Age of Information in Random Access Channels

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Background & Motivation

- Communication networks have witnessed rapid growth in the past few decades

  cyber-physical systems, the Internet of Things, smart cities, healthcare systems

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- We design for the first time decentralized age-based transmission policies
- Provide analytical results on the age of information

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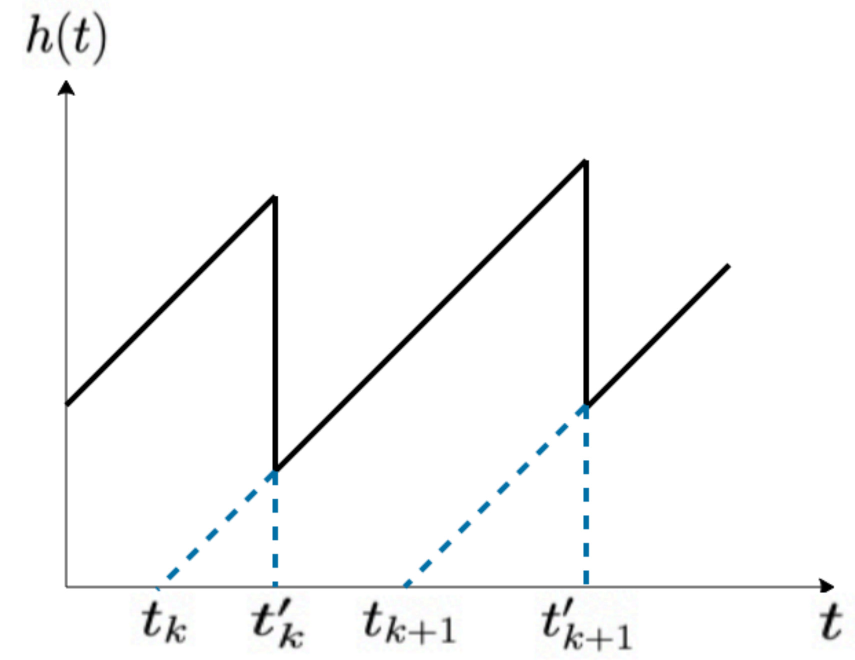

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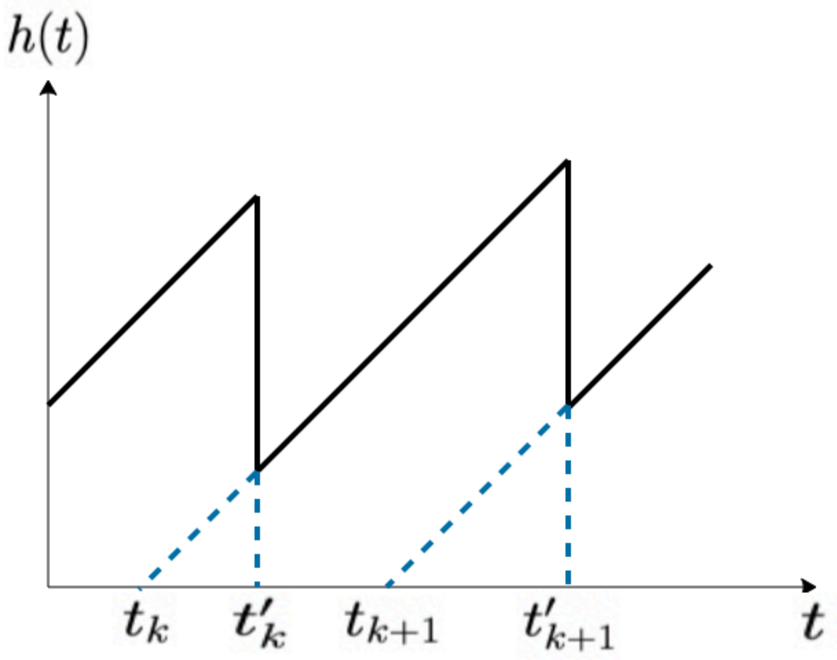
- Time average age: $\lim_{T\to\infty} \frac{1}{T} \int_0^T h(t)$



System Model

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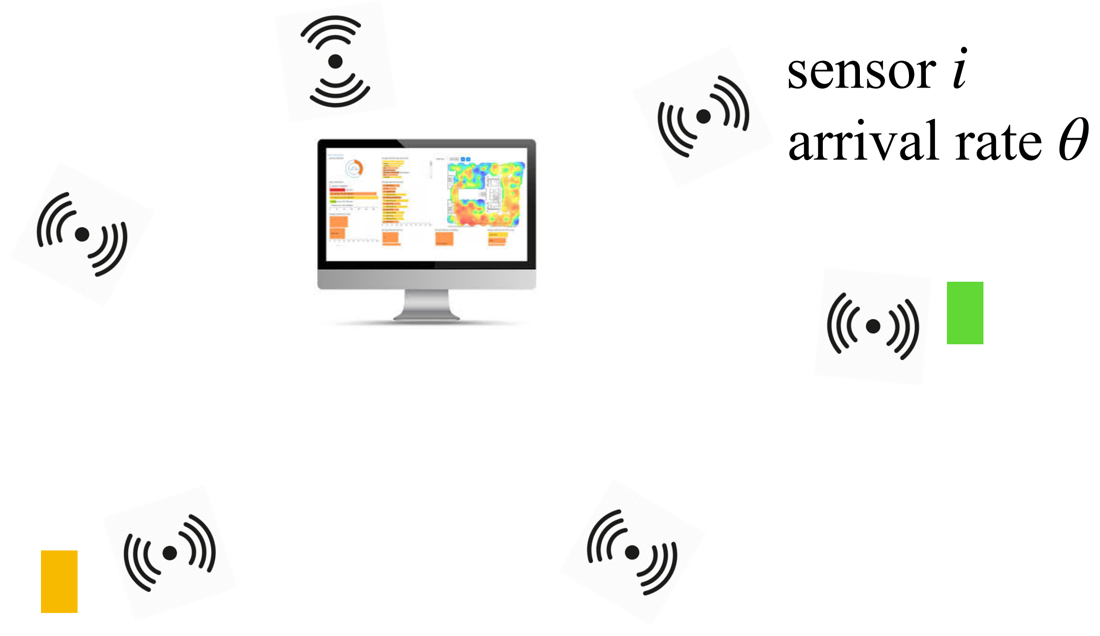

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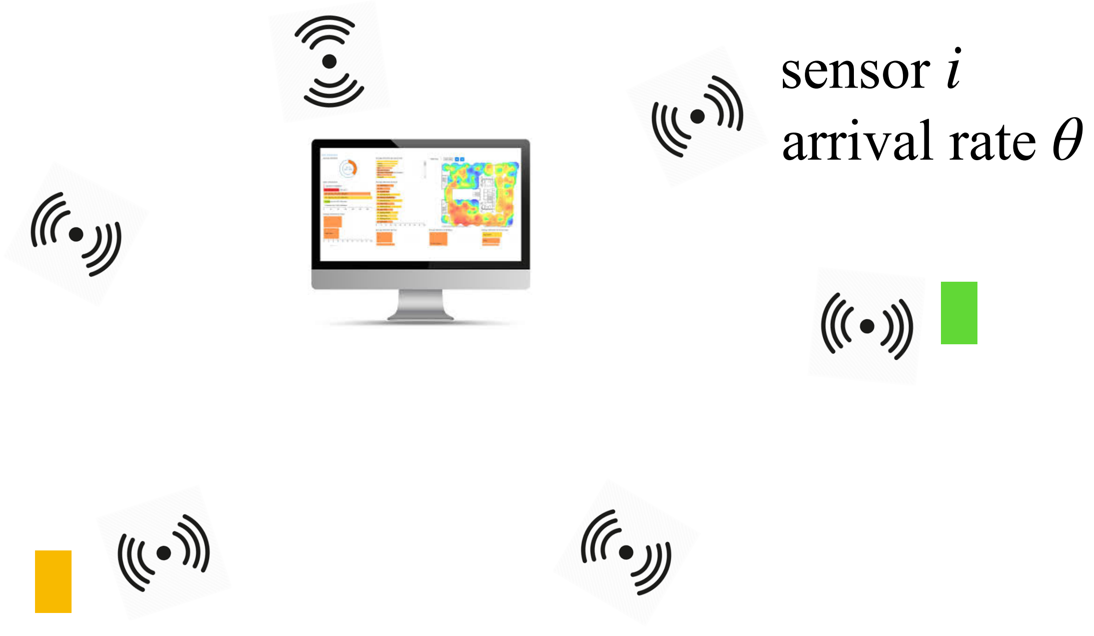

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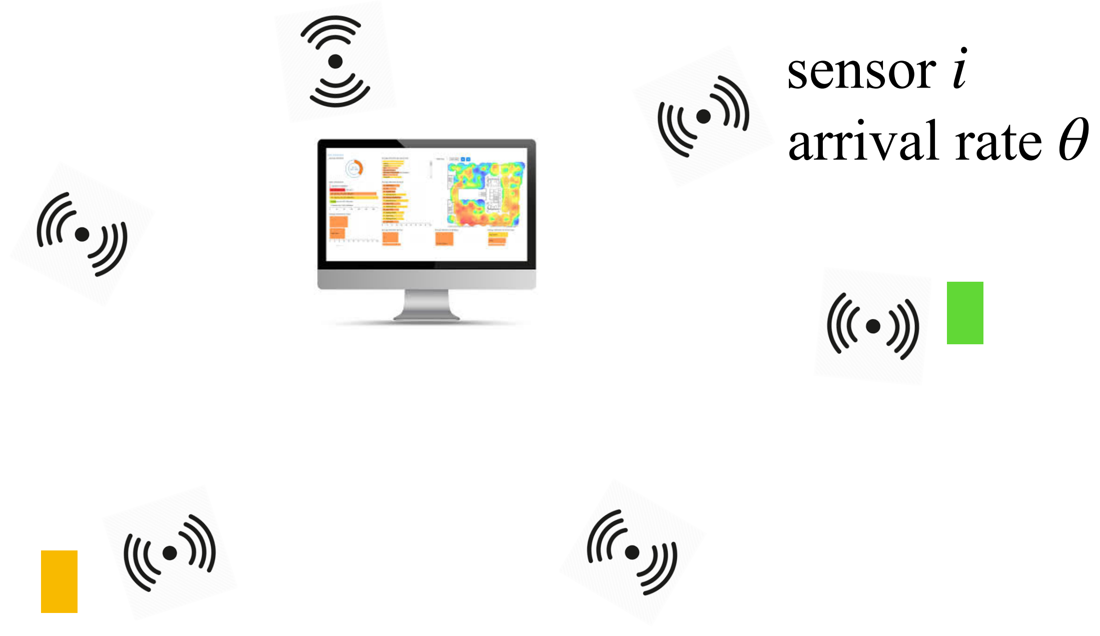

System Model

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- Slotted time
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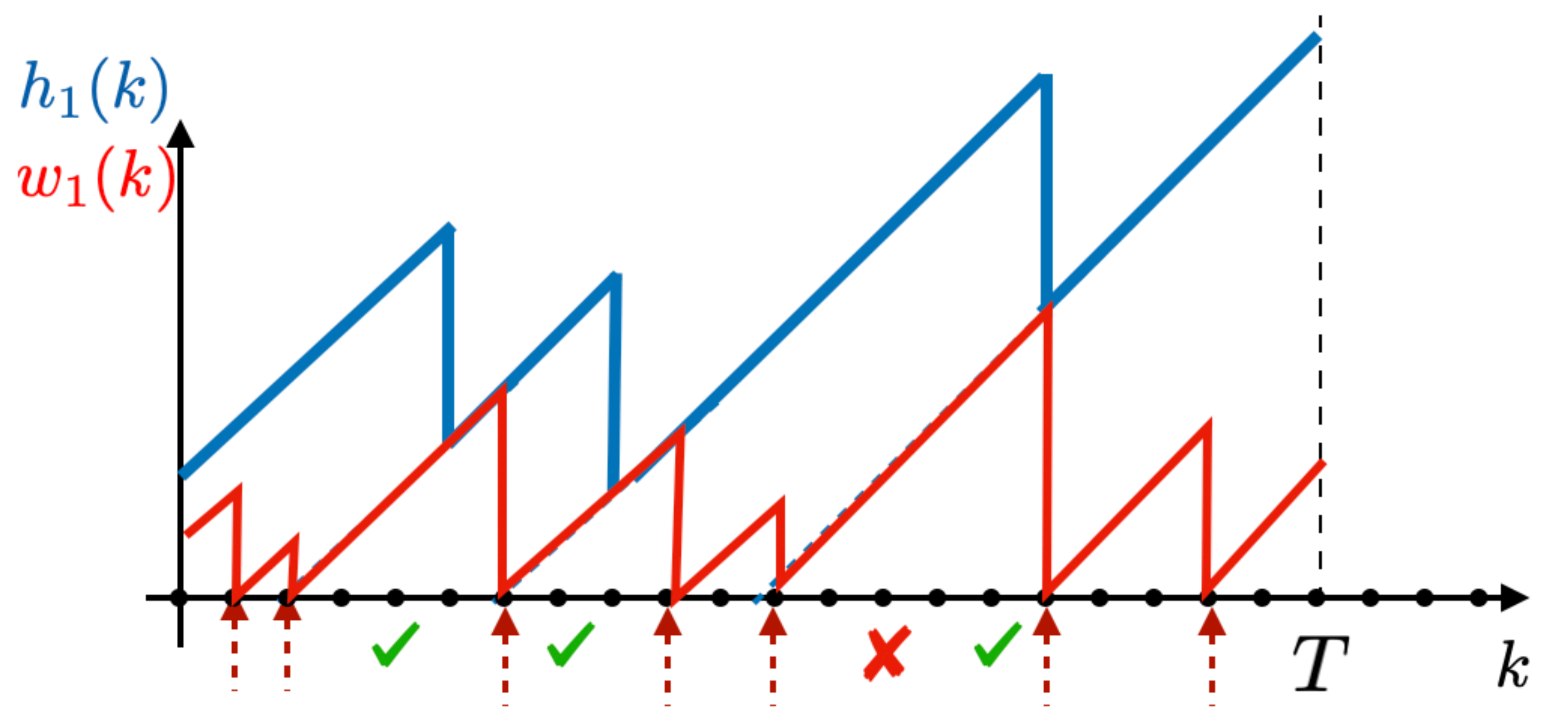
- One unit transmission delay
- Find transmission policy π that minimizes Normalized Expected Weighted Sum AoI (NEWSAoI) $\lim_{K\to\infty} \frac{1}{KM^2} \sum_{i=1}^{M} \sum_{k=1}^{K} h_i^{\pi}(k)$

Evolution of Age

Source AoI $$w_i(k+1) = \begin{cases} w_i(k) + 1 & \text{no new packet arrives} \\ 0 & \text{a new packet arrives} \end{cases}$$

Destination AoI $$h_i(k+1) = \begin{cases} w_i(k) + 1 & \text{a packet is delivered} \\ h_i(k) + 1 & \text{no packet is delivered} \end{cases}$$



Lower Bound

Theorem: For any transmission policy, NEWSAoI is lowered bounded by

1) NEWSAoI $\geq \frac{1}{M\theta}$ small arrival rates

2) NEWSAoI $\geq \frac{1}{2C_{RA}} + \frac{1}{2M}$ large arrival rates

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- RA with feedback $C_{RA} \leq 0.568 \quad (M \to \infty)$
  [Tasybakov-Likhanov] *Probl. Peredachi Inf*, vol. 23

- RA with CSMA $C_{RA} \leq 1$

- RA without feedback $C_{RA} \leq \dfrac{1}{e} \quad (M \to \infty)$

Decentralized Age-based Policies

Small arrival rate: slotted ALOHA

Slotted ALOHA: transmitters send packets immediately upon arrival
they are "backlogged" after a collision
a backoff probability

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Theorem: Suppose $\theta \leq \frac{1}{eM}$ and define $\eta = \lim_{M\to\infty} M\theta$. Any stabilized slotted ALOHA scheme achieves

$$\lim_{M\to\infty} \text{NEWSAoI}(M) = \frac{1}{\eta}.$$

Moreover, (stabilized) slotted ALOHA are asymptotically optimal in terms of NEWSAoI.

Decentralized Age-based Policies

Large arrival rate: Age-based Thinning

- When the arrival rate $\theta = \dfrac{1}{eM}$, then NEWSAoI of slotted ALOHA is around e.

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- Is the slotted ALOHA unstabilized (large AoI) when $\theta > \frac{1}{eM}$?
- Can we get benefits (small AoI) by increasing arrival rate?
- What should the transmitters do in order to ensure a small age of information when $\theta > \frac{1}{eM}$?

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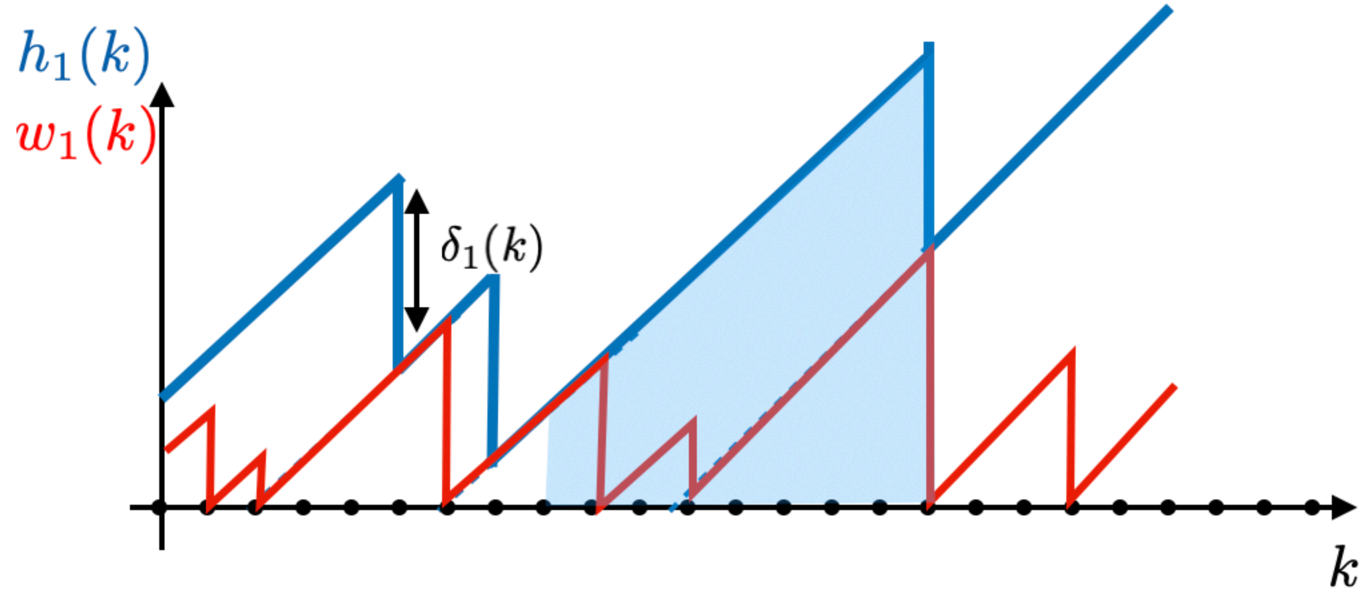
- We defined age-gain as: $\delta_i(k) = h_i(k) - w_i(k)$



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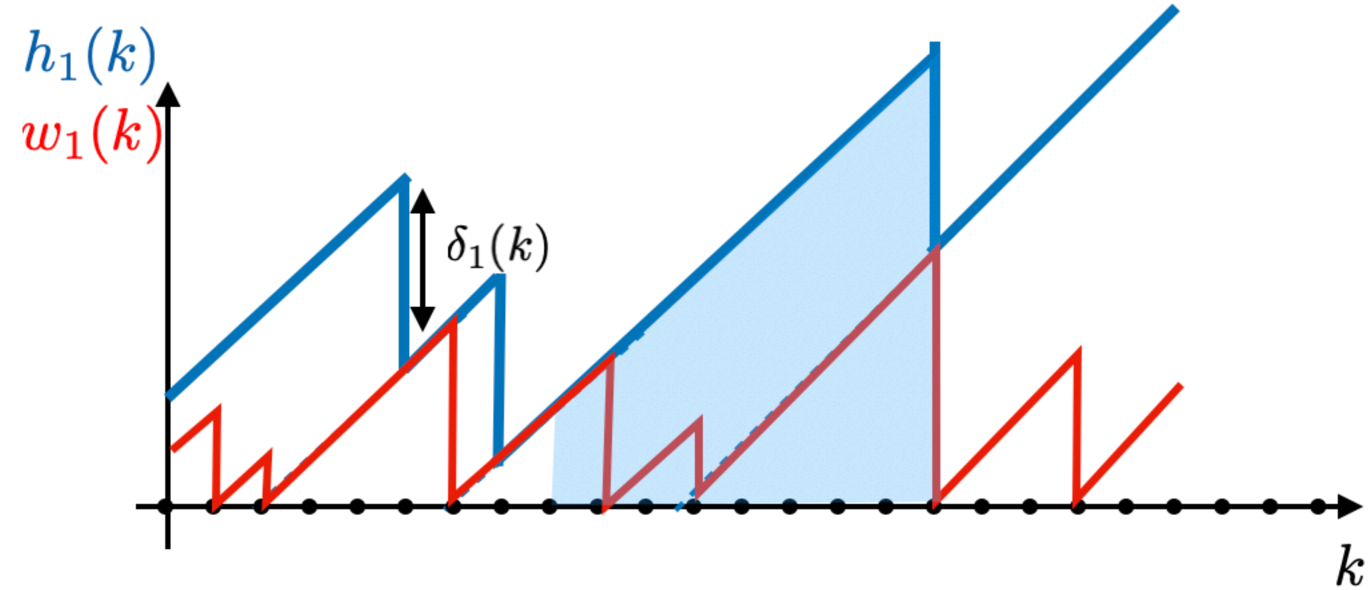

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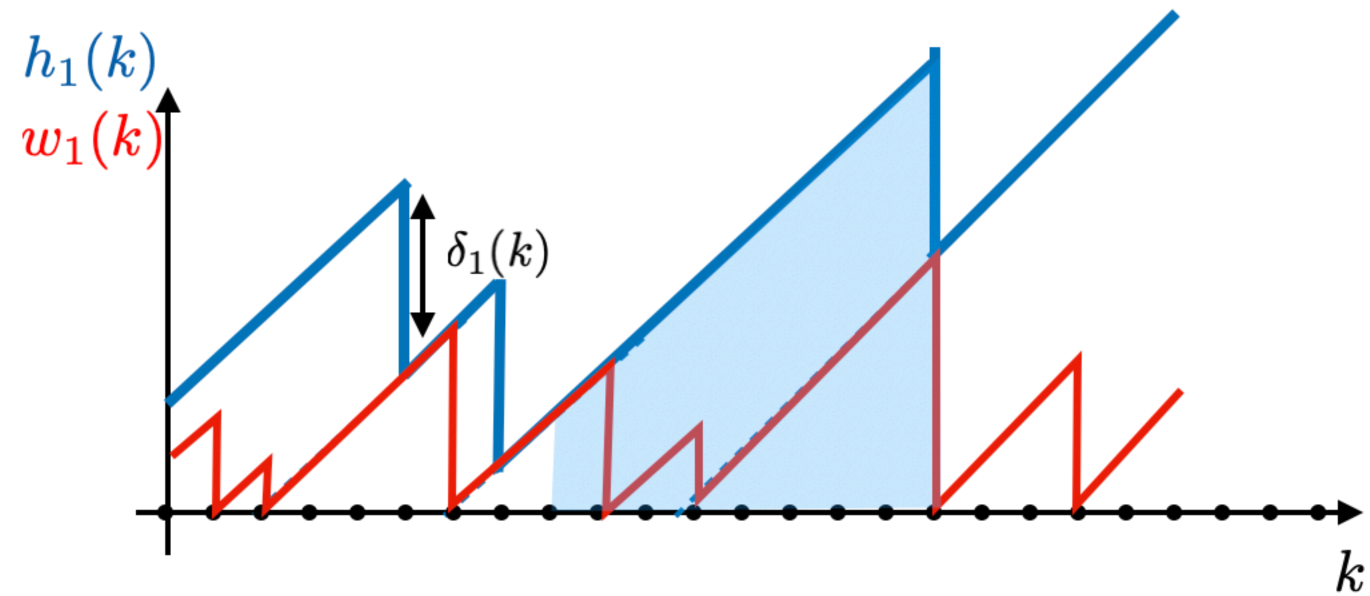

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- Adaptive threshold policy: node i: $\begin{cases} \text{active} & \delta_i(k) \geq \mathtt{T}(k) \\ \text{inactive} & 0 \leq \delta_i(k) < \mathtt{T}(k) \end{cases}$

- Stationary threshold policy: node i: $\begin{cases} \text{active} & \delta_i(k) \geq \mathtt{T}^* \\ \text{inactive} & 0 \leq \delta_i(k) < \mathtt{T}^* \end{cases}$

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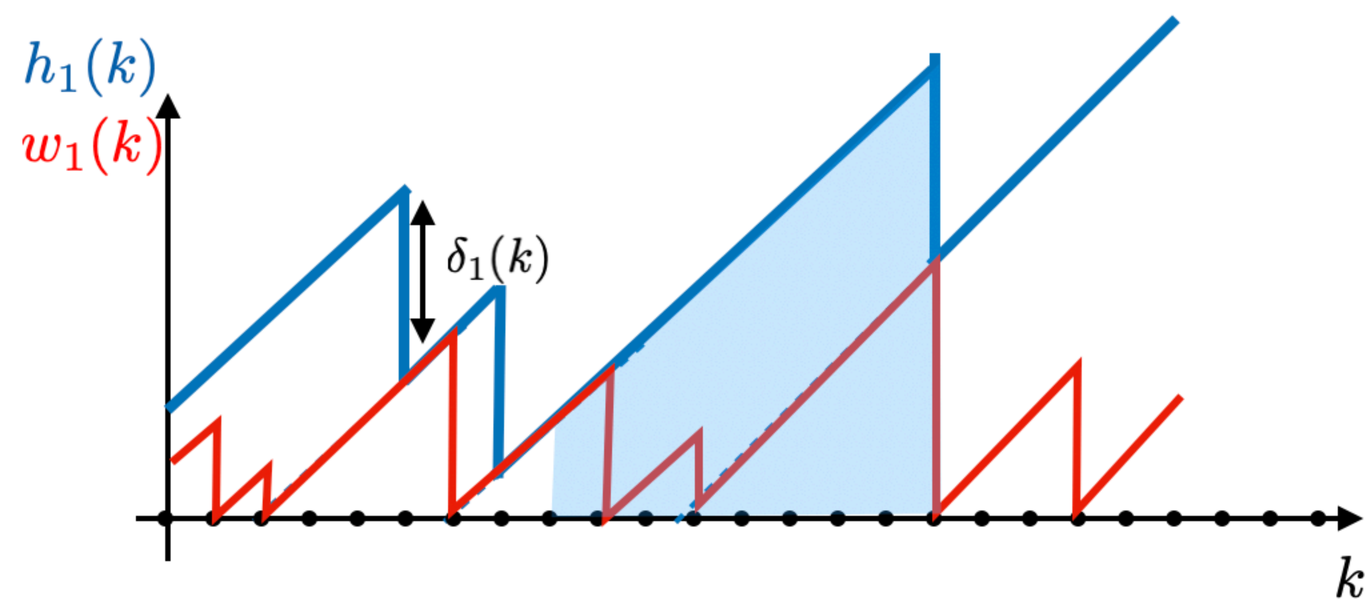

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- Active nodes follow slotted ALOHA protocol and inactive nodes remain silent

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node i is m-order at time k if $\delta_i(k) = m$

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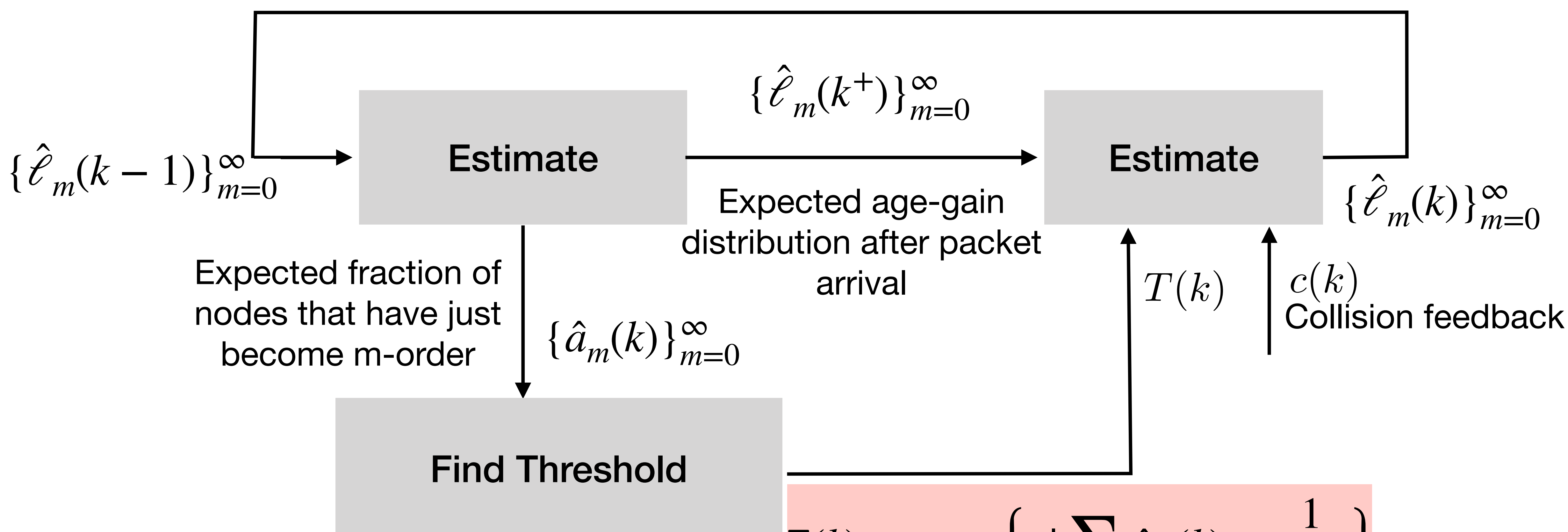

$$\mathtt{T}(k) = \max\left\{ t \,\middle|\, \sum_{m \geq t} \hat{a}_m(k) \geq \frac{1}{eM} \right\}$$

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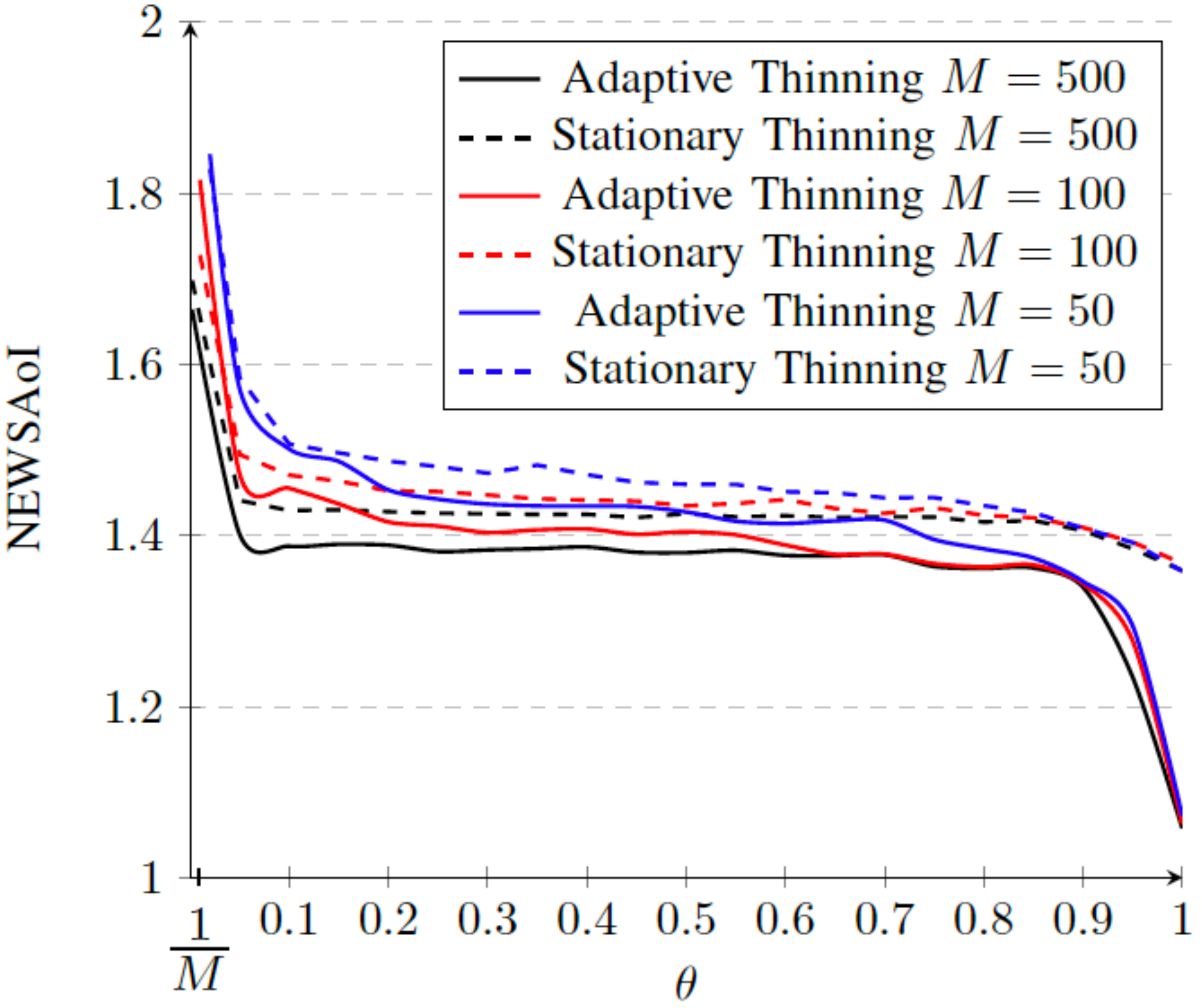

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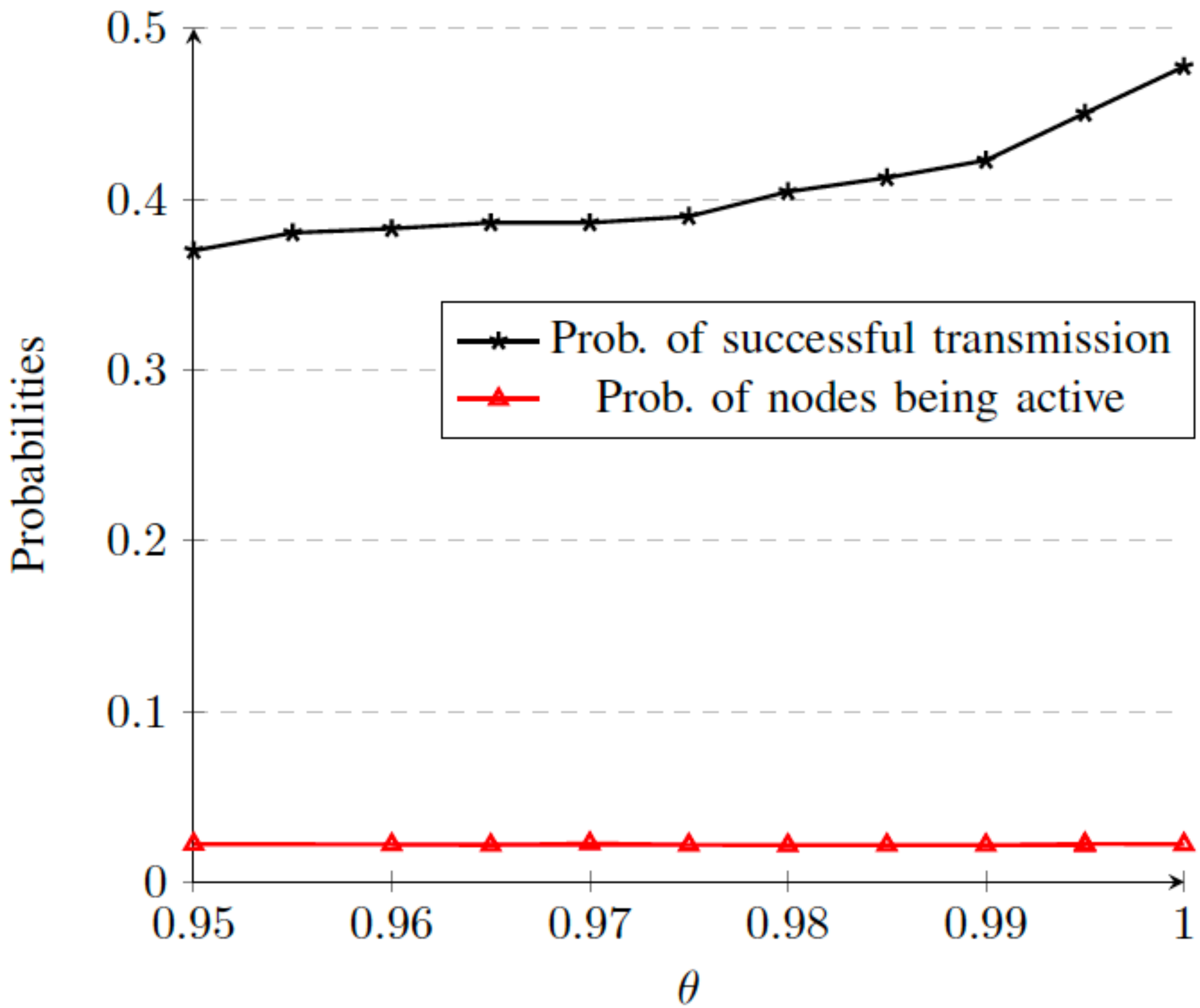
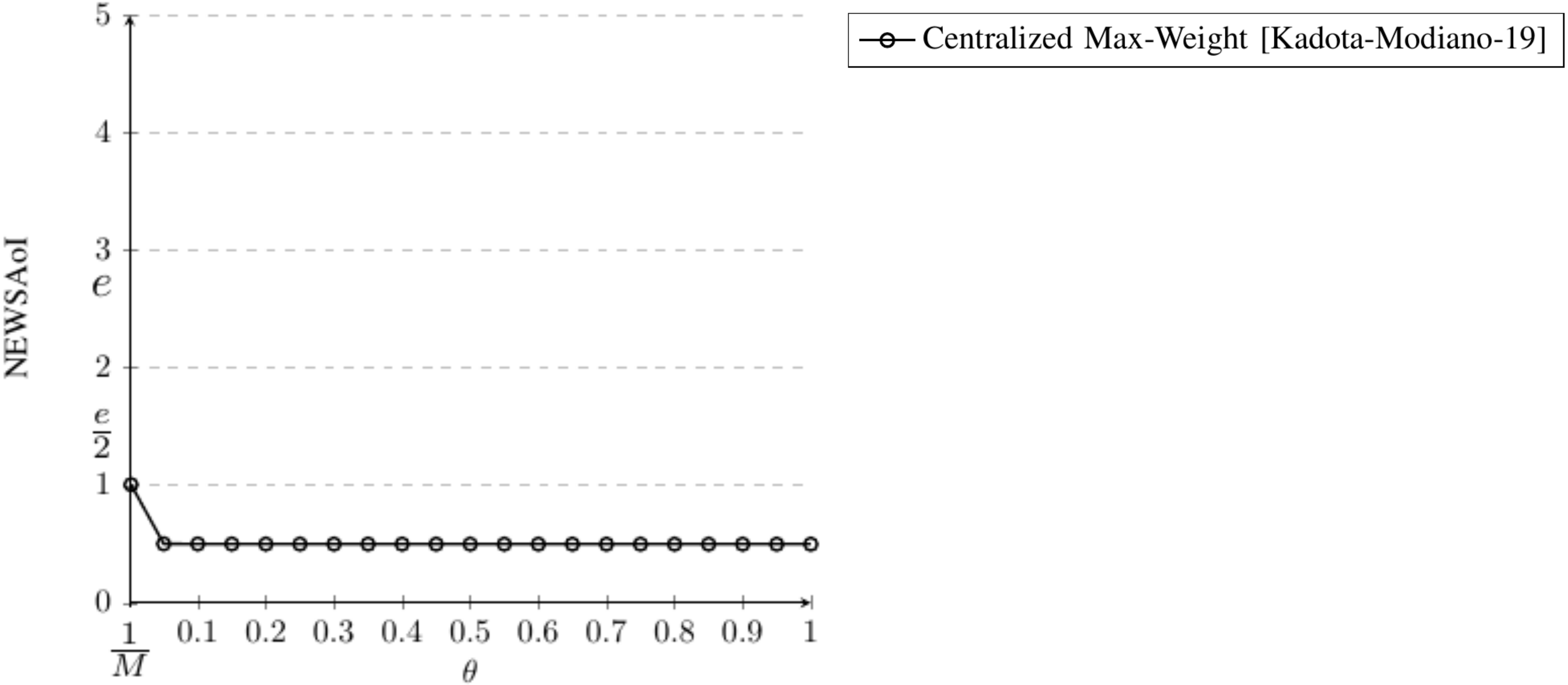


Throughput/rate ↑

Age of Information ↓

Numerical Results



(a) $M = 500$, $\theta \in (\frac{1}{M}, 1]$

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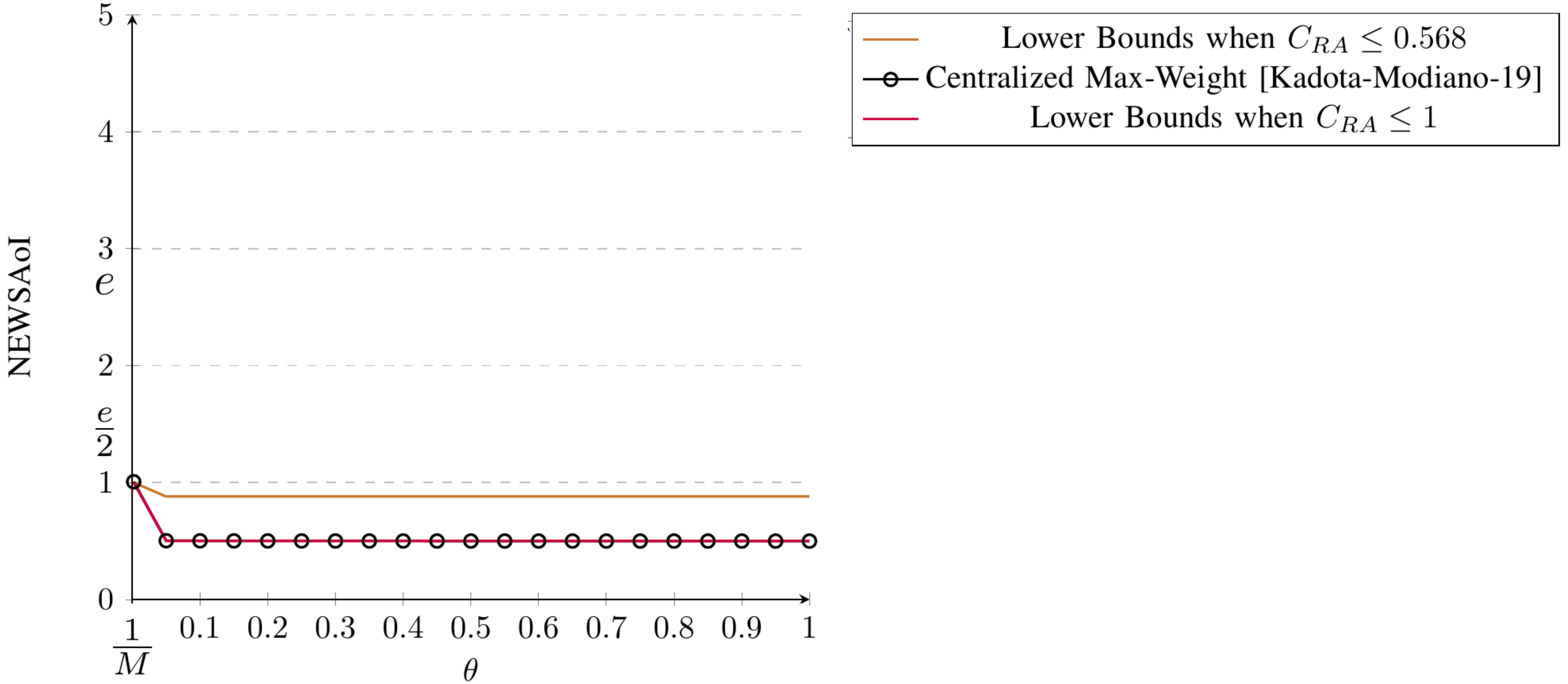

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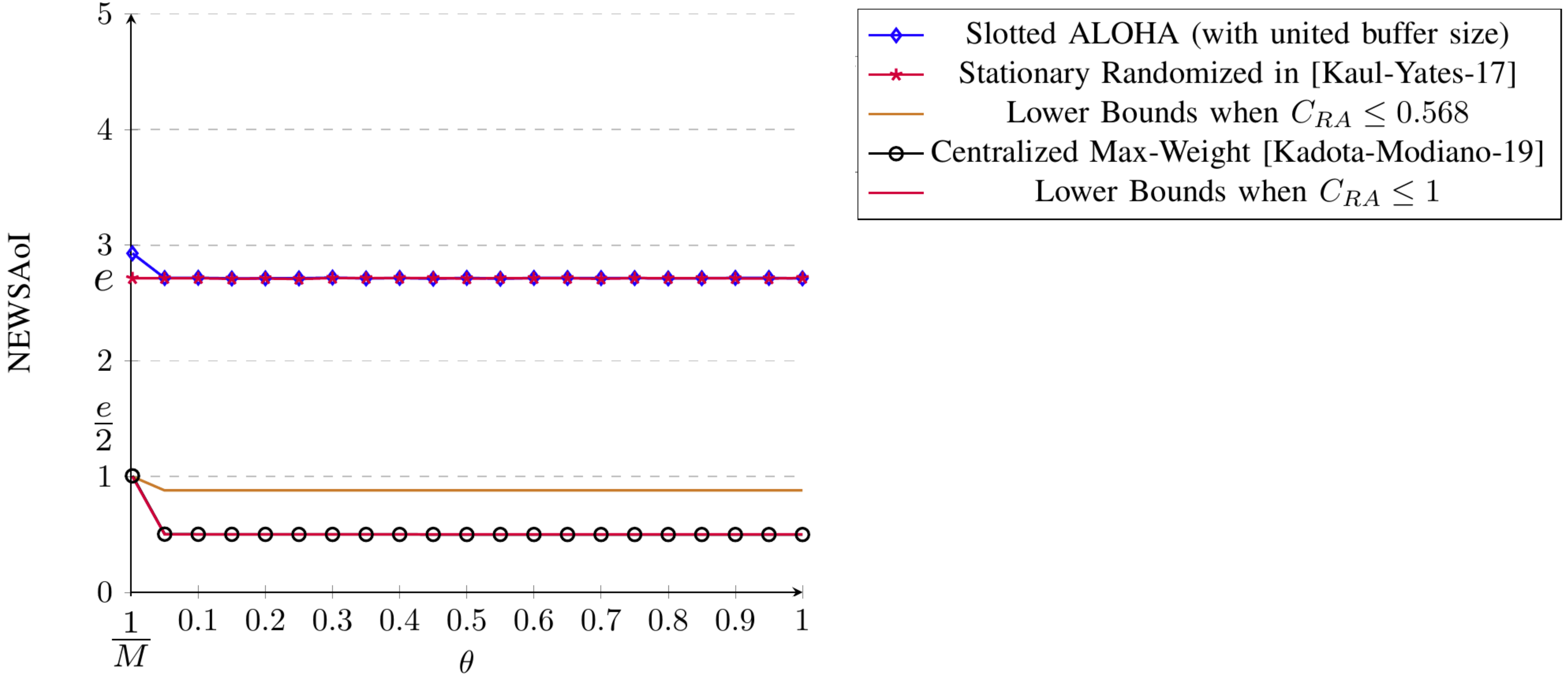

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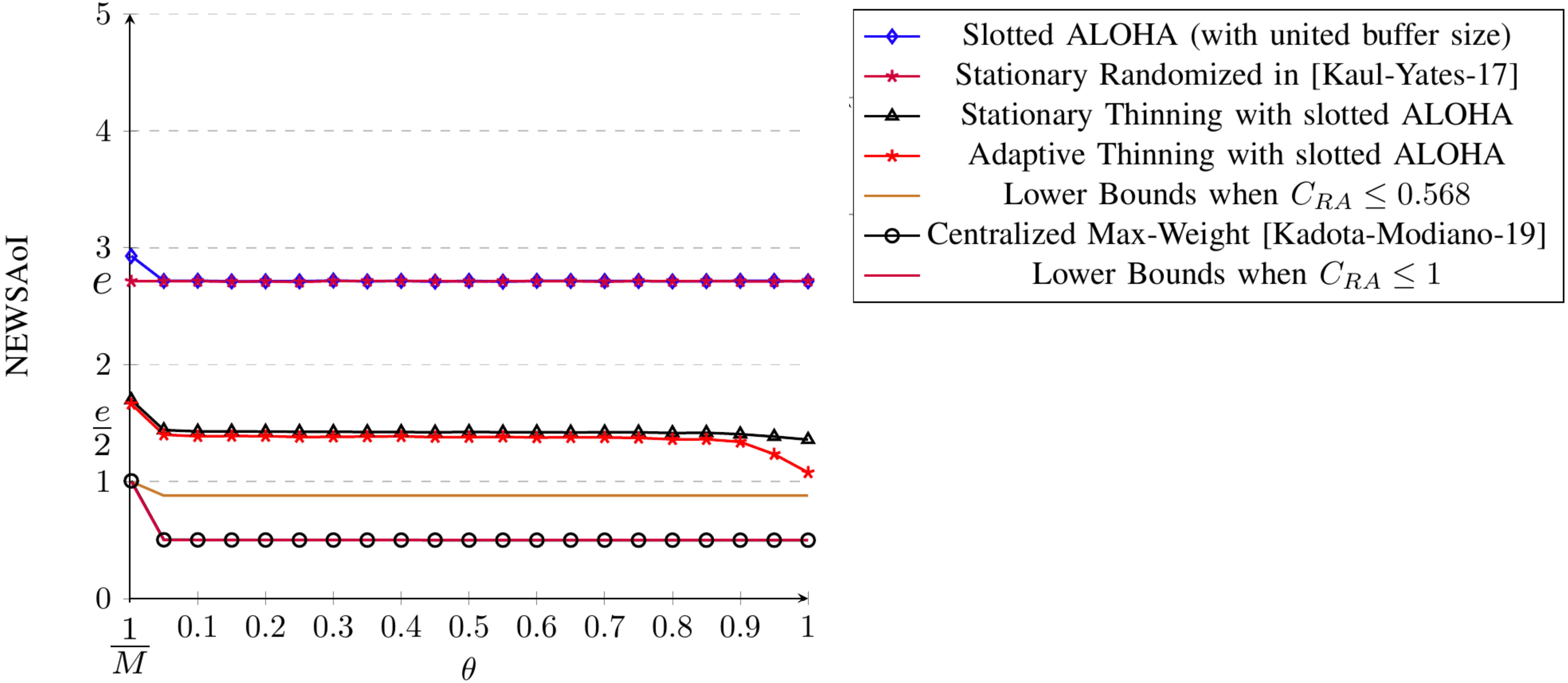

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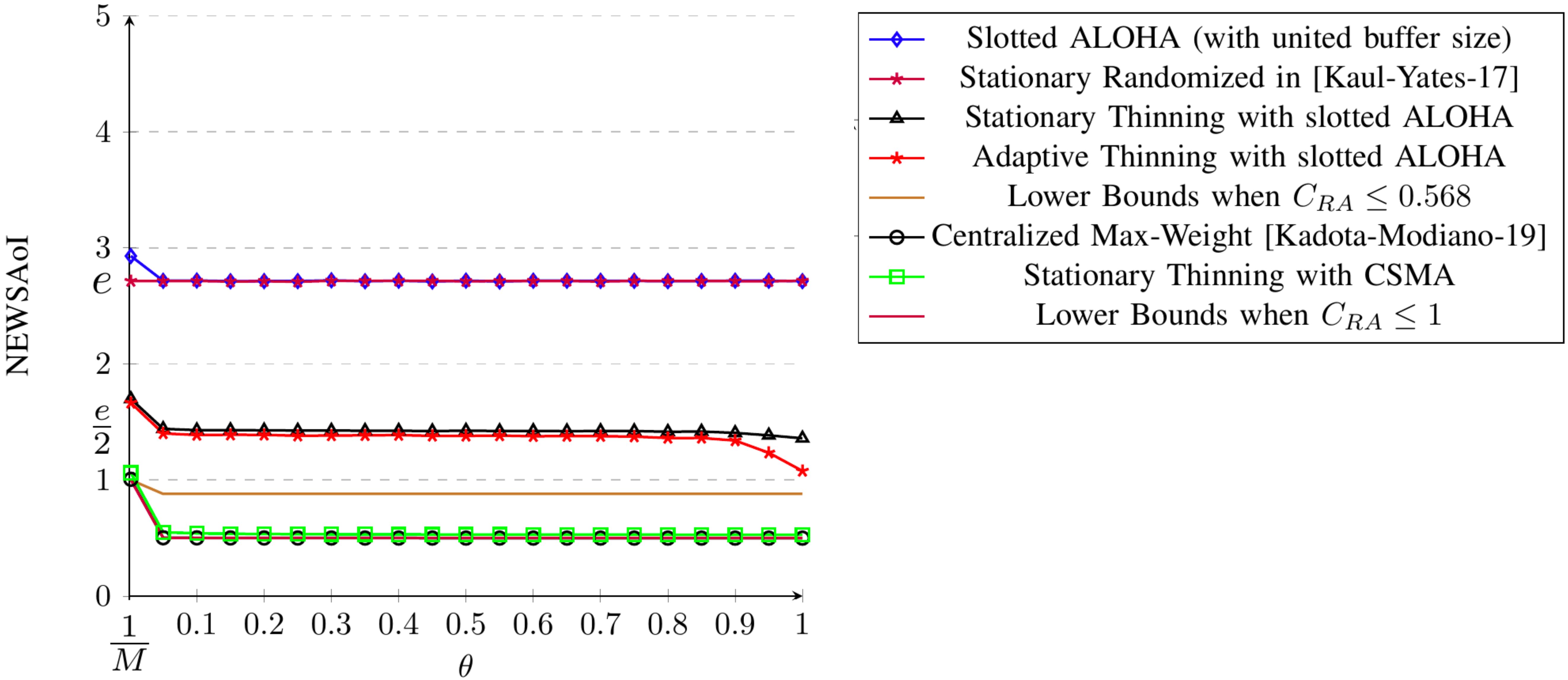

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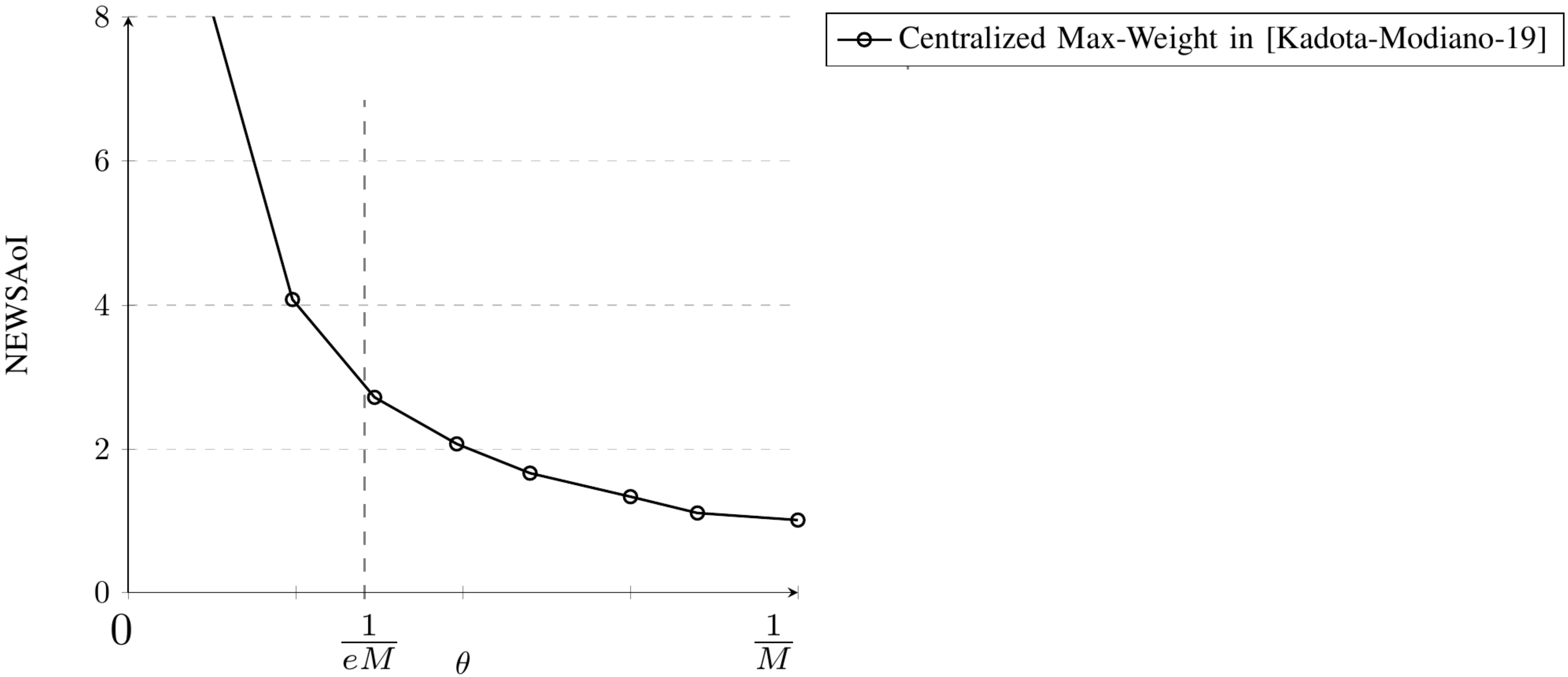

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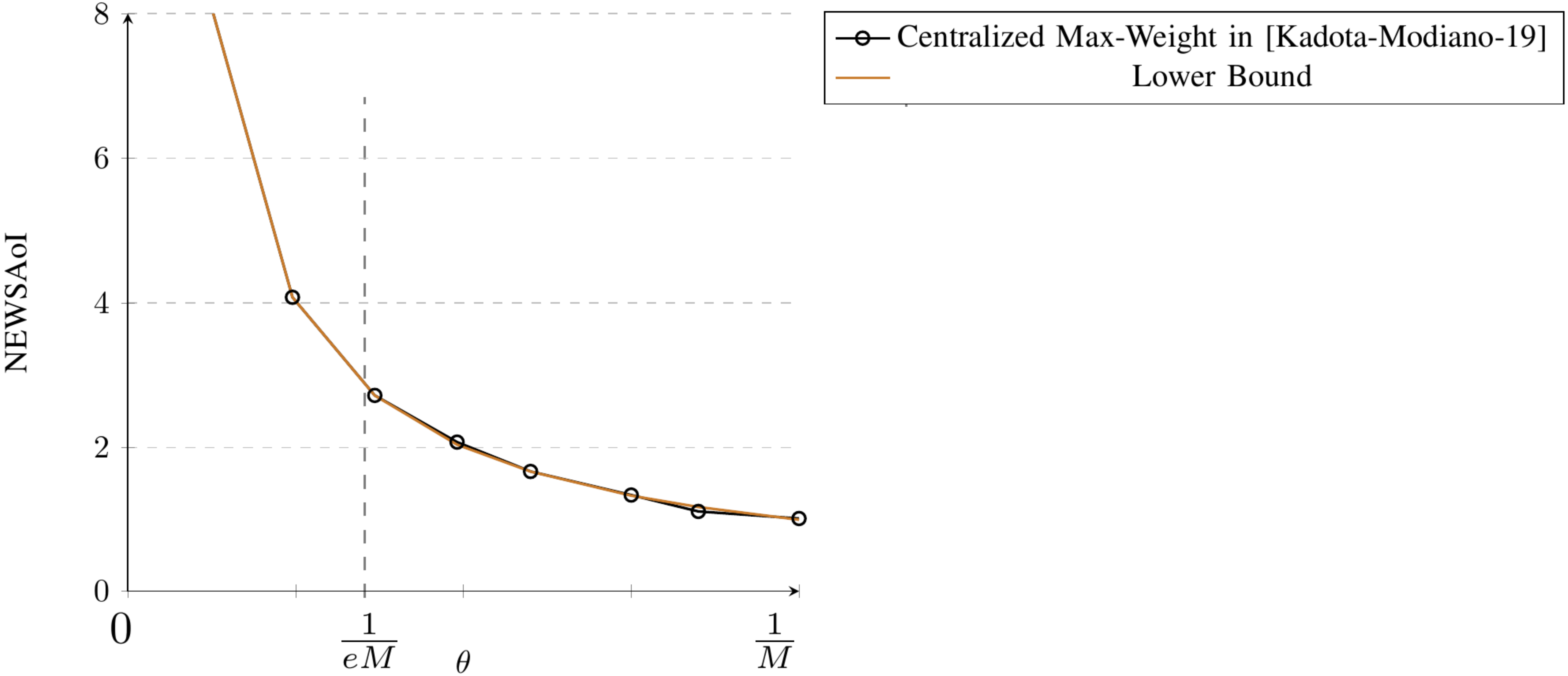

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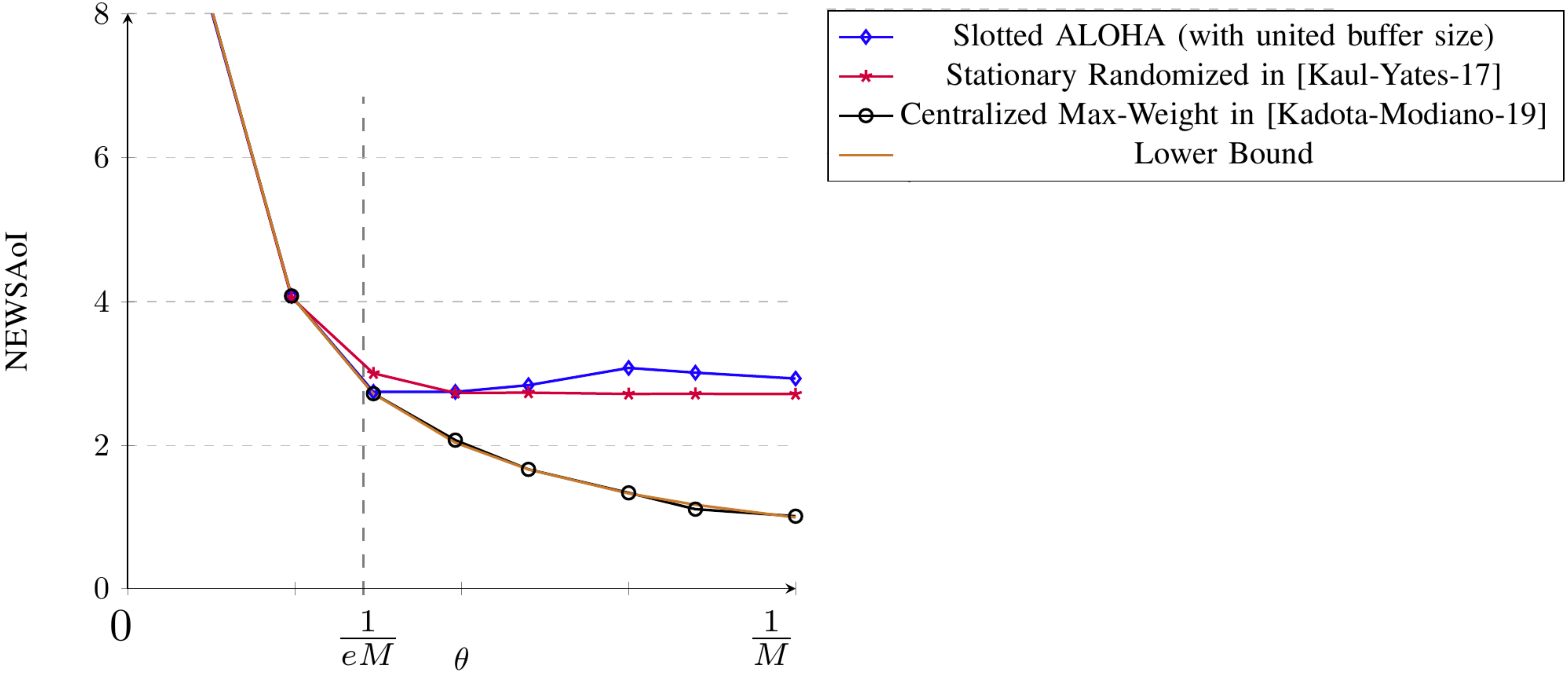

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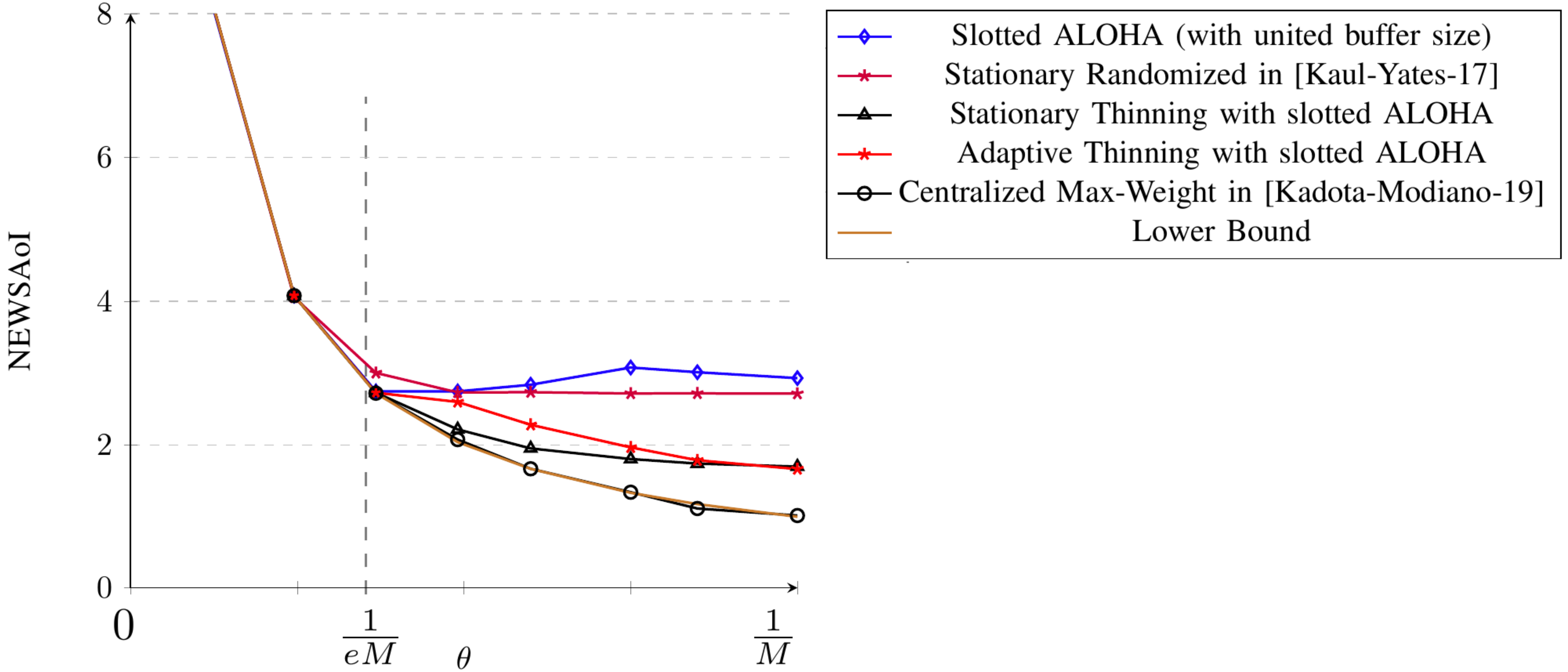

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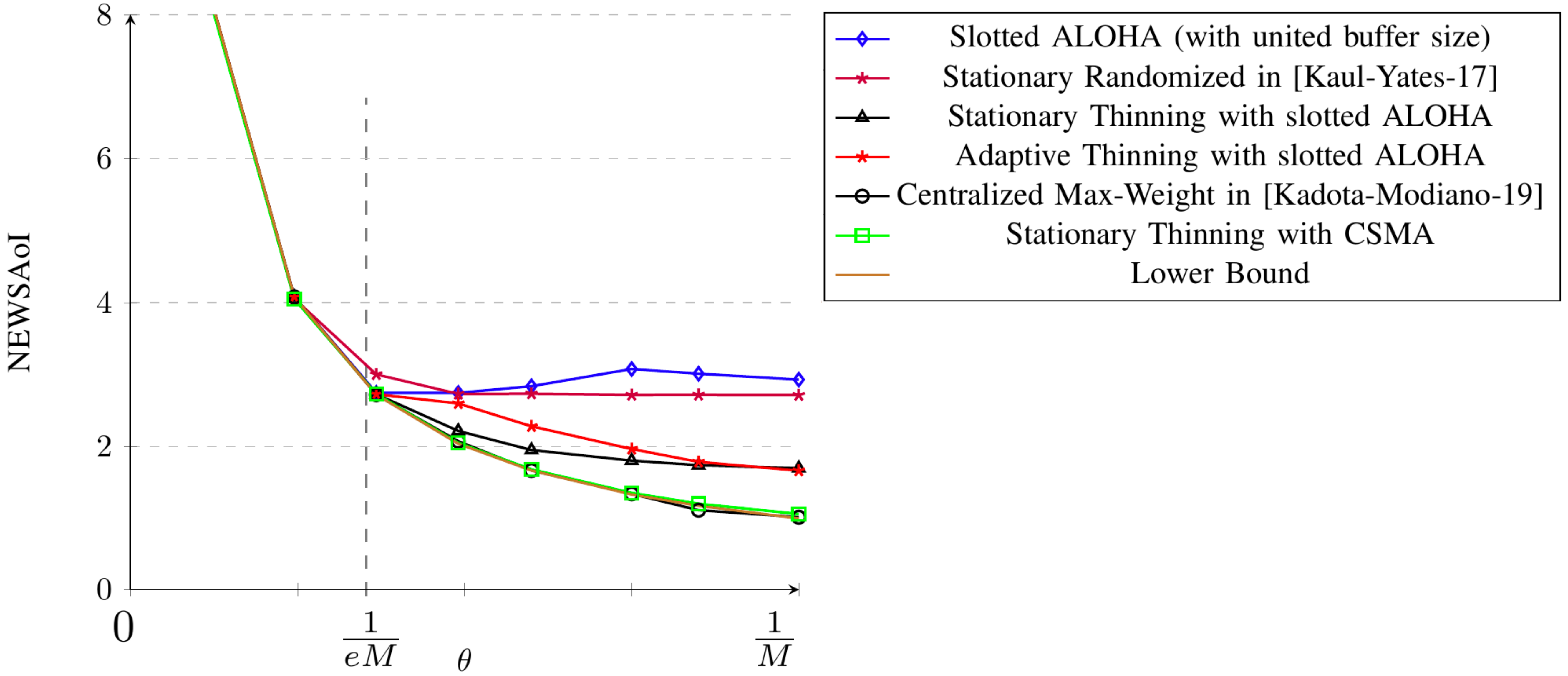

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