Distributed Scheduling Algorithms for Optimizing Information Freshness in Wireless Networks

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Motivation: Information Freshness

Information Freshness Critical for Performance of UAV networks, vehicular networks, CPS

Utilizing the resource (e.g. queue, network)

Packet generation rate too high → Congestion

Packet generation rate too low → Infrequent updates

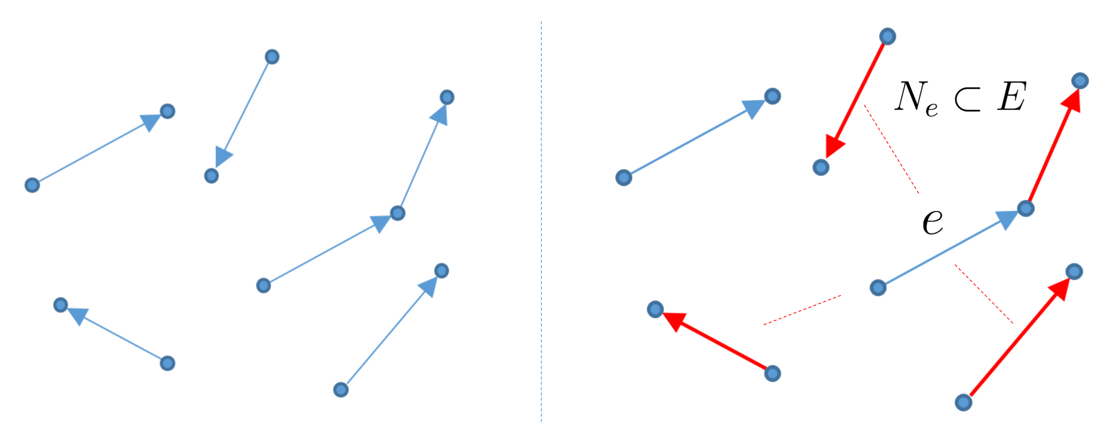
Resource = Wireless Network with Interference

Contribution: Distributed scheduling algorithm for age minimization

System Model

Network $G = (V, E)$ Directed Links

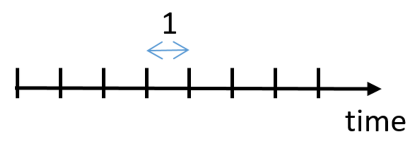
Source-destination pair for every $e \in E$



Interference

- Interfering subset $N_e \subset E$ for each link e
- Popular k-hop interference model is a special case

Slotted time



Channel Process

- Channel state for link e: $S_e(t) \in \{0, 1\}$ (OFF, ON) i.i.d. across t
- Independent across links

$$\gamma_e = \mathbb{P}[S_e(t) = 1]$$ Channel Statistic

Distributed Stationary Scheduling Policy

- Link e attempts transmission with probability p_e

Active Sources and Age Evolution

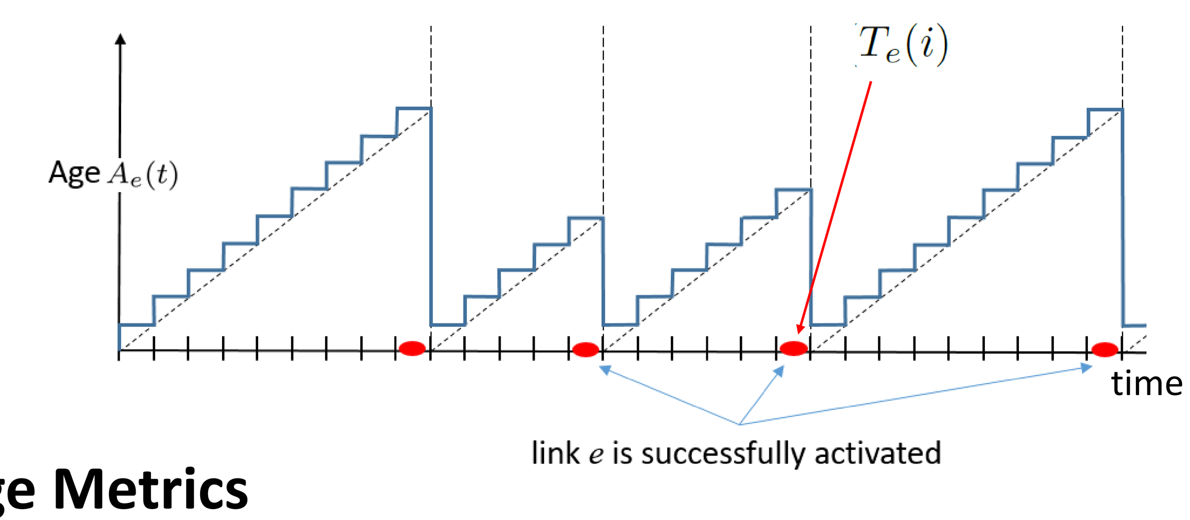
Active source: generates fresh updates for every Tx

Buffered source: can only transmit queued up updates

- Studied in [Talak et al. Mobihoc'18]

We consider all sources to be active sources

Age Evolution



Age Metrics

Average age: time-average of age

$$A_e^{\text{ave}} = \limsup_{T\to\infty} \frac{1}{T}\sum_{t=1}^{T} A_e(t)$$

Peak age: average of age peaks

$$A_e^{\text{p}} = \limsup_{T\to\infty} \frac{1}{N_e(T)}\sum_{i=1}^{N_e(T)} A_e(T_e(i))$$

Network Age Minimization

Lemma: Peak and average age are equal $A_e^{\text{ave}} = A_e^{\text{p}} = \frac{1}{\gamma_e f_e}$

where $f_e = p_e \prod_{e' \in N_e} (1 - p_{e'})$ link activation frequency

Network age optimization problem

$$\underset{\mathbf{p}\in[0,1]^{|E|}, \mathbf{f}\in\mathbb{R}^{|E|}}{\text{Minimize}} \quad \sum_{e\in E} \frac{w_e}{\gamma_e f_e}$$
$$\text{subject to} \quad f_e = p_e \prod_{e'\in N_e} (1 - p_{e'}) \;\; \forall\, e \in E$$

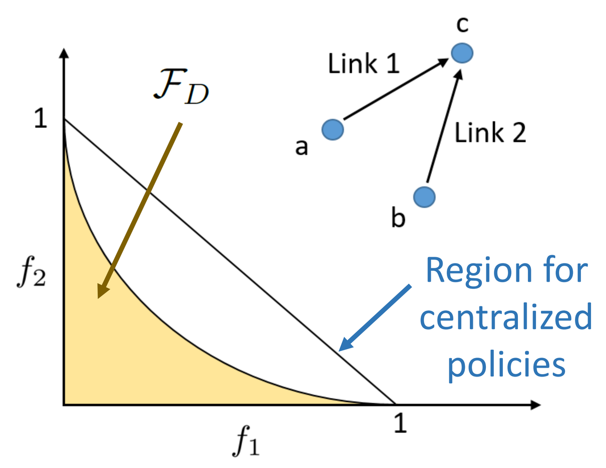
Network Age $A^{\text{ave}} = \sum_{e\in E} w_e A_e^{\text{ave}}$

- Non-convex constraint set:

$$\mathcal{F}_D = \left\{ \mathbf{f} \in \mathbb{R}^{|E|} \mid f_e = p_e \prod_{e'\in N_e} (1 - p_{e'}) \text{ and } 0 \le p_e \le 1 \right\}$$

Theorem: $p_e^* = \dfrac{w_e A_e^*}{w_e A_e^* + \sum_{e': e \in N_{e'}} w_{e'} A_{e'}^*}$

- Requires centralized computation



Distributed Computation

Theorem: Network age problem is equivalent to

$$\underset{\lambda_e \ge 0}{\text{Maximize}} \sum_{e\in E} \left(\lambda_e + \sum_{e': e\in N_{e'}} \lambda_{e'}\right) H\left(\frac{\lambda_e}{\lambda_e + \sum_{e': e\in N_{e'}} \lambda_{e'}}\right) + \sum_{e\in E} \lambda_e \left[1 + \log\left(\frac{w_e}{\lambda_e}\right)\right]$$

where $H(p) = p \log\left(\frac{1}{p}\right) + (1-p)\log\left(\frac{1}{1-p}\right)$ is the entropy function.

- λ_e is proxy for weighted age $w_e A_e^*$ $\qquad p_e^* = \dfrac{\lambda_e^*}{\lambda_e^* + \sum_{e': e\in N_{e'}} \lambda_{e'}^*}$

Projected gradient descent has a distributed implementation

- We use the proxy for weighted age λ_e and iterate over time frames m
- Proxy for age: $\lambda_e(m)$ and $\theta_e(m) = \sum_{e'\in N_e} \lambda_{e'}(m)$
- Attempt probability:

$$p_e(m) = \frac{\lambda_e(m)}{\lambda_e(m) + \theta_e(m)}$$

Symmetric Interference Case $N_e = \{e' \in E \mid e \in N_{e'}\}$

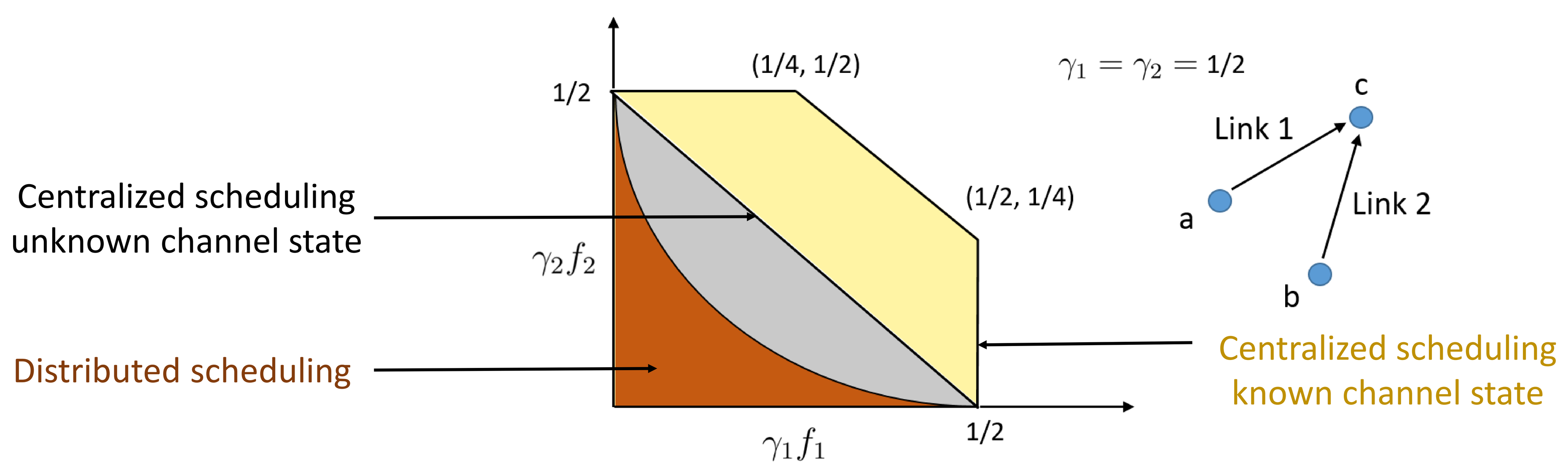
- Local Updates:

$$\lambda_e(m+1) \leftarrow \Pi_{I_e}\left[\lambda_e(m) + \eta_m \left\{ \log\left(\frac{w_e}{\lambda_e(m)}\right) + \log\left(1 + \frac{\theta_e(m)}{\lambda_e(m)}\right) + \sum_{e'\in N_e} \log\left(1 + \frac{\lambda_{e'}(m)}{\theta_{e'}(m)}\right) \right\}\right]$$

Links exchange $\lambda_e(m)$ and $\theta_e(m)$

Our Recent Work

Age can be improved by centralized scheduling algorithms. Centralized policies and buffered sources studied in [Talak et al. Mobihoc 2018]



Age can be improved by using channel state information [Talak et al. WiOpt 2018]

Stationary policies for multi-hop wireless networks [Talak et al. Allerton 2017]

Age-based and virtual queue based scheduling for wireless networks under general inference constraints [Talak et al. ISIT 2018]