Status Updating Systems and Networks

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V2V Safety Messaging

Large Networks (Hundreds of cars)

Frequent Updates (1 – 10Hz/ car)

Reliability and Timeliness are required
V2V Safety Messaging

- DSRC standard MAC protocol
  - Message Scheduling, Forwarding/Piggybacking
  - Power/rate adaptation, coverage ...
- Performance Metrics?
The DSRC Network

On-road DSRC infrastructure
Wi-Fi like (802.11p CSMA) radios @ 5.9GHz
• Car u sends updates to car v
• Updates pass through network/service system
• Car v wants latest state information.

• **Metric:** Age of the latest update
Simple Analytic Models

- Service system = Queue
- Sender $u$ offers updates
  - without knowledge of the queue state
More Status Updates

• How often is too often?
Google Reader

- Idiosyncratic Service Discipline/Model
Performance Metric

Status Update Age

• Latest update $i$ sent at time $t_i$
• Reaches subscriber at time $t'_i$
• At time $t'_i$: Status Age $= t'_i - t_i$
• At time $t > t'_i$: Status Age $= t - t_i$

Age grows in absence of new updates
Update Age

$\Delta(t)$

$t_1$  $t_1'$  $t_2$  $t_2'$

Update
Arrival (sent)

Departure (rec'd)
Geometry of Triangles

$\Delta(t)$

$\Delta(\text{arrival})$

$\Delta(\text{departure})$

$\Delta(t)$

Update
 Arrival
 Departure

$t_1$

$t_1'$
Geometry

$\Delta(t)$

$t_1$ $t_1'$

$\Delta$
Update Age

- Low Update Rate
  \[ \Rightarrow \text{Age gets large between updates} \]
Update Age

\[ \Delta(t) \]

- High Update Rate \(\Rightarrow\) Queueing Delay
Average Update Age

\[ \Delta(t) \]

- **Update Rate:**
  - High \( \Rightarrow \) Queuing delays
  - Low \( \Rightarrow \) Infrequent updates

\[ \Delta_\tau = \frac{1}{\tau} \int_0^\tau \Delta(t) \, dt \]

High Average Age
FCFS Average Update Age

\[ \Delta(t) \]

\[ \frac{1}{2} [(X+T)^2 - T^2] = \frac{1}{2} X^2 + XT \]

- \( X \): Interarrival Time
- \( T \): System Time

\[ \Delta = \lim_{\tau \to \infty} \Delta_{\tau} = \lambda \left( \frac{1}{2} \mathbb{E} \left[ X^2 \right] + \mathbb{E} \left[ XT \right] \right) \]
FCFS Average Update Age

\[ \Delta(t) \]

\[ \Delta = \lambda \left( \frac{1}{2} E[X^2] + E[XT] \right) \]

- \( X = \) Interarrival Time
- \( T = \) System Time

- Weak ergodicity requirements is tricky!
- \( X \) and \( T \) negatively correlated
M/M/1 FCFS

Average Age

- Arrival Rate $\lambda$, Service Rate $\mu$
- Load $\rho = \frac{\lambda}{\mu}$

$$\Delta = \frac{1}{\mu} \left[ 1 + \frac{1}{\rho} + \frac{\rho^2}{1 - \rho} \right]$$
M/M/1 FCFS
Average Age

• Load $\rho = \frac{\lambda}{\mu}$

$\rho^* = 0.53$
D/M/1 FCFS

Service Rate $\mu$, Load $\rho = \frac{\lambda}{\mu}$

$$\Delta = \frac{1}{\mu} \left[ \frac{1}{2\rho} + \frac{1}{1 - \beta} \right]$$

$$\beta = -\rho \mathcal{W} \left( -\frac{e^{-1/\rho}}{\rho} \right)$$

Optimal Load $\rho^* = 0.515$
**M/M/1 FCFS**

**Average Age**

- **Load** $\rho = \frac{\lambda}{\mu}$
Update Age: Lower Bound

• Sender
  – sees queue state
  – Schedules **just-in-time updates**

\[ \Delta^* = \frac{1}{\mathbb{E}[S]} \left[ \frac{\mathbb{E}[S^2]}{2} + (\mathbb{E}[S])^2 \right] \]

– Service Time $S$
Age Lower Bounds
(Just-in-time updates)

• Exponential Service $E[S] = \frac{1}{\mu}$

$$\Delta^* = 2 \left( \frac{1}{\mu} \right)$$

• Deterministic Service $S = \frac{1}{\mu}$

$$\Delta^* = 1.5 \left( \frac{1}{\mu} \right)$$
Average Age

- **M/M/1**
- **M/D/1**
- **D/M/1**

Age $\Delta$ vs. Server Utilization $\rho$
Average Age

- M/M/1 FCFS
- M/D/1 FCFS
- D/M/1 FCFS
- M/M/1 LCFS w/o preemption

Age $\Delta$

Server Utilization $\rho$
LCFS w/o pre-emption

Pre-emption of waiting packet
(1 packet waiting room)
Competing Updates

• How often is too often?
Multiple Sources
Multiple Sources

Models for Source 2:
- Competing status updater
- Other traffic
Average Update Age

$$\Delta(t)$$

$$\Delta = \lambda \left[ \frac{E[X^2]}{2} + E[XT] \right]$$

- $X = \text{Interarrival Time}$
- $T = \text{System Time}$

- $X, T = \text{interarrival and system time for source 1}$
- $T$ depends on interfering traffic
Multiple Sources

\[ \Delta_1 = \frac{1}{\mu} \left[ \frac{\rho_1^2(1 - \rho \rho_2)}{(1 - \rho)(1 - \rho_2)^3} + \frac{1}{1 - \rho_2} + \frac{1}{\rho_1} \right] \]
Multiple Sources
FCFS Status Age Region
Multiple Sources

FCFS Trunking Efficiency

\[ \Delta_2 \]

Optimal Partitioning

Optimal Sharing

\[ \Delta_1 \]
FCFS Competing Updaters

Nash Equilibrium
• Queueing delays increases status age
• Reduce/Eliminate the queues?
LCFS
Pre-emption & Discarding
(No Queueing)

Source 1

\[ \lambda_1 \]

Source 2

\[ \lambda_2 \]

\[ \mu \]

Monitor
V2V Safety Messaging

Sources (sensors in a car)

- Tire pressure
- Velocity
- Brake Light

To other cars via Network

- Multiple Sources
- Fast local server interface
- Slow Server
Multiple Sources

FCFS/LCFS Age

\[ \Delta_2 \]

\[ \Delta_1 \]

\[ \lambda = 0 \]

\[ \lambda = 0.6 \]

\[ \lambda = 1 \]

\[ \lambda = 2 \]
Timely Compression
A Status Updating Problem

- Encoder input symbol = status update
- Block coding ➔ Bursty bit arrivals at FIFO buffer
  Bit pipe queueing delay
  Decoding delay

Encoder ➔ FIFO buffer ➔ Rate R bit pipe ➔ Decoder

\(a_1a_2a_3...\)  \(01\ 110\ 11...\)  \(a_1a_2a_3...\)
Timely Compression
A Status Updating Problem

\[ a_1 \ a_2 \ a_3 \ a_4 \ a_5 \ a_6 \ a_7 \ldots \]

\[ 01 \ 110 \ 11\ldots \]

\[ a_1 \ a_2 \ a_3a_4 \ldots \]
Time Compression

Huffman Coding Example

Channel Rate R

High rate pipe: use small blocks

Low rate pipe: use large blocks
Summary

• New **status age** performance metric

• Status Age Minimization Principles
  – Match the load to the network/system
  – Redesign the system
    • Give priority to timely updates
    • Discard stale updates

• Many applications