DORA: Dynamic Optimal Random Access for Vehicle-to-Roadside Communications

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References

- Man Hon Cheung, Fen Hou, Vincent W.S. Wong, and Jianwei Huang, "DORA: Dynamic optimal random access for vehicle-to-roadside communications," *IEEE Journal on Selected Areas in Communications*, vol. 30, no. 4, pp. 792–803, May 2012.
- Man Hon Cheung, Fen Hou, Vincent W.S. Wong, and Jianwei Huang, "Dynamic optimal random access for vehicle-to-roadside communications," in *Proc. of IEEE International Conference on Communications (ICC)*, Kyoto, Japan, June 2011.

Outline

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Dynamic Optimal Random Access (DORA)

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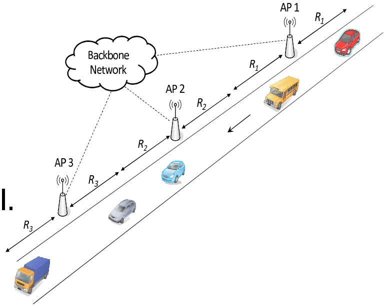
Drive-thru Random Access Problem

Drive-thru scenario:

- Limited communication opportunities.
- Varying channel contention level.
- Varying data rate.

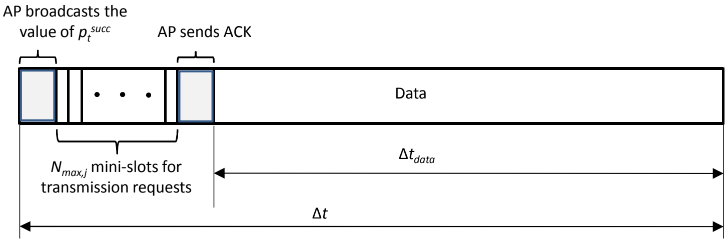


Question

How to design a dynamic and optimal uplink data transmission scheme in a drive-thru scenario?

Outline

The structure of a time slot



p_t^{succ} : probability of successful transmission at time t.

Δt : length of a time slot.

Δt_{data} : duration in a time slot for data transmission.

The structure of a time slot

1. Vehicles send requests in one of the $N_{max,j}$ mini-slots in the j^{th} coverage range.
2. AP sends ACK.
3. Data transmission by the vehicle that has received ACK.

Single AP with Random Vehicular Traffic

- Traffic model from transportation engineering:

  The arrival of vehicles follows a Poisson distribution.

$$\lambda = \rho\nu,$$
$$\nu = \nu_f(1 - \rho/\rho_{max}),$$

  where λ: arrival rate, ρ: density, ν: speed.

- Varying data rate:

$$w_t = W \log_2 \left(1 + \frac{P}{N_0 W d_t^\gamma}\right).$$

- Transmission request payment per time slot is q.
- Aim: To achieve a good tradeoff between uploaded file size and total payment to the APs.

Single AP with Random Vehicular Traffic

- 1) Decision epochs: $t \in \mathcal{T} = \{1, \ldots, T\}$.
- 2) State: (s, p^{succ})

  s: remaining size of the file to be uploaded.

  p^{succ}: probability of successful transmission.
- 3) Action: $a \in \mathcal{A} = \{0, 1\}$

  $a = 0 \Rightarrow$ remains idle in a time slot.

  $a = 1 \Rightarrow$ transmits in a time slot.
- 4) Transmission cost in each time slot:

  $c_t(s, p^{succ}, a) = aq, \;\; \forall\, t \in \mathcal{T}$.
- 5) Self-incurred penalty after leaving the coverage range:

  $\hat{c}_{T+1}(s, p^{succ}) = h(s)$.

Single AP with Random Vehicular Traffic

- 6) State transition probability: $p_t\big((s', p^{succ'}) \,|\, (s, p^{succ}), a\big)$

$$p_t\big((s', p^{succ'}) \,|\, (s, p^{succ}), a\big) = p_t\big(s' \,|\, (s, p^{succ}), a\big)\; p_t\big(p^{succ'} \,|\, p^{succ}\big).$$

With action $a = 1$, we have

$$p_t\big(s' \,|\, (s, p^{succ}), 1\big) = \begin{cases} p^{succ}, & \text{if } s' = [s - w_t \Delta t_{data}]^+; \\ 1 - p^{succ}, & \text{if } s' = s, \\ 0, & \text{otherwise.} \end{cases}$$

Single AP with Random Vehicular Traffic

With action $a = 0$, we have

$$p_t\big(s' \,|\, (s, p^{succ}), 0\big) = \begin{cases} 1, & \text{if } s' = s, \\ 0, & \text{otherwise.} \end{cases}$$

With Poisson arrival of vehicles, we have

$$p_t\big(p^{succ'} \,|\, p^{succ}\big) = p_t\big(g(n') \,|\, g(n)\big) = p_t\big(n' \,|\, n\big)$$
$$= \begin{cases} \frac{(\lambda \Delta t)^{n'-n+l_{t+1}}}{(n'-n+l_{t+1})!\,\phi_t(n)}, & \text{if } n - l_{t+1} \leq n' \leq N_{max}, \\ 0, & \text{otherwise.} \end{cases}$$

Single AP with Random Vehicular Traffic

- Decision rule at state (s, p^{succ}) at time slot t: $\delta_t(s, p^{succ})$.
- Policy: $\boldsymbol{\pi} = (\delta_t(s, p^{succ}), \forall\, s \in \mathcal{S}, p^{succ} \in \mathcal{P}, t \in \mathcal{T})$.
- Optimization problem: To minimize the expected total cost and the self-incurred penalty

$$\min_{\boldsymbol{\pi}\in\Pi} E_{\boldsymbol{\pi},(S,p_1^{succ})}\left[\sum_{t=1}^{T} c_t\Big(s_t^{\boldsymbol{\pi}}, p_t^{succ,\boldsymbol{\pi}}, \delta_t(s_t^{\boldsymbol{\pi}}, p_t^{succ,\boldsymbol{\pi}})\Big) + \hat{c}_{T+1}(s_{T+1}^{\boldsymbol{\pi}}, p_{T+1}^{succ,\boldsymbol{\pi}})\right].$$

- A general dynamic optimal random access (DORA) algorithm is proposed.

Special Case with Threshold Policy

Theorem 5.2

If (1) the self-incurred penalty function $h(s)$ is a convex and non-decreasing function in s, and (2) the data rate w_t is fixed (i.e., $w_t = w, \forall t \in \mathcal{T}$),

then we have a threshold optimal policy

$\boldsymbol{\pi}^* = (\delta_t^*(s, p^{succ}), \forall s \in \mathcal{S}, p^{succ} \in \mathcal{P}, t \in \mathcal{T})$ in s as follows:

$$\delta_t^*(s, p^{succ}) = \begin{cases} 1, & \text{if } s > s_t^*(p^{succ}), \\ 0, & \text{otherwise.} \end{cases}$$

- Monotone DORA algorithm with a lower complexity.

Multiple APs with Traffic Pattern Estimation

- Traffic pattern estimation: To estimate the number of vehicles within the coverage range of each AP at each time by installing a traffic monitor.

  $\Rightarrow p_t^{succ}, \forall\, t \in \mathbb{T}$ can be obtained accurately.

- Optimization problem: To minimize the expected total cost and the self-incurred penalty in multiple APs.

$$\min_{\boldsymbol{\pi}\in\Pi} E_{\boldsymbol{\pi},(S,p_1^{succ})}\Bigg[\sum_{j=1}^{J}\Bigg[\sum_{\tau=1}^{T_j} c_{\zeta(j,\tau)}\Big(s^{\boldsymbol{\pi}}_{\zeta(j,\tau)}, p^{succ,\boldsymbol{\pi}}_{\zeta(j,\tau)}, \delta_{\zeta(j,\tau)}(s^{\boldsymbol{\pi}}_{\zeta(j,\tau)}, p^{succ,\boldsymbol{\pi}}_{\zeta(j,\tau)})\Big)\Bigg] + \hat{c}_{\zeta(J,T_J+1)}(s^{\boldsymbol{\pi}}_{\zeta(J,T_J+1)}, p^{succ,\boldsymbol{\pi}}_{\zeta(J,T_J+1)})\Bigg].$$

- A joint DORA (JDORA) algorithm is proposed.

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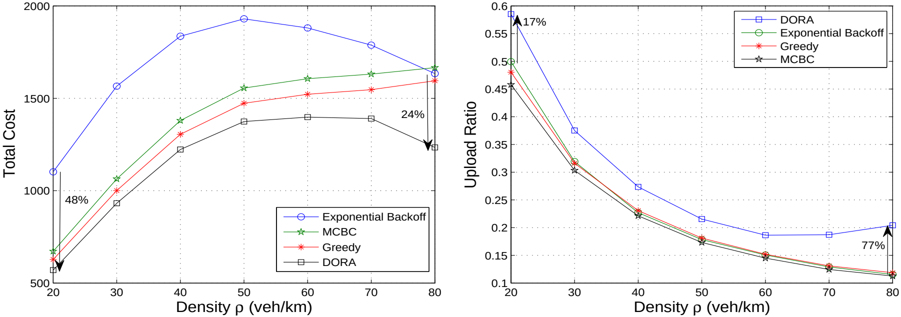
Performance Evaluations

- Compare four schemes:
  1. Dynamic optimal random access (DORA)
  2. Greedy
  3. Exponential backoff
  4. Multi-carrier burst contention (MCBC) [1]

1. B. Roman, I. Wassell, and I. Chatzigeorgiou, "Scalable cross-layer wireless access control using multi-carrier burst contention," *IEEE J. Select. Areas Commun.*, vol. 29, no. 1, pp. 113–128, Jan. 2011.

Performance Evaluation

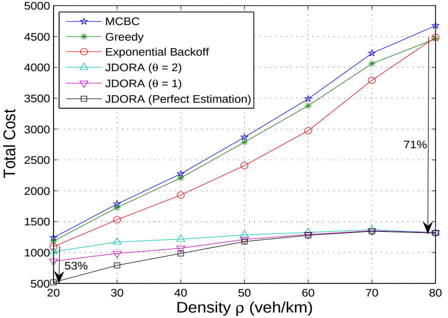
Setting: Single AP, random vehicular traffic arrival, $S = 200$ Mbits.

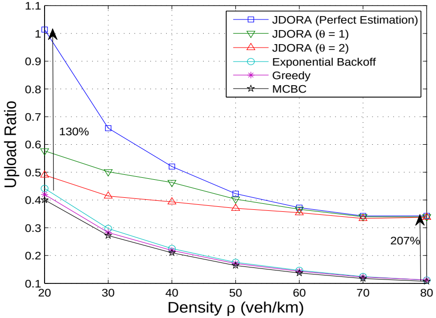


- Upload ratio = total uploaded file size / total payment to the AP.
- Our DORA scheme achieves (a) the minimal total cost and (b) the highest upload ratio.

Performance Evaluation

Setting: 5 APs, traffic pattern estimation, $S = 500$ Mbits.





- Our JDORA scheme achieves (a) the minimal total cost and (b) the highest upload ratio.
- Performance improves when the variance θ of the traffic pattern estimation is reduced.

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- Problem: To find the V2R uplink transmission policy in a dynamic drive-thru scenario, where both the channel contention level and channel capacity vary over time.
- Algorithm design: We applied finite-horizon dynamic programming to design DORA algorithms for single-AP and multi-AP scenarios.
- Performance evaluation: Our scheme achieves the minimal total cost and the highest upload ratio as compared with three other heuristic schemes.

Thank you!