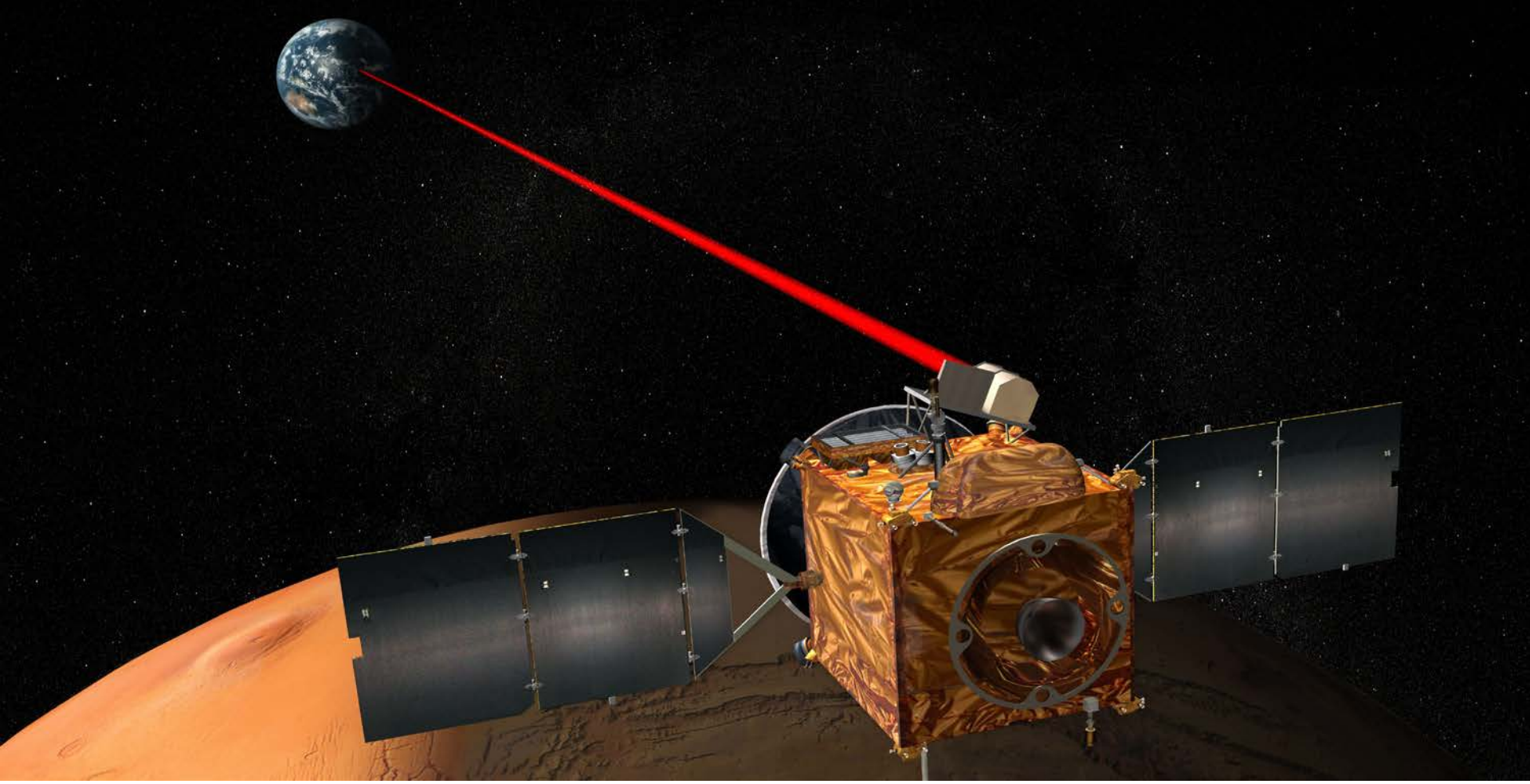

Deep Space Optical Link ARQ Performance Analysis

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OUTLINE

- ARQ Optical Link Overview & Context
- System Model
  - Weather effects
  - Buffering pending ARQ acknowledgments
- Performance Metrics
  - Buffer size distribution
  - Loss rate due to buffer overflow
  - Delivery latency
- Results for Example Mission Scenario
- Summary

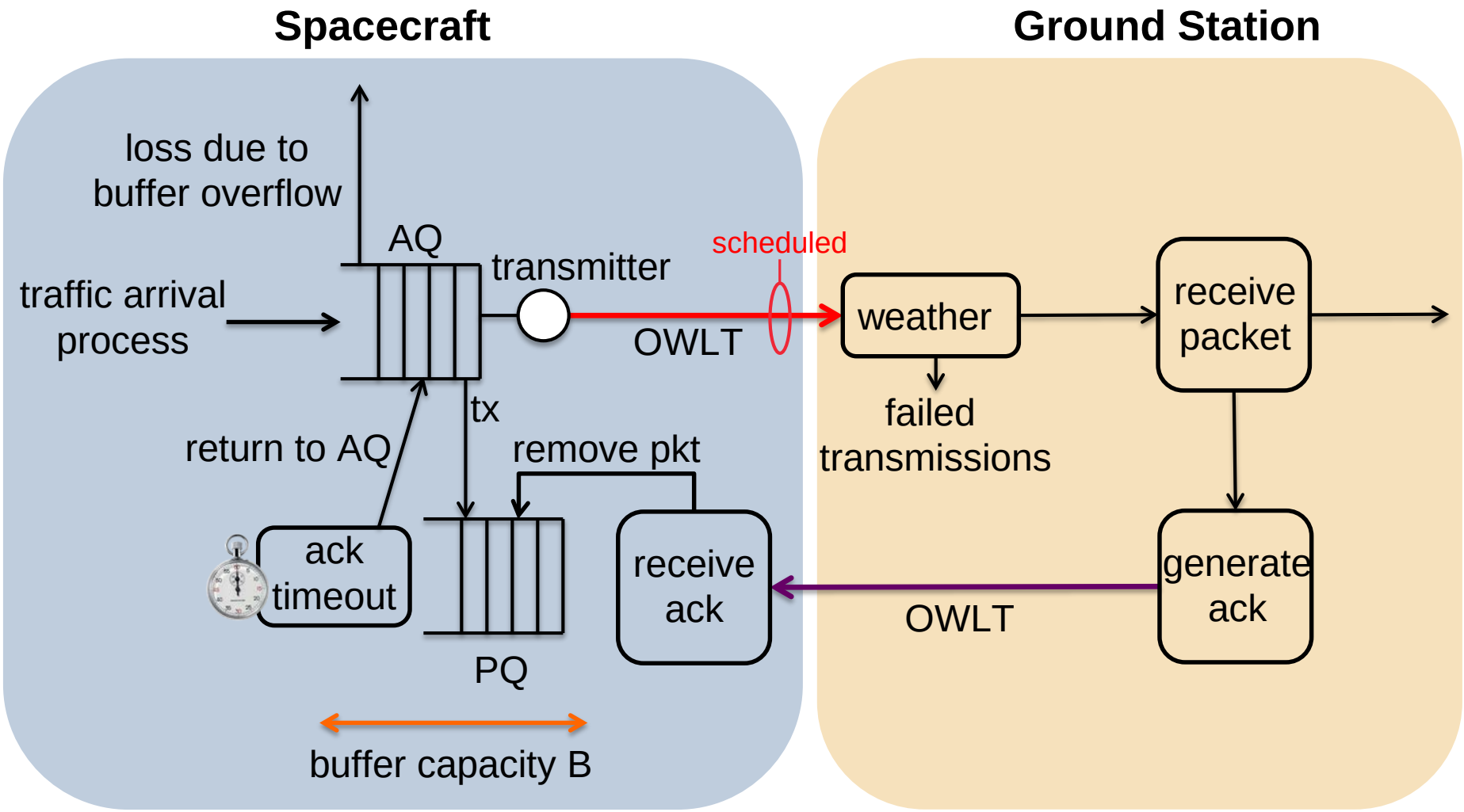
ARQ Optical Link Overview & Context

- Deep Space Optical Communications promises much higher data volume compared to current RF
- However, subject to stochastic weather effects that cause link outages
- Make the link reliable by applying Automatic Retransmission Query (ARQ)
  - Adds latency to data delivery time
  - Some loss due to spacecraft buffer overflow
  - Assume LTP: Selective Repeat/schedule-aware ARQ for disruption tolerant networks (DTNs)
- Early deployment limited to single ground station
- Analyze performance with simulation

ARQ Optical Link System Model

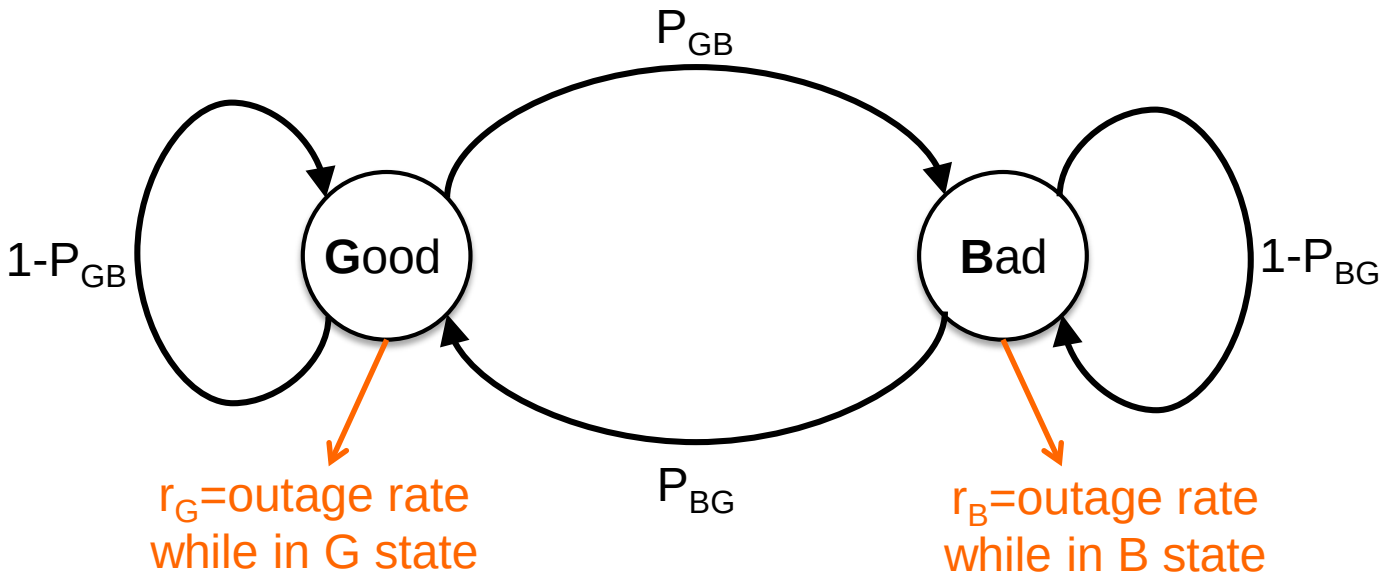
- Focus on spacecraft-to-Earth (“return”) link
- Spacecraft ARQ operation
  - New information packets arrive, place in Active Queue
  - When schedule indicates link active, transmit packet and place copy in Pending Queue
  - Receive acknowledgments from Ground Station, remove packets from PQ; if timeout, move to AQ
  - If a new packet arrives to full buffer, it is dropped
- Ground Station: acknowledge received packets
- Earth-to-spacecraft link assumed to be reliable

ARQ Optical Link System Model



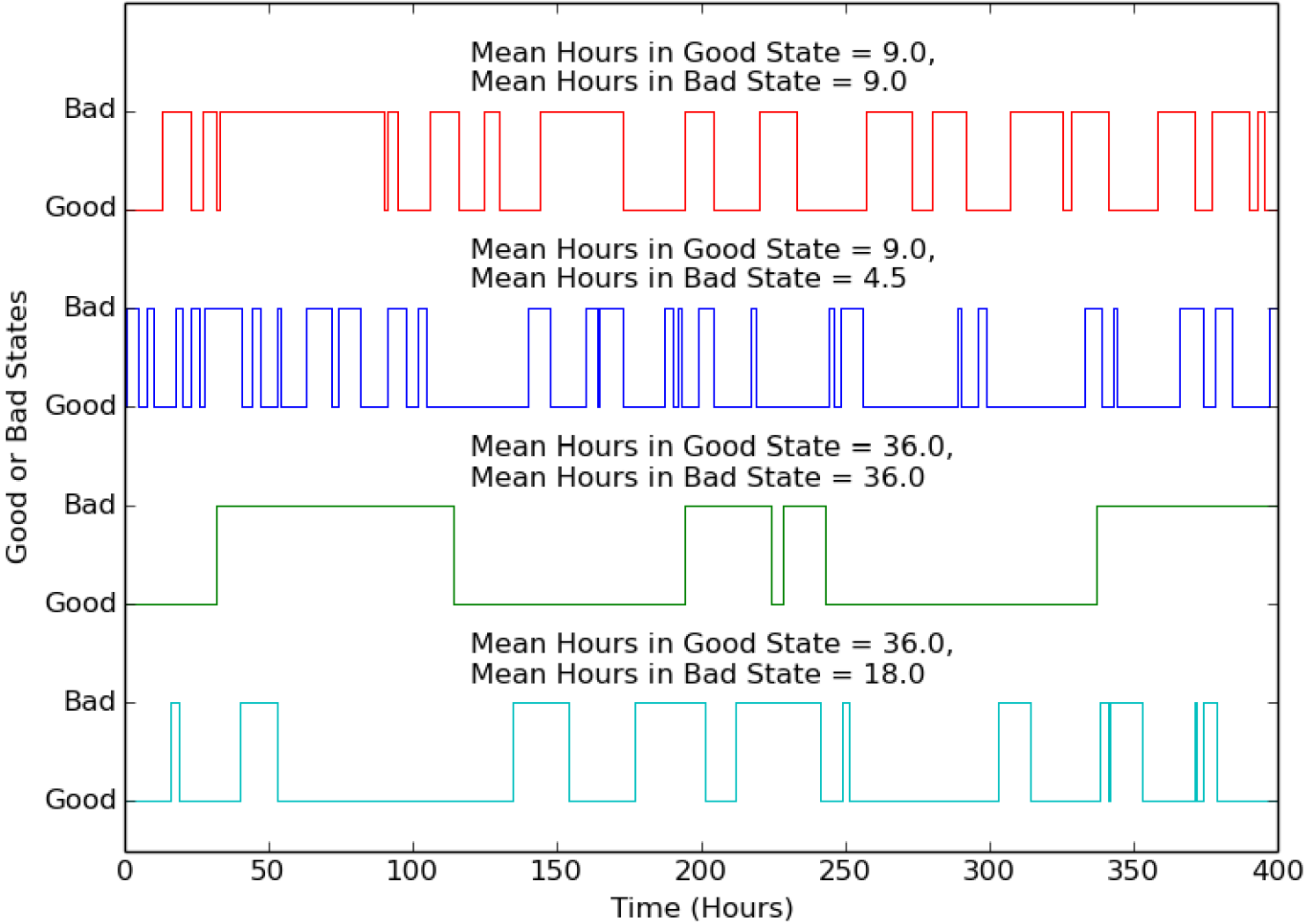
Weather: Gilbert-Elliot Model

- Weather outages are modeled using a 2-state discrete-time Markov chain

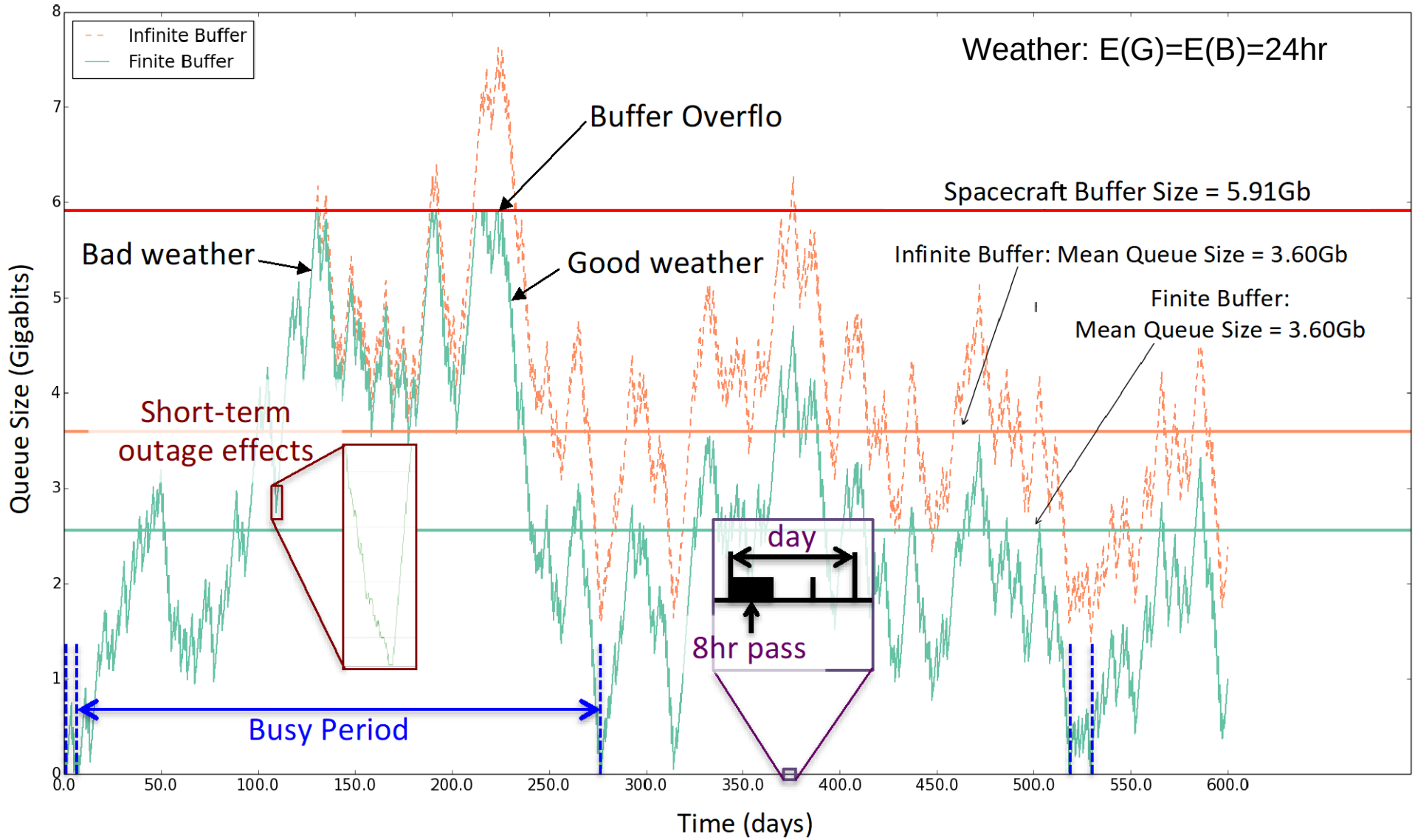


Mean sojourn time in G state = $E(G) = 1/P_{GB}$
Mean sojourn time in B state = $E(B) = 1/P_{BG}$

Example Weather Model Realizations



Example Spacecraft Queue-Size Processes



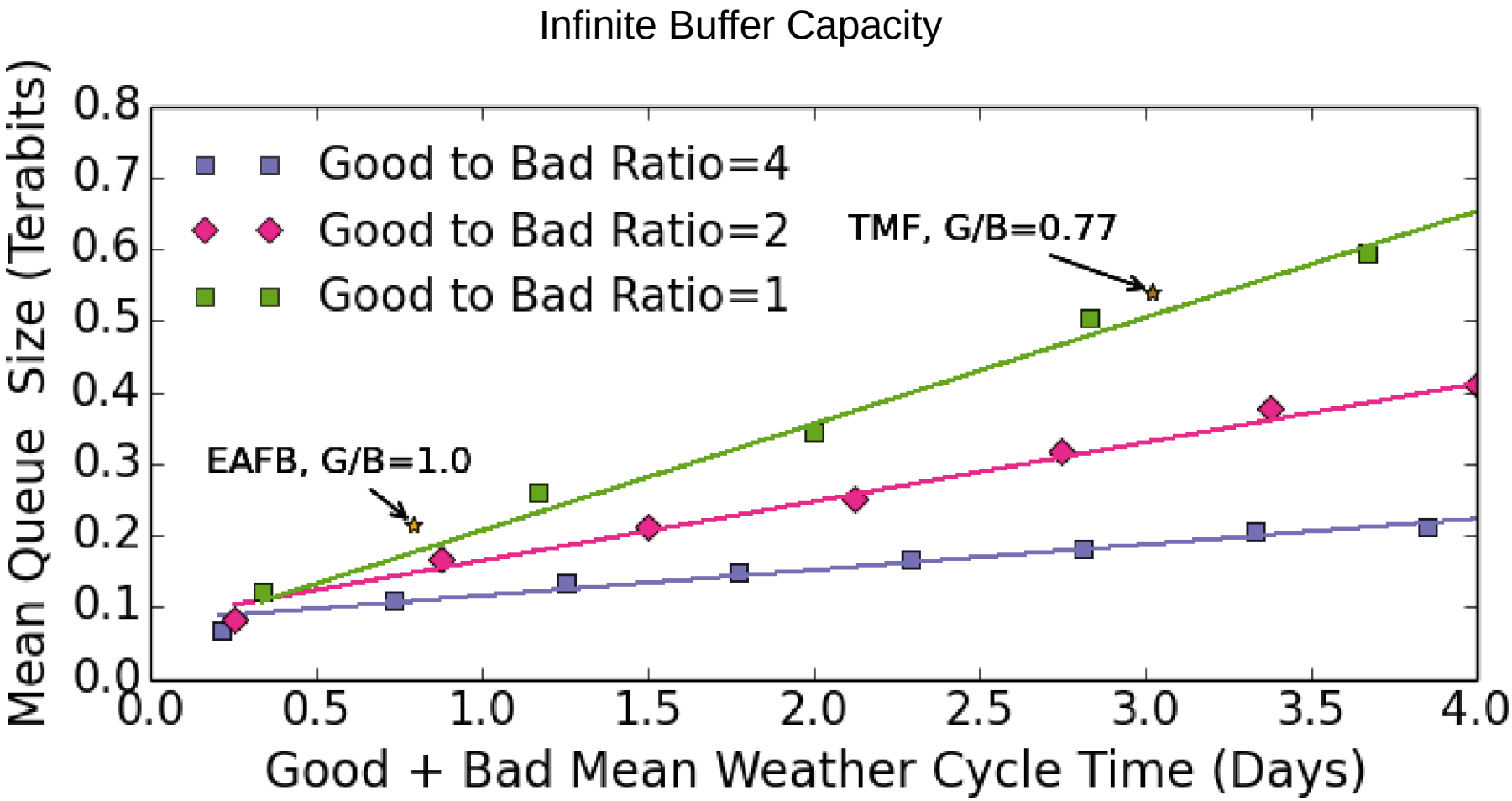
Performance Metrics

- Generally focus on equilibrium behavior
  - Equilibrium always exists with finite buffer
  - Constrain offered load<channel capacity if infinite buffer
  - Channel capacity depends on E(G)/E(B)
- Throughput and channel utilization
- Loss rate due to buffer overflow
- Latency probability distribution
- Queue-size probability distribution
  - Buffer occupancy
- Busy Period probability distribution
  - Measure of buffer congestion

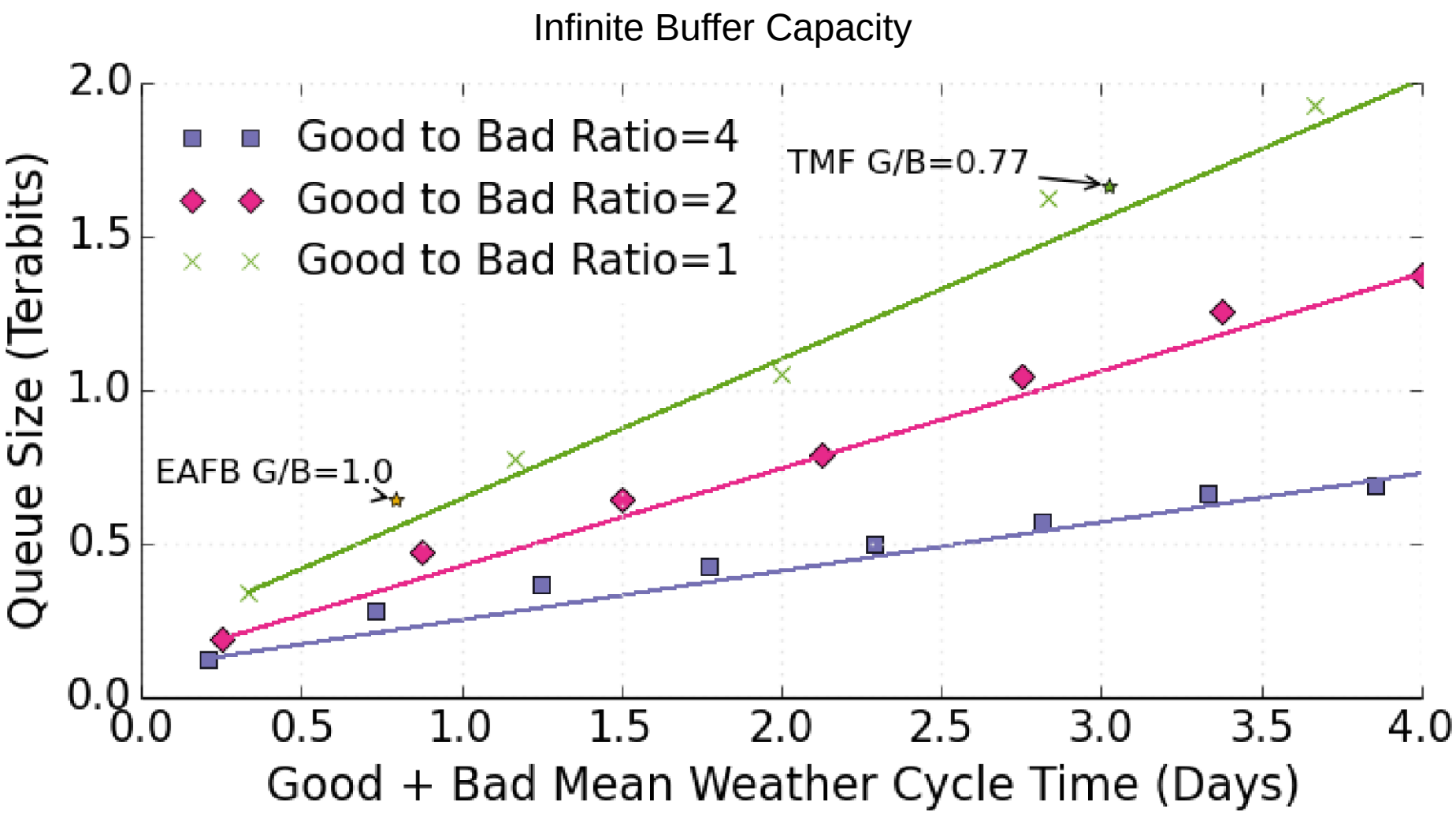
Parameters for Example Scenarios

- Constant arrival process
- 8hr/day passes (single ground station)
- One-Way Light Time = 22.4 min (Earth-Mars max distance)
- r_G=0 (no outage in Good State)
  r_B=0 (no transmissions succeed in Bad State)
- Offered traffic arrival rate = 80% of channel capacity
- Burst transmission rate = 10 Mb/s
- "packet" transmission time = 10sec;
  "packet" size = 100 Mb
- Vary weather parameters E(G) & E(B)
  - "Weather cycle" = E(G)+E(B)
- Vary buffer capacity

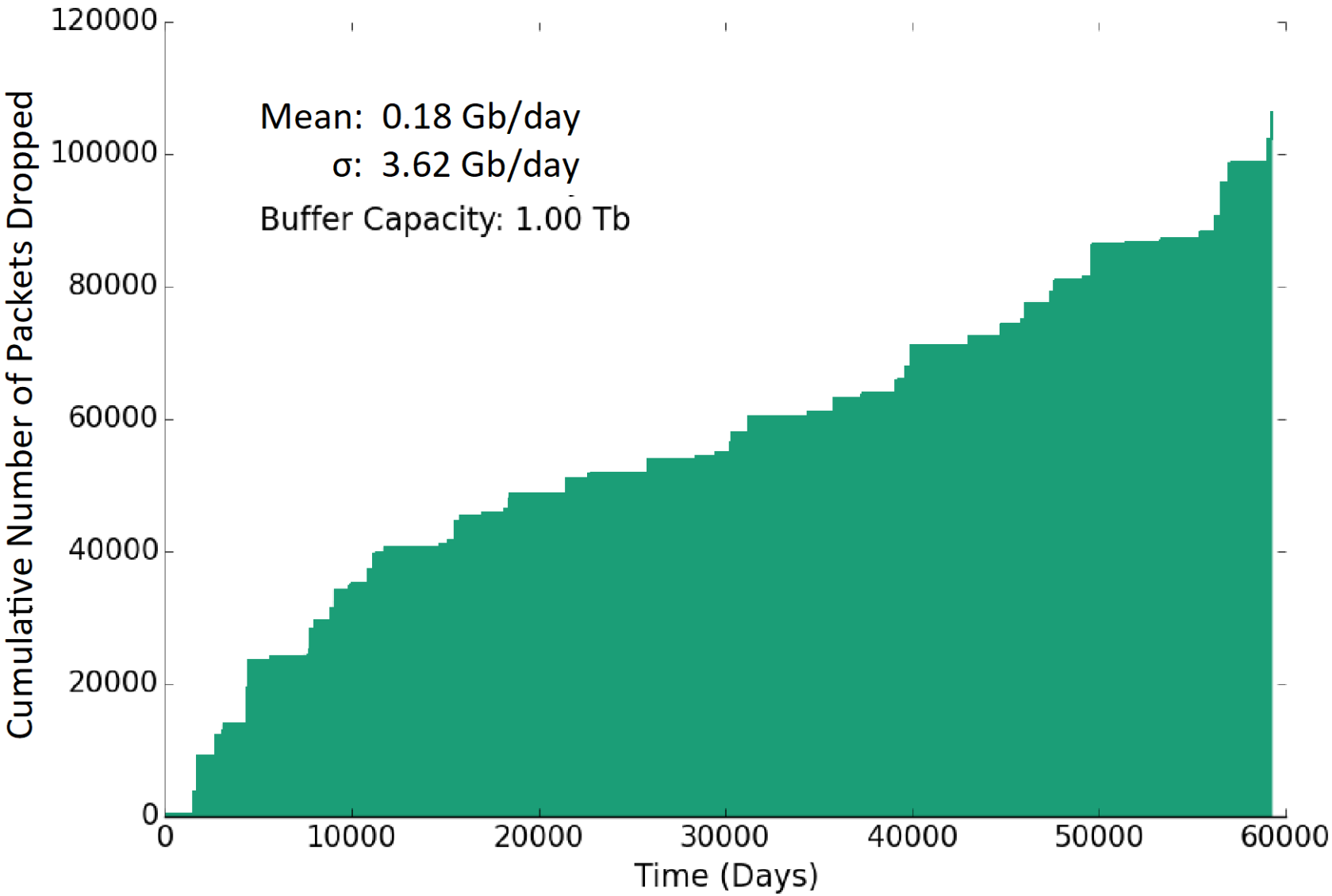
Mean Queue Size vs. Weather Cycle Time



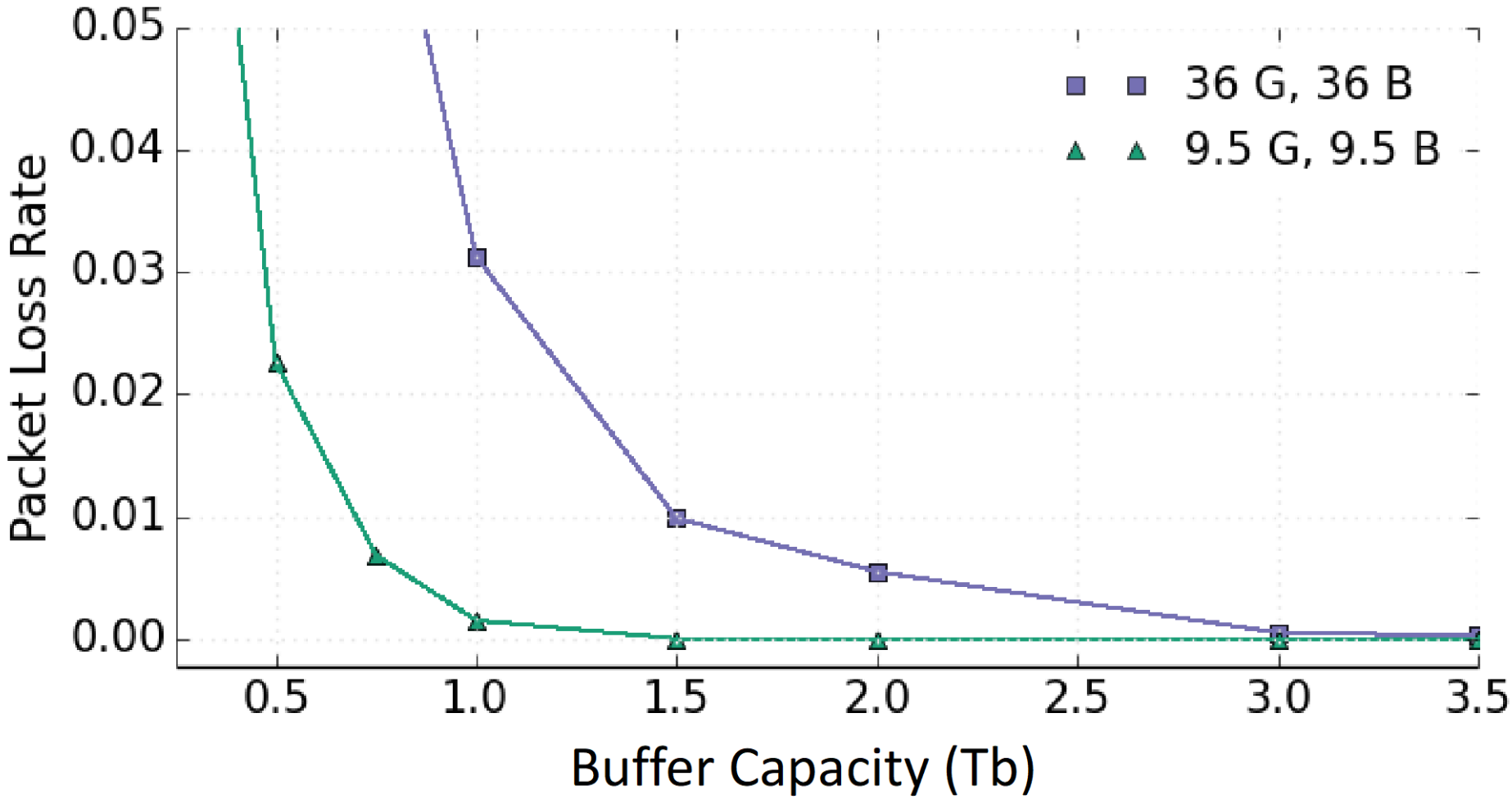
95th-percentile Queue Size vs. Weather Cycle Time



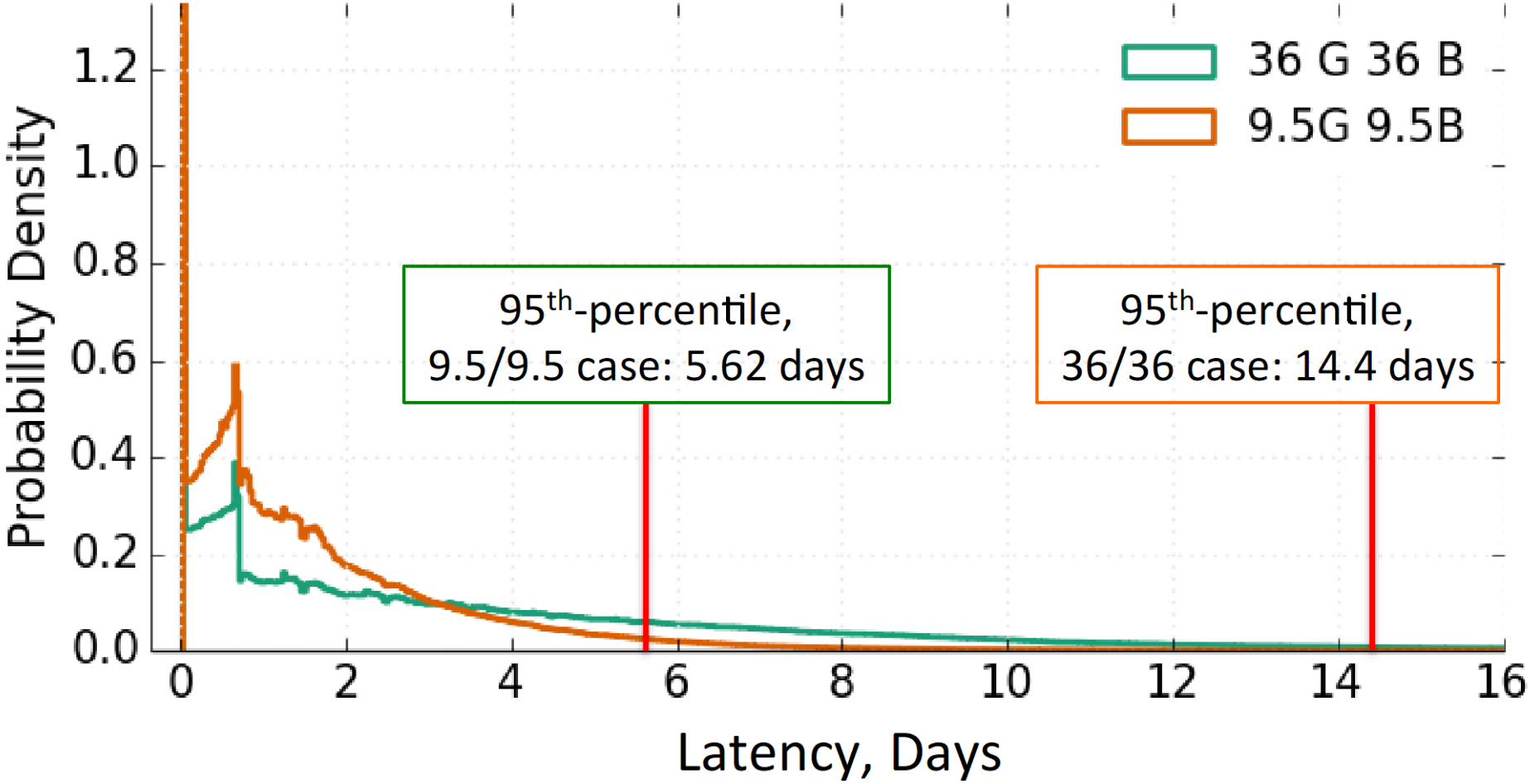
Cumulative Lost Packets vs. Time



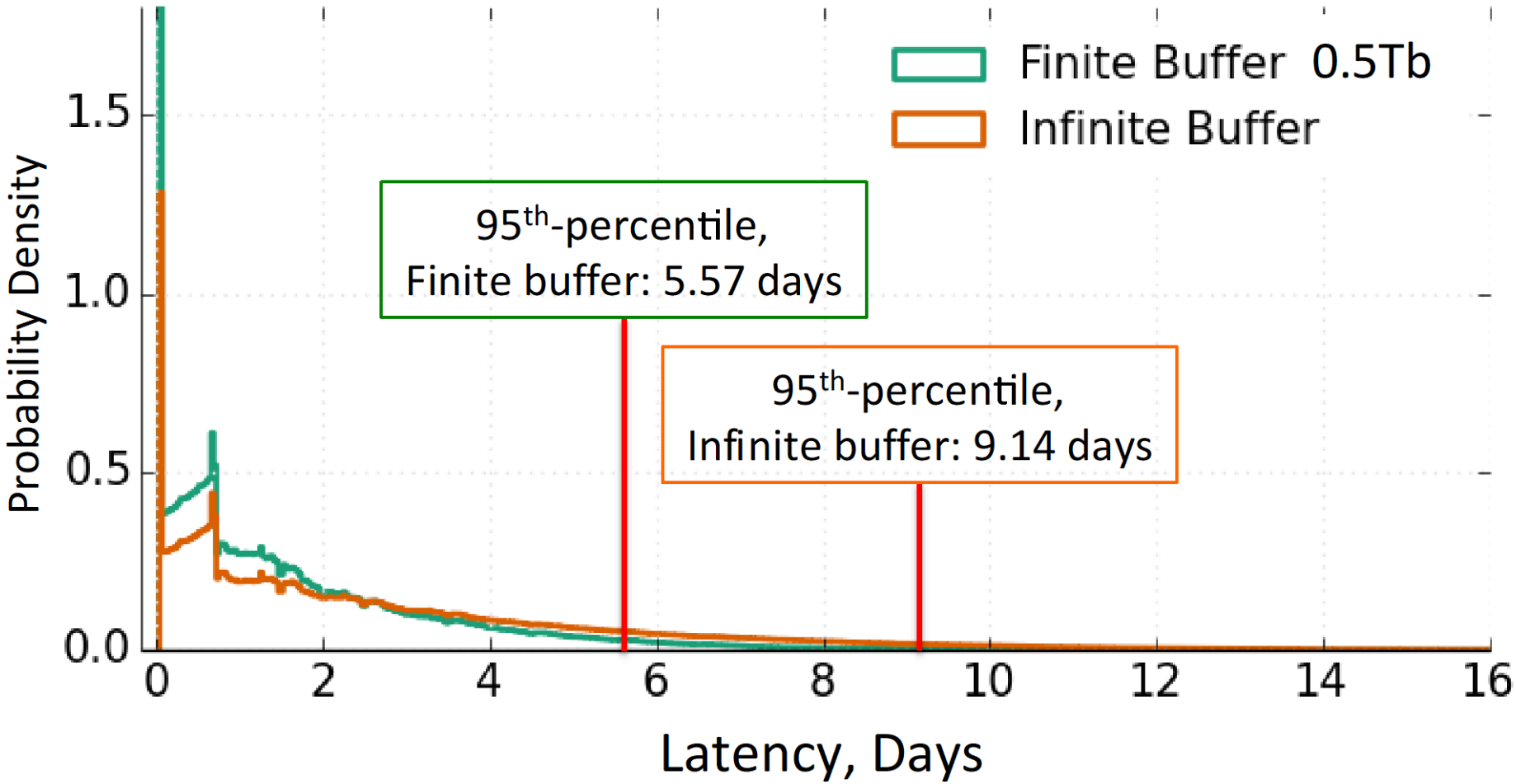
Loss Rate vs. Buffer Capacity



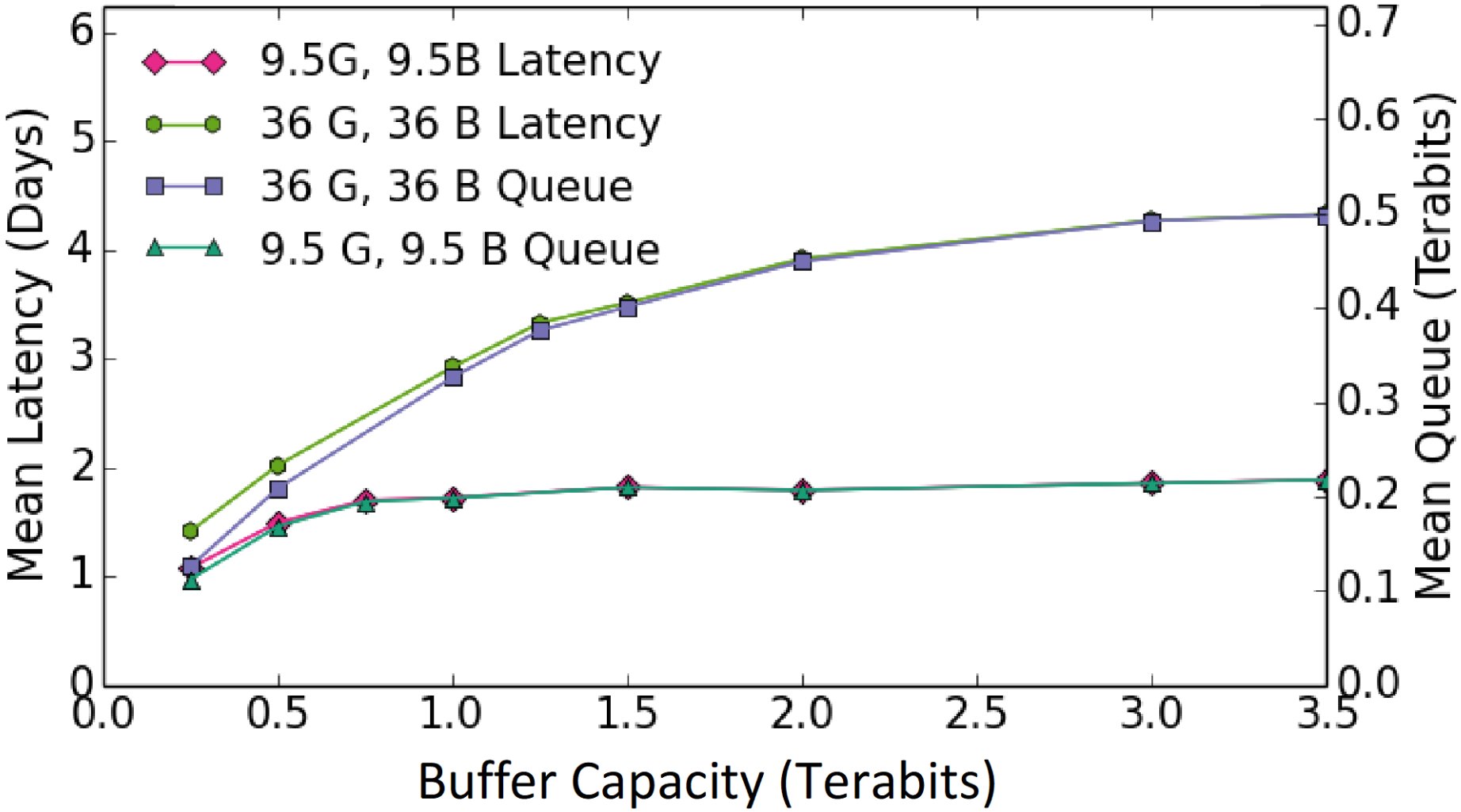
Latency Histogram: Short & Long Weather Cycles



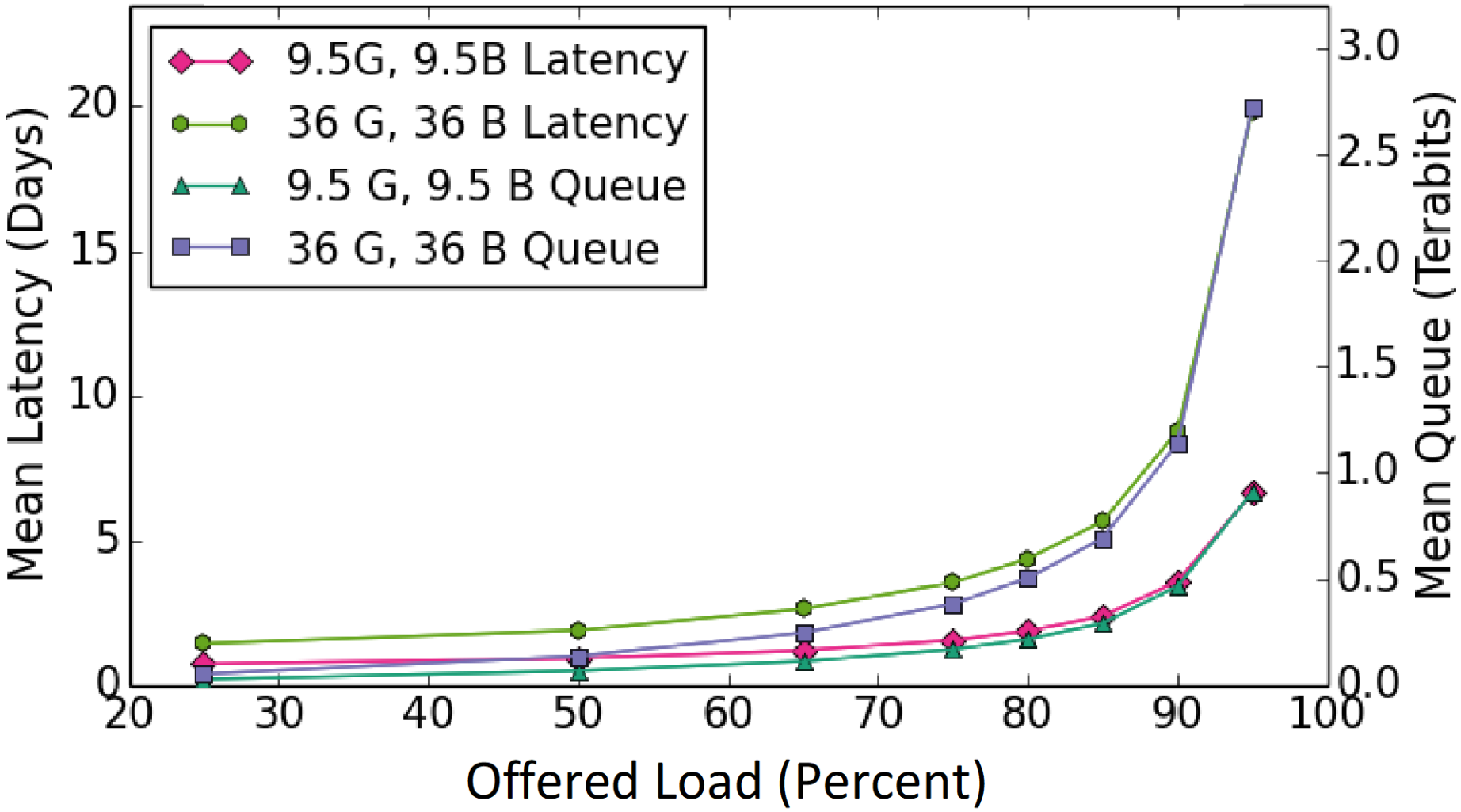
Latency Histogram: Finite & Infinite Buffer Capacities



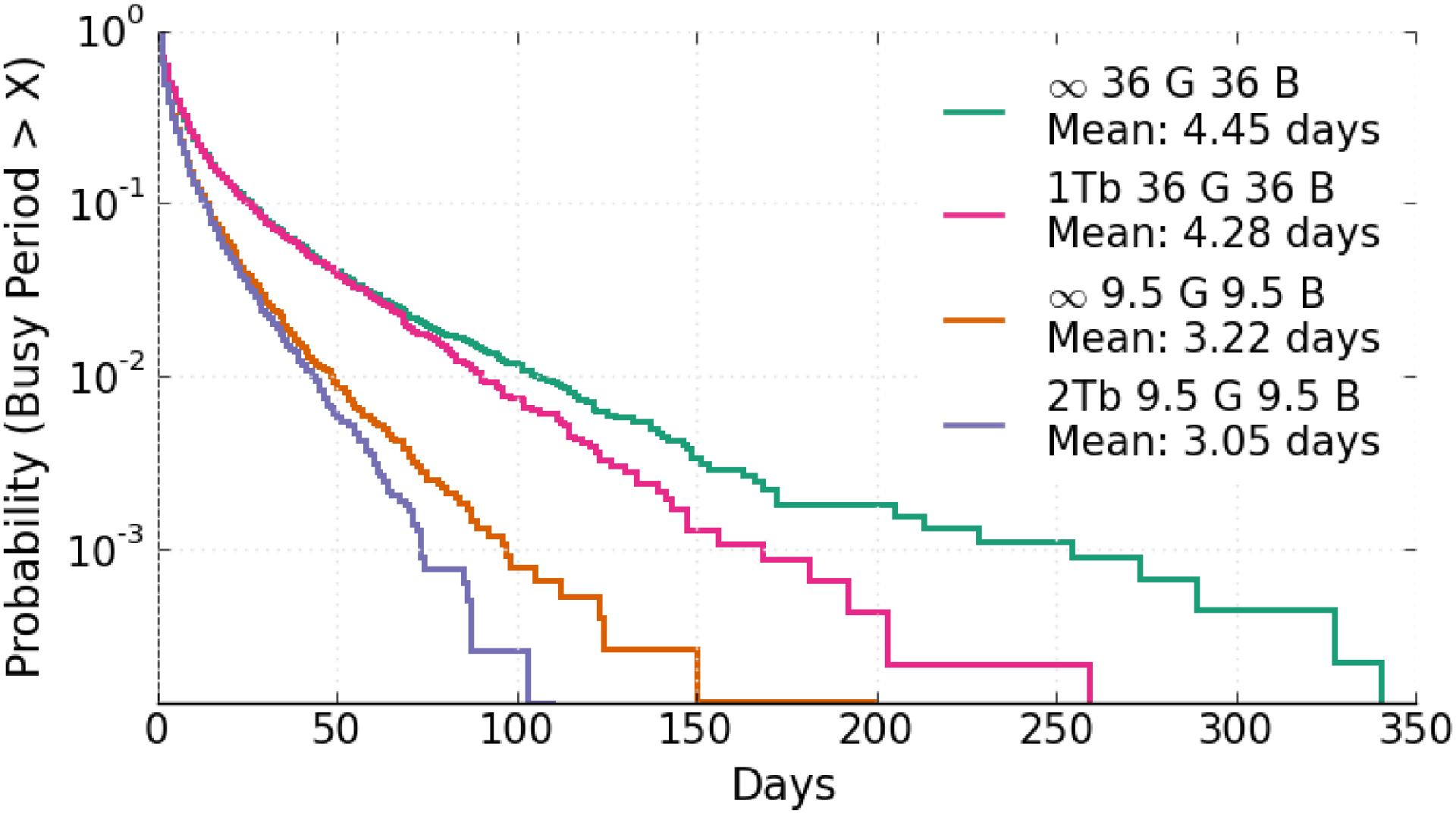
Mean Queue Size & Mean Latency vs. Buffer Capacity



Mean Queue Size & Mean Latency vs. Offered Load



Busy Period Survivor Functions



Summary

- Evaluated performance of deep space optical communications link that uses ARQ to mitigate weather outages
- 2-state weather model incorporates temporal memory
- Analyses show weather has strong performance impacts that may persist
  - “fat tail” behavior is apparent
- High offered loads shown to produce large latencies and generate heavy buffer use
- Determined buffer capacity required to meet maximum overflow loss rate
- Demonstrated feasibility of operating deep space optical communications that is reliable and enables large data volume return

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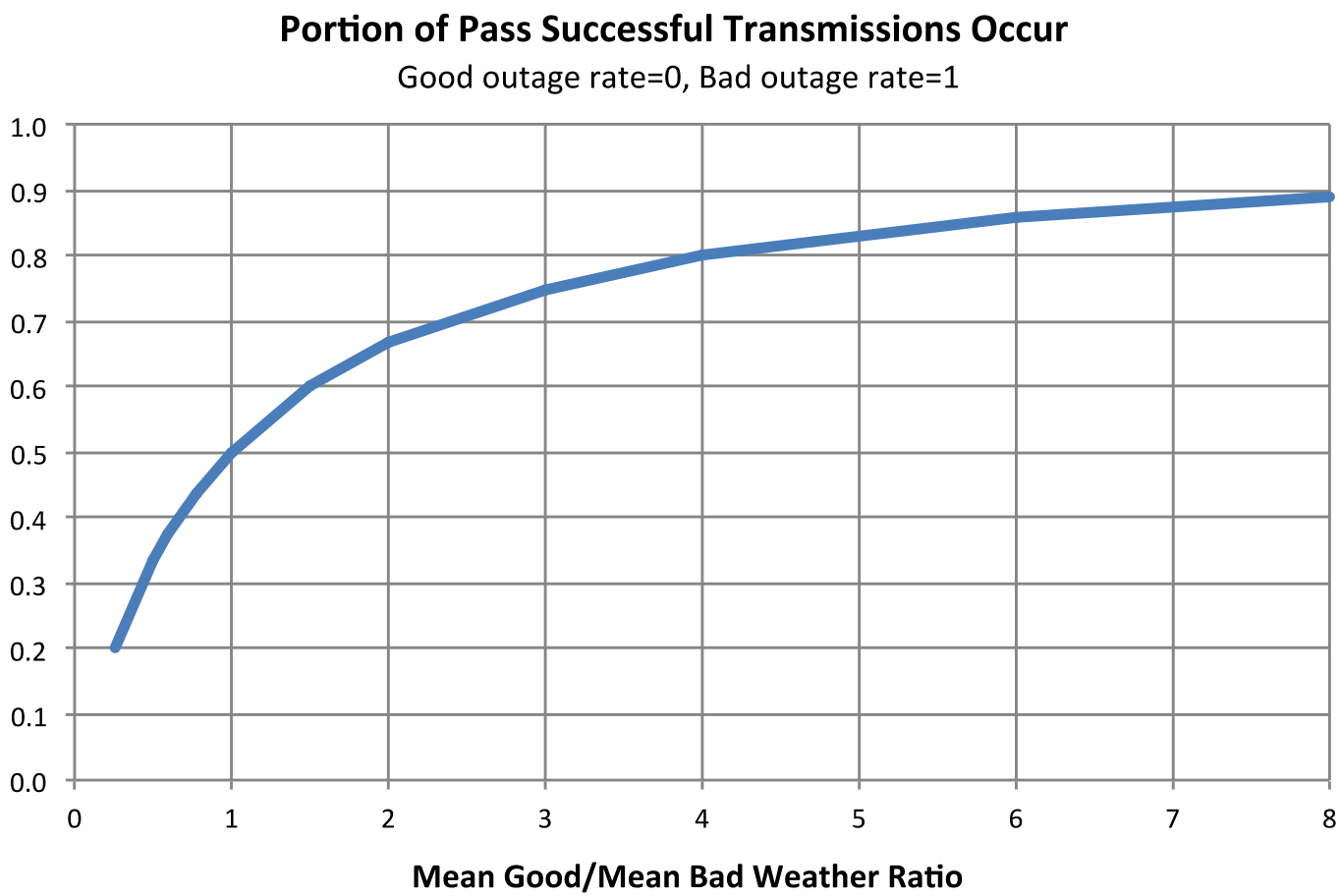
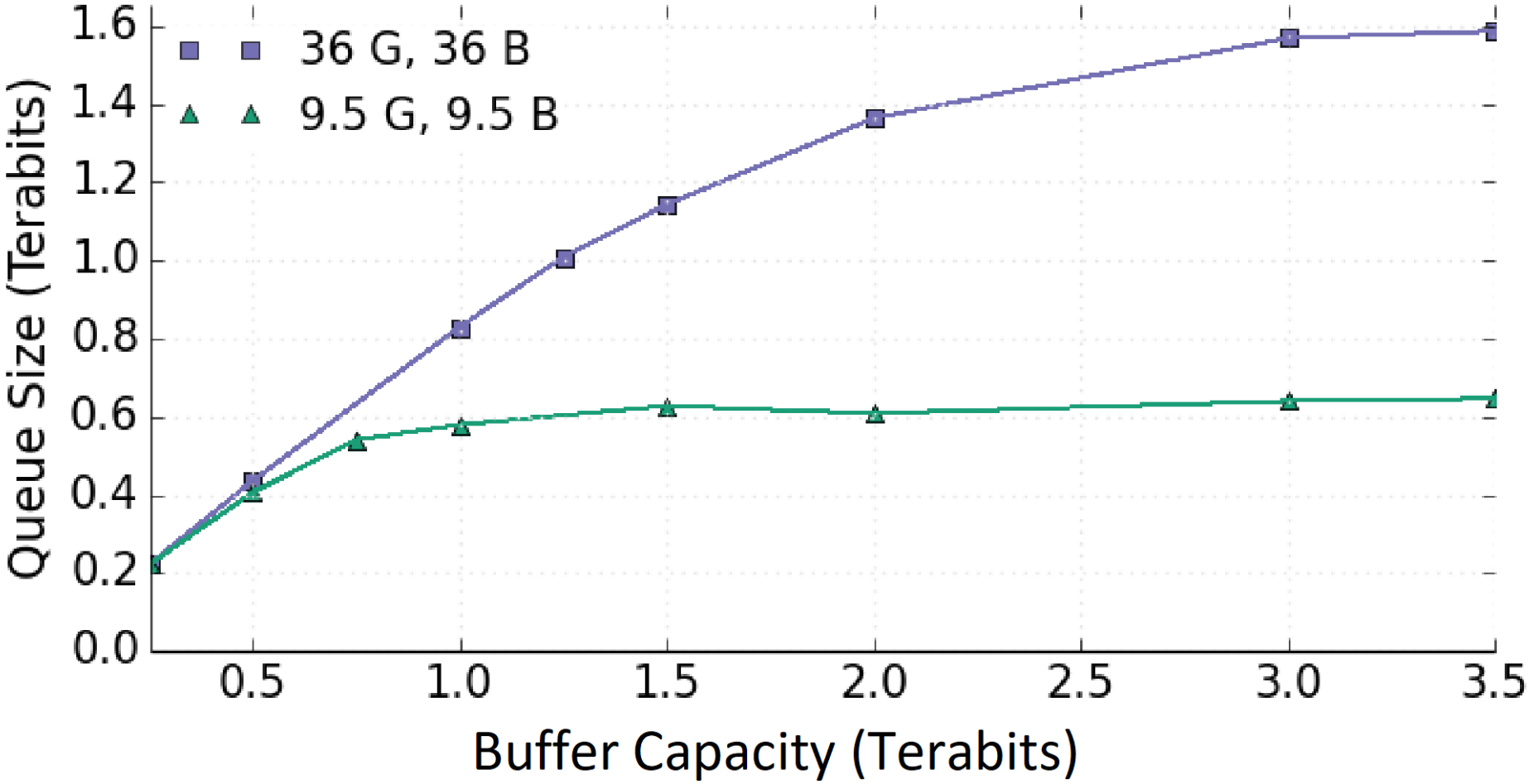
Backup Charts

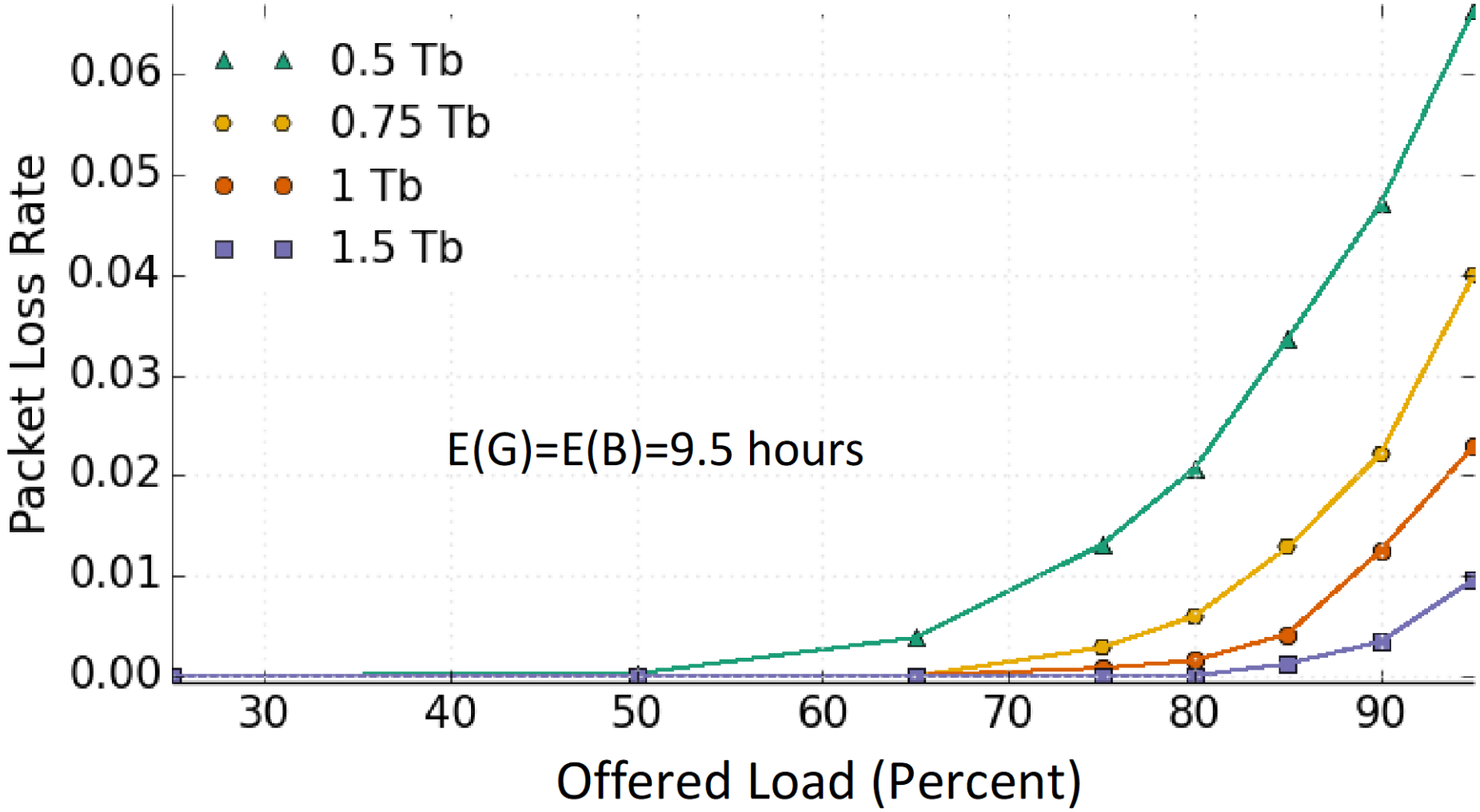
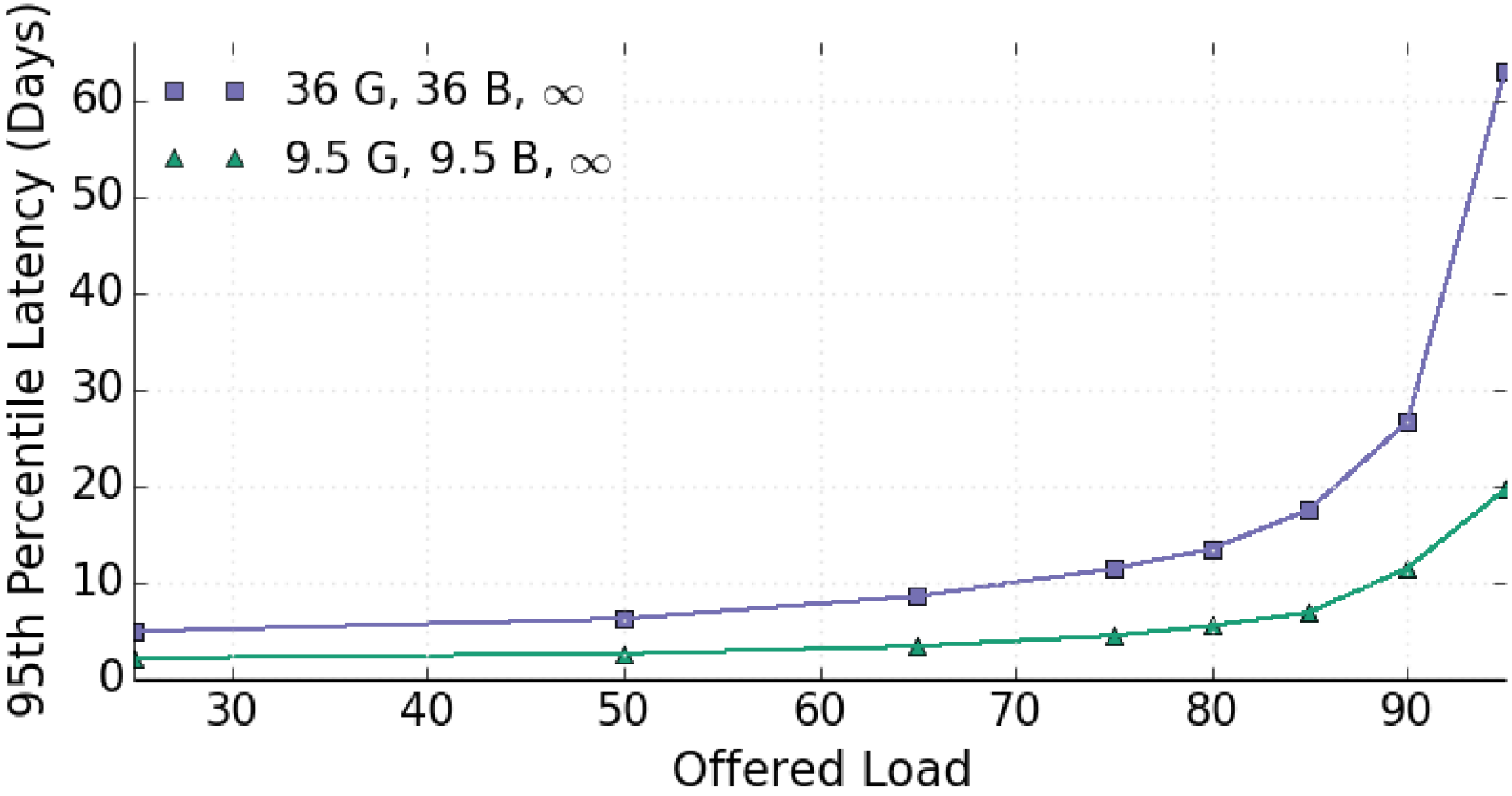
Successful transmission rate as ratio of mean weather times E(G)/E(B)



95th-percentile Queue Size vs. Buffer Capacity



Loss Rate vs. Offered Load



95th-percentile Latency vs. Offered Load