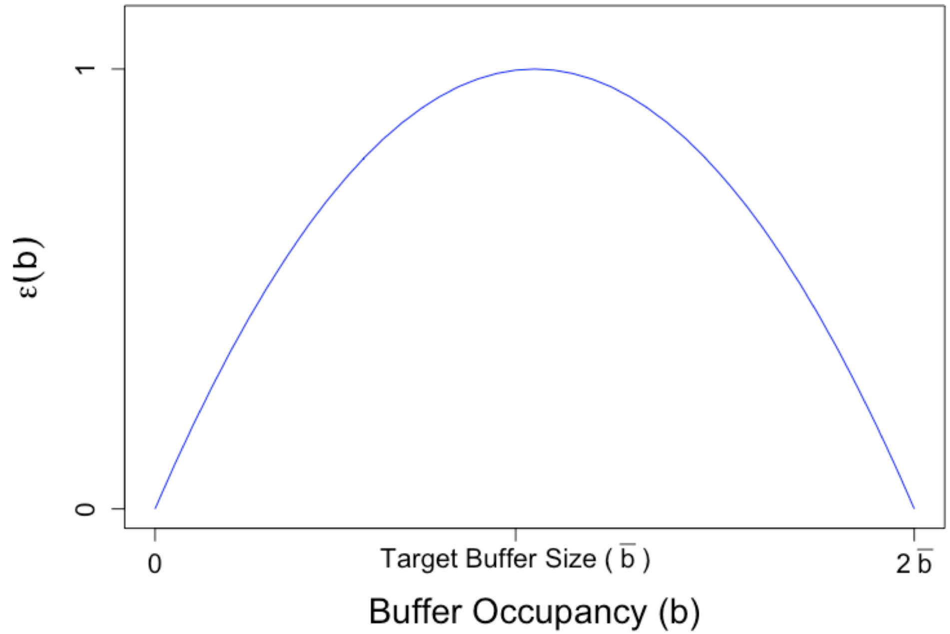
1. i is the current video chunk.
2. W is the size of the look-ahead.
3. $\gamma \cdot \epsilon(b)$ is the newly added terminal cost.
4. b is the buffer size at the end of the look-ahead.
5. γ scales the weight of the terminal cost.

The key question is how to determine the terminal cost.

Terminal cost design considerations

- Optimizing terminal cost: $\gamma \cdot \epsilon(b)$.
  - A larger term indicates more insurance, but sacrifices quality.
  - Need to fill up the buffer to a "sweet spot."
  - We design an $\epsilon(b)$ that is quadratic in the buffer occupancy b:
    - $\epsilon(b)$ reaches a maximum of 1 when $b=\bar{b}$ but is 0 when $b=0$, or $b \geq 2\bar{b}$.

$$\epsilon(b) = \frac{\bar{b}^2 - (\min(b, 2\bar{b}) - \bar{b})^2}{\bar{b}^2}$$



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Connecting UAS flight path to terminal cost

- The key question is how to set the parameters $\bar{b}$ (target buffer size) and γ (terminal cost weight).
  - Tuned to UAS flight network characteristics (e.g. dropout duration).
- We devise two schemes to select terminal cost parameters:
  - **Proteus** (buffer insurance parameters are chosen based on distance).
    - Same $\bar{b}$ and γ for entire circle.
  - **Proteus-Orient** (parameters based on both distance orientation).
    - We allow for a different $\bar{b}$ and γ (based on circle orientation).

We carefully select parameters to optimize Proteus for UAS networks.

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A test bed for emulated UAS flight network testing

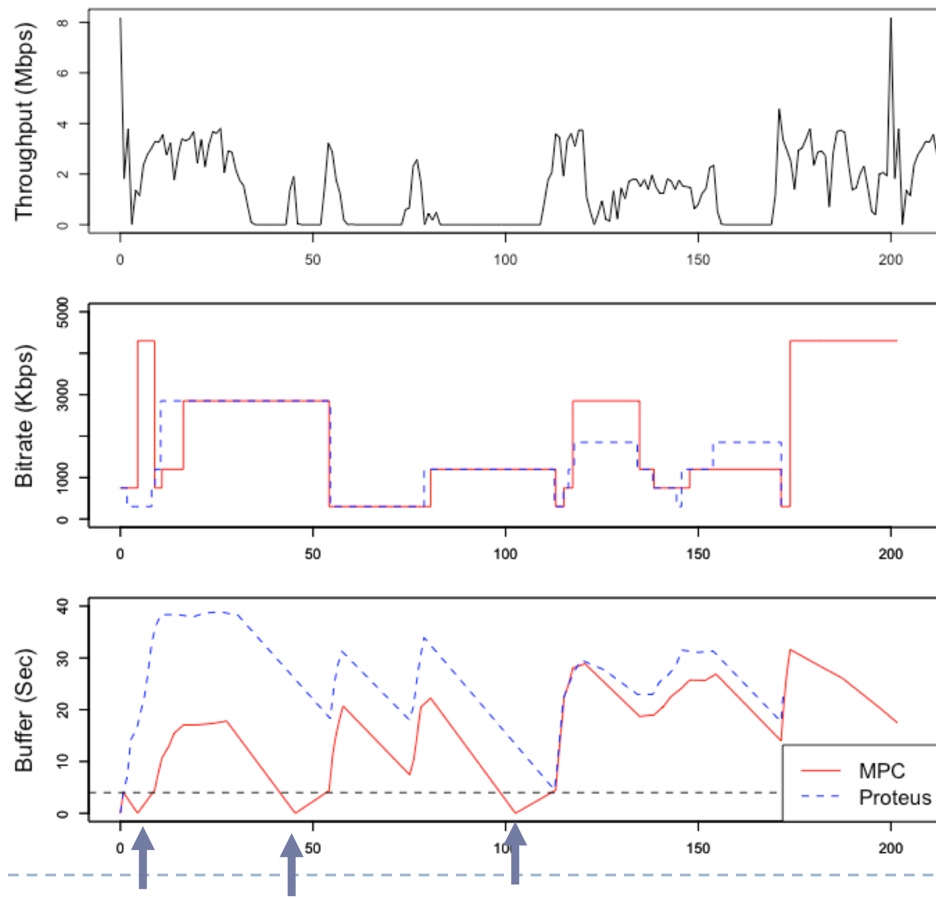
- Emulation test-bed with real-world flight traces
  - Video streaming server (UAS) and separate client (GCS), using Dash.js.
  - Integrated flight path throughput, location, and orientation.
  - Used Mahimahi to ensure our network throughput and latency mimicked real-world flight traces.
- QoE metric:
  - Positive reward for higher bitrate chunks.
  - Negative reward for changes in bitrate (smoothness) and rebuffering/delays.

Emulation bed integrates UAS flight path + location into test.

Benefits of Proteus

- Proteus significantly out-performs MPC by reducing rebuffering.
  - Only slightly lower bitrate.
- Due to its greedy nature, MPC leaves the buffer nearly empty, resulting in rebuffering.

Circ(4) orbit test.

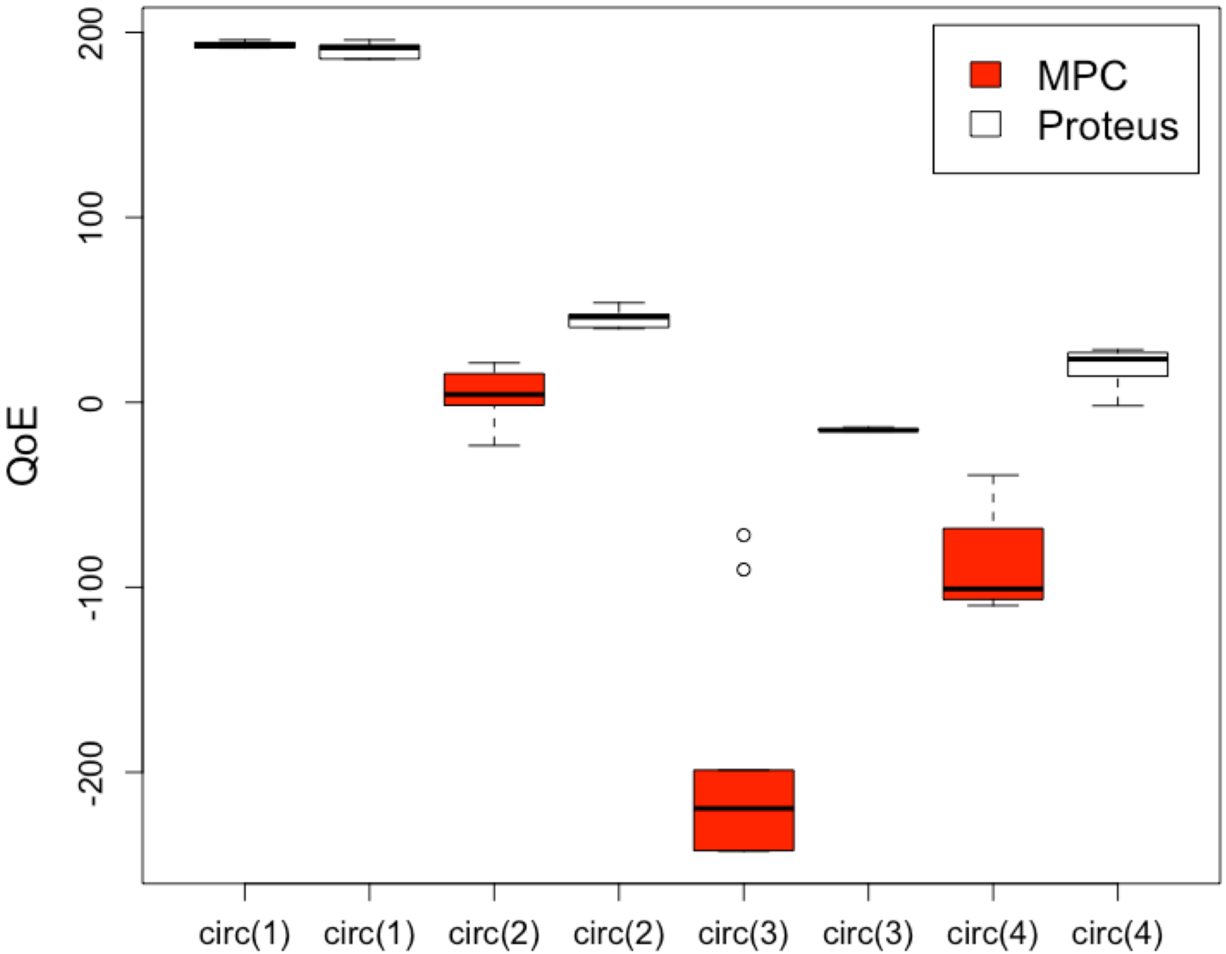


MPC Rebuffering Events (eliminated with Proteus)

Benefits of Proteus across all traces

- Proteus significantly improves performance for circ(2-4).
  - Proteus greatly reduces rebuffering, while only slightly reducing bitrate.

Higher QoE is better.



Summary of other results

- **Proteus-Orient:** Considering orientation helps.
  - Increased video bitrate by 14.38% while reducing rebuffering by 2.34% (circ(3))
- **Learning across traces:**
  - Proteus can learn parameters in one trace and using them in a separate test, with further benefits (over 15% increase in QoE).
- **Predictor Sensitivity**: Proteus sees benefits with other predictors.
  - Proteus performed better with a Hidden Markov Model (HMM) predictor, (circ(2) QoE improved from 13.05 to 47.84, with other traces showing similar increases).
  - Still even with a perfect Oracle, Proteus saw benefits.

Conclusion

- Motivated by real-world UAS flight test data, we designed Proteus, the first system for long-range UAS video streaming.
  - Based on a control-theoretic ABR algorithm approach.
  - Carefully constructed *terminal cost* integrated into the receding-horizon optimization at each point in time.
  - Terminal cost parameters carefully chosen based on UAS flight path (both distance and orientation).
- Proteus out-performs state-of-the-art ABR.
  - Reduce rebuffering ratio by 18.15% with most challenging trace.
    - Net QoE improvement increase from -198.84 to 3.83.
  - Benefits hold across traces and distances, and even with a perfect oracle predictor.

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Thank you!