Joint Back-pressure Power Control and Interference Cancellation for Wireless Multi-hop Networks

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## ACKs

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Outline

- Routing: shortest path vs. back-pressure
- Back-pressure for wireless multi-hop networks: interference
- Back-pressure power control: complexity
- Back-pressure power control: algorithms
- Interference management: joint back-pressure PC and IC
- Illustrative numerical results
- Take-home points & research outlook
Multi-hops routing: shortest path

Connectivity

Shortest paths

- weights ~ load, delay, "cost"
- for all weights equal
Back-pressure routing

- Back-pressure opposed to the desired flow of a fluid in a pipe
- Favor links with low back-pressure (hence name)
- Backtracking / looping possible!
### Shortest path vs. dynamic back-pressure

<table>
<thead>
<tr>
<th>SP</th>
<th>BP [Tassiulas ’92]</th>
</tr>
</thead>
<tbody>
<tr>
<td>DP: BF, FW, ...</td>
<td>One-hop differential backlog</td>
</tr>
<tr>
<td>Distributed ✓</td>
<td>Distributed ✓ Lightweight ✓</td>
</tr>
<tr>
<td>Must know arrival rate</td>
<td>Auto-adapts ✓</td>
</tr>
<tr>
<td>Quasi-static, slow to adapt to</td>
<td>Highly dynamic, agile ✓</td>
</tr>
<tr>
<td>changing arrivals/load</td>
<td>Claim: maximal stable throughput (all paths)</td>
</tr>
<tr>
<td>availability/failure</td>
<td>... but delay can be large - ( U(\text{load}) ), ( \emptyset \to \text{rand walk} )</td>
</tr>
<tr>
<td>fading/interference patterns</td>
<td></td>
</tr>
<tr>
<td>Claim: Low delay (shortest path)</td>
<td></td>
</tr>
<tr>
<td>... but only at low system loads</td>
<td></td>
</tr>
</tbody>
</table>
Back-pressure routing

- Multiple destinations, commodities?
  - multiple queues per node
  - (max diff backlog) winner-takes-all per link

- Wireline: local computation

- Wireless?

- Broadcast medium: interference

- Link rates depend on transmission scheduling, power of other links

- Globalization - but also opportunity to shape-up playing field ...

- ... through appropriate scheduling, power control
Back-pressure power control

**SINR**

\[
\gamma_\ell = \frac{G_{\ell\ell} p_\ell}{\sum_{k \in \mathcal{L}, k \neq \ell} G_{k\ell} p_k + V_\ell}
\]

**Link capacity**

\[
c_\ell = \log(1 + \gamma_\ell)
\]

**Diff backlog link** \( \ell = (i \to j) \) @ time \( t \)

\[
D_\ell(t) := \max \{ 0, W_i(t) - W_j(t) \}
\]

**BPPC**

\[
\max_{\{p_\ell\}_{\ell \in \mathcal{L}}} \sum_{\ell \in \mathcal{L}} D_\ell(t) c_\ell
\]

s.t. \( 0 \leq \sum_{\ell : \text{Tx}(\ell) = i} p_\ell \leq P_i, \forall i \in \mathcal{N} \)

\[
p_\ell \leq P^{(\ell)}, \ell \in \mathcal{L}
\]
**Back-pressure power control**

**BPPC**

\[
\max_{\{p_\ell\}_{\ell \in \mathcal{L}}} \sum_{\ell \in \mathcal{L}} D_\ell(t)c_\ell
\]

\[\text{s.t. } 0 \leq \sum_{\ell: \text{Tx}(\ell)=i} p_\ell \leq P_i, \forall i \in \mathcal{N}\]

\[p_\ell \leq P^{(\ell)}, \ell \in \mathcal{L}\]

**[Tassiulas et al, ’92 →]**

- Max stable throughput ✓
- Countable control actions: random, adopt if > current
- Still throughput-opt! [Tass’98]
  - but D ↑
- Continuous opt vars? - non-convex due to
  \[c_\ell \sim \log(1+\gamma_\ell)\] - diff of concave

**Link activation / scheduling:**

\[p_\ell \in \left\{0, P^{(\ell)}\right\}, \ell \in \mathcal{L}\]
Reminiscent of ...

**DSL: sum-rate maximization**

- Listen-while-talk ✓
- Dedicated (Tx, Rx)
- Free choice of $G_{k,\ell}$’s
- NP-hard [Luo, Zhang]

**Multi-hop network**

- No listen-while-talk X
- Shared Tx, Rx ⇒
- Restricted $G_{k,\ell}$’s
- NP-hard?

**BPPC**

- Single-hop DSL
  - Listen-while-talk ✓
  - Dedicated (Tx, Rx)
  - Free choice of $G_{k,\ell}$’s
  - NP-hard [Luo, Zhang]
Backlog reduction $\rightarrow$ BPPC contains DSL $\rightarrow$ also NP-hard
Algorithms

- Good news: can adopt (weighted) sum rate maximization algorithms from the PHY literature, originally developed for DSL and single-hop wireless networks

- Successive convex approximation from below: SCALE [Papandriopoulos and Evans, 2006]

\[ \alpha \log(z) + \beta \leq \log(1 + z) \quad \text{for} \quad \begin{cases} \alpha = \frac{z_o}{1 + z_o} \\ \beta = \log(1 + z_o) - \frac{z_o}{1 + z_o} \log(z_o) \end{cases} \]

- Start from high SINR, tighten bound at interim solution steps

- WMMSE [Christensen et al 2008; Shi et al 2011] - more on WMMSE later

- SCALE cumbersome; WMMSE relatively lightweight, faster ✓

- Monotonic WSR improvement ✓, stationary point ✓

- No global opt in general ✗
Key difference with DSL

- BPPC problem must be solved repeatedly for every slot
- Batch algorithms: prohibitive complexity
- Need adaptive, lightweight solutions (to the extent possible)
- Normally, one would init using solution of previous slot; take refinement step
- Doesn’t work ...
- Why?
Proper warm-start

- No listen-while-talk, shared Tx/Rx
- Push-pull ‘wave’ propagation
- Solution from previous slot very different from one for present slot
- Even going back a few slots
- (Quasi-)periodic behavior emerges
Proper warm-start

- (Quasi-)periodic behavior emerges
- Idea: hold record of solutions for $W$ previous slots. $W >$ upper bound on period
- $W$ evaluations of present objective function (cheap!)
- Pick the best to warm-start present slot
- Needs few steps to converge
Quality of approximation?

- Max lower bound $\Rightarrow$ link rates attainable
- Sims indicate solutions far outperform prior art in networking in terms of key network metrics: throughput, delay, stability margin
- OK, but upper bound?
- Normally, dual problem
- Here computing dual function is also NP-hard :-(

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Simulation setup

- $N = 6$ nodes, low-left = s, top-right = d, $L = 21$ links
- $G_{\ell,k} \sim 1/d^4$, $G = 128$, no-listen-while-talk $1/\epsilon$
- $V_\ell = 10^{-12}$, $P^{(\ell)} = 5$, $\forall \ell$
- Deterministic (periodic) arrivals
Successive Approximation

Scenario 1, Batch S.A. algorithm;

arrival rate per slot = 10.4

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Successive Approximation

Scenario 1, Batch S.A. algorithm;
arrival rate per slot = 10.8
Best Response

Scenario 1: Back Pressure Best Response algorithm; arrival rate per slot = 5.8
Interference Mitigation: Next Steps

- Interference Cancellation vs. Interference Alignment
- CSIT, signaling overhead, complexity, practical impairments (synchronization, fading, ...)
- PHY-layer IC @ Rx can boost NET throughput
- ... provided interfering signal can be reliably decoded
- Power control can help ensure this! 🤔
- → PC and IC problems intertwined
- Consider joint BPPC-IC problem
System Model

- SINR at Rx of link $\ell$ when decoding data from link $k$ is
  \[
  \Gamma_{\ell k} = \frac{G_{\ell k} p_k}{\frac{1}{G_{sg}} \sum_{m=1}^{L} G_{\ell m} p_m + \sigma^2_{\ell}} \quad \forall k \in \mathcal{L}\{\ell\}, \forall \ell \in \mathcal{L}
  \]

- $\Gamma_{\ell k} \geq T \implies$ Rx of link $\ell$ can reliably decode Tx of link $k$.

- Define $\mathcal{L}_{\ell^-} = \{0\} \cup \{\mathcal{L}\{\ell\}\}$

- $\{\{c_{\ell k}\}_{k \in \mathcal{L}_{\ell^-}}\}_{\ell \in \mathcal{L}}$ = interference cancellation coefficients.
  - For $k \neq 0$,
    \[
    c_{\ell k} = \begin{cases} 
    1, & \text{if link } \ell \text{ cancels link } k \\
    0, & \text{if link } \ell \text{ does not cancel link } k 
    \end{cases}
    \]
  - For $k = 0$,
    \[
    c_{\ell 0} = \begin{cases} 
    1, & \text{if } c_{\ell k} = 0, \forall k \in \mathcal{L}_{\ell^-} \{0\}, \forall \ell \in \mathcal{L} \\
    0, & \text{otherwise}
    \end{cases}
    \]
System Model

- Rx of link $\ell \in \mathcal{L}$ can cancel at most one interfering link
  \[ \sum_{\substack{k=0 \atop k \neq \ell}}^{L} c_{\ell k} = 1, \quad \forall \, \ell \in \mathcal{L} \]

- Maximum achievable rate for link $\ell \in \mathcal{L}$ is
  \[ R_{\ell} = \sum_{\substack{m=0 \atop m \neq \ell}}^{L} \log (1 + c_{\ell m} \gamma_{\ell m}) \]

  where
  \[ \gamma_{\ell m} = \frac{G_{\ell \ell} p_{\ell}}{\frac{1}{G_{sg}} \sum_{\substack{k=1 \atop k \neq \ell, m}}^{L} G_{\ell k} p_{k} + \sigma_{\ell}^2} \]

- $\gamma_{\ell m} =$ SINR at Rx of link $\ell$ after cancelling link $m$
Joint BPPC-IC Problem Formulation

\[ \Pi_1 \max_{\{p_\ell\}_{\ell \in L}} \sum_{\ell=1}^L D_{\ell}(t) \sum_{m=0}^{L} \log (1 + c_{\ell m} \gamma_{\ell m}) \]

s.t. \[0 \leq p_\ell \leq P \quad \forall \ell \in L,\]
\[c_{\ell k} \in \{0, 1\} \quad \forall k \in L_{\ell-} \quad \forall \ell \in L,\]
\[\sum_{k=0}^{L} c_{\ell k} = 1 \quad \forall \ell \in L\]
\[\Gamma_{\ell k} \geq T c_{\ell k} \quad \forall k \in L_{\ell-} \setminus \{0\}, \quad \forall \ell \in L\]

Interval Relaxation

- Consider IC constraints in $\Pi_1$ for $\ell \in \mathcal{L}$ and candidates $m, n \in \mathcal{L}_{\ell-}, m \neq n$

\[
\frac{G_{\ell m} p_m}{\frac{1}{G_{sg}} \sum_{j=1}^{L} G_{\ell j} p_j + \sigma^2_{\ell}} \geq T c_{\ell m}, \quad \frac{G_{\ell n} p_n}{\frac{1}{G_{sg}} \sum_{j=1}^{L} G_{\ell j} p_j + \sigma^2_{\ell}} \geq T c_{\ell n}
\]

\[
\Rightarrow \frac{T c_{\ell m}}{G_{sg}} \leq \frac{G_{\ell m} p_m}{G_{\ell n} p_n} \leq \frac{G_{sg}}{T c_{\ell n}} \quad \therefore \quad c_{\ell m} c_{\ell n} \leq \frac{G_{sg}^2}{T^2}
\]

1. If $c_{\ell m} > 0$, $c_{\ell n} \leq \frac{G_{sg}^2}{T^2 c_{\ell m}} \forall n \in \mathcal{L}_{\ell-} \setminus \{0, m\}$
2. For high $T$, for every $\ell \in \mathcal{L}$, at most one \{c_{\ell k}\}_{k \in \mathcal{L}_{\ell-} \setminus \{0\}} can be significant.
3. Motivates relaxing $c_{\ell k} \in \{0, 1\}$ to $c_{\ell k} \in [0, 1]$
Extended WMMSE (E-WMMSE) for BPPC-IC

- **WMMSE algorithm** - Turns WSR maximization to WMSE minimization admitting simple block coordinate updates [Christensen *et al.*’08, Shi *et al.*’11]
- **E-WMMSE** - extension to BPPC-IC setup, which includes IC coefficients

Define \( v_\ell = \sqrt{p_\ell}, \ \forall \ \ell \in \mathcal{L} \) and \( H_{\ell k} = \sqrt{G_{\ell k}} \ \forall \ k, \ell \in \mathcal{L} \), \( \mathbf{v} = [v_1, v_2, \ldots, v_L]^T \)
E-WMMSE Problem Formulation

$$\Pi_3$$

$$\min_{u,v,w,c} \sum_{\ell \in \mathcal{L}} D^{(t)}_{\ell} \sum_{m \in \mathcal{L}_{\ell}} (w_{\ell m} e_{\ell m}(u_{\ell m}, c_{\ell m}, v) - \log w_{\ell m})$$

s.t. 0 ≤ $v_{\ell}^2$ ≤ $P$  ∀ $\ell \in \mathcal{L}$, (2a)

$c_{\ell k} \in [0, 1]$  ∀ $k \in \mathcal{L}_{\ell -}$, ∀ $\ell \in \mathcal{L}$, (2b)

$$\sum_{k \in \mathcal{L}_{\ell -}} c_{\ell k} = 1$$  ∀ $\ell \in \mathcal{L}$, (2c)

$$\frac{1}{G_{sg}} \sum_{m=1}^{L} \frac{H_{\ell m}^2 v_m^2}{H_{\ell k}^2 v_k^2} + \sigma_{\ell}^2$$

≥ $T c_{\ell k}$  ∀ $k \in \mathcal{L}_{\ell -} \setminus \{0\}$, ∀ $\ell \in \mathcal{L}$. (2d)
Here

\[ e_{\ell m}(u_{\ell m}, c_{\ell m}, v) = (u_{\ell m}H_{\ell \ell} \sqrt{c_{\ell m}} v_{\ell} - 1)^2 + \]

\[ \frac{1}{G_{sg}} \sum_{k=1}^{L} (u_{\ell m}H_{\ell k} v_k)^2 + \sigma_{\ell}^2 u_{\ell m}^2, \forall m \in \mathcal{L}_{\ell} - \forall \ell \in \mathcal{L} \]  \hspace{1cm} (3)

- \( w_{\ell m} \in \mathcal{R}^+ \) and \( u_{\ell m} \in \mathcal{R}^1 \) - auxiliary variables.
- \( u = \{\{u_{\ell m}\}_{m \in \mathcal{L}_{\ell}}\}_{\ell \in \mathcal{L}}, w = \{\{w_{\ell m}\}_{m \in \mathcal{L}_{\ell}}\}_{\ell \in \mathcal{L}} \) and
- \( c = \{\{c_{\ell m}\}_{m \in \mathcal{L}_{\ell}}\}_{\ell \in \mathcal{L}} \)
- Since \( w \) and \( u \) do not appear in the constraints, \( u_{\ell m}^* \) and \( w_{\ell m}^* \) obtained from \( \frac{\partial f_{wmmse}(\ell)}{\partial u_{\ell m}} = 0 \) and \( \frac{\partial f_{wmmse}(\ell)}{\partial w_{\ell m}} = 0 \)
- where

\[ f_{wmmse}(\ell) = \sum_{m \in \mathcal{L}_{\ell}} (w_{\ell m} e_{\ell m}(u_{\ell m}, c_{\ell m}, v) - \log w_{\ell m}) \]
Equivalence of E-WMMSE formulation and BPPC-IC

\[ \frac{\partial f_{wmmse}}{\partial u_{\ell m}} = 0, \quad \frac{\partial f_{wmmse}}{\partial w_{\ell m}} = 0 \Rightarrow \]

\[ u_{\ell m}^* = \frac{H_{\ell \ell} \sqrt{c_{\ell m}} v_{\ell}}{(H_{\ell \ell} \sqrt{c_{\ell m}} v_{\ell})^2 + \frac{1}{G_{sg}} \sum_{L_{k=1}}^{L_{k \neq \ell, m}} (H_{\ell k} v_{k})^2 + \sigma_{\ell}^2}, \]

\[ w_{\ell m}^* = (e_{\ell m}(u_{\ell m}^*, c_{\ell m}, v))^{-1} = (1 - u_{\ell m}^* H_{\ell \ell} \sqrt{c_{\ell m}} v_{\ell})^{-1} \]

Substituting (4) and (5) into (3) and \( \Pi_3 \), we get the BPPC-IC problem
Block Coordinate Descent: $v$-update

- Treating $w$, $u$ and $c$ as constants in $\Pi_3$, we get

$$\Pi_5 \min_v \sum_{\ell=1}^L D^{(t)}_{\ell} \sum_{m \in \mathcal{L}_{\ell^-}} \left( w^{*}_{\ell m} e_{\ell m} (u^{*}_{\ell m}, c_{\ell m}, v) \right)$$

s.t.  

$$v^2_{\ell} \leq P \quad \forall \ell \in \mathcal{L},$$

$$\frac{G_{\ell k} v^2_k}{\frac{1}{G_{sg}} \sum_{j \neq k, j=1}^L G_{\ell j} v^2_j + \sigma^2_{\ell}} \geq T c_{\ell k} \quad \forall k \in \mathcal{L}_{\ell^-}, \forall \ell \in \mathcal{L}.$$  (6a, 6b)

- $\Pi_5$ - non-convex formulation ((6b) - non-convex in $v$)
- But $e_{\ell m}(u^{*}_{\ell m}, c_{\ell m}, v)$ and constraints - functions of $\{v^2_{\ell}\}_{\ell \in \mathcal{L}}$
- Hence can introduce restriction $v_{\ell} \geq 0, \forall \ell \in \mathcal{L}$
v-update cont’d.

\[ \Pi_6 \quad \min_v \sum_{\ell=1}^L D_{\ell}^{(t)} \sum_{m \in \mathcal{L}_\ell} w_{\ell m} e_{\ell m}(u_{\ell m}^*, c_{\ell m}, v) \]

s.t. \[ v_{\ell}^2 \leq P \quad \forall \ell \in \mathcal{L}, \quad (7a) \]
\[ v_{\ell} \geq 0 \quad \forall \ell \in \mathcal{L}, \quad (7b) \]
\[ \|v_{\ell k}^T\| \leq \left( \sqrt{G_{\ell k} + \frac{T G_{\ell k} c_{\ell k}}{G_{sg}}} \right) v_k \quad \forall k \in \mathcal{L}_\ell \quad \forall \ell \in \mathcal{L}. \quad (7c) \]

where \[ v_{\ell k}^T = \left[ \{ \sqrt{G_{\ell m} T c_{\ell k}} v_m \}_{m \in \mathcal{L}}, \sqrt{\sigma_{\ell}^2 T c_{\ell k}} \right]^T \]

- \( \Pi_6 \) is convex in \( v \) - quadratic obj. with cone constraints.
Block Coordinate Descent: c-update

- Fix $\mathbf{w}$, $\mathbf{u}$, $\mathbf{v}$ and update $\mathbf{c}$. With $p_\ell = (v_\ell^*)^2$, $\forall \ell \in \mathcal{L}$.

\[
\Pi_7
\max_{\{\{c_{\ell m}\}_{m \in \mathcal{L}_\ell^-}\}} \sum_{\ell=1}^{L} D^{(t)}_\ell \sum_{m \in \mathcal{L}_\ell^-} \log \left( 1 + \frac{G_{\ell\ell} p_\ell c_{\ell m}}{\frac{1}{G_{sg}} \sum_{k \neq \ell, m} G_{\ell k} p_k + \sigma_{\ell}^2} \right)
\]

s.t. $c_{\ell m} \in [0, 1] \quad \forall m \in \mathcal{L}_\ell^- \quad \forall \ell \in \mathcal{L}$,  
\[
(8a)
\]
\[
\sum_{m \in \mathcal{L}_\ell^-} c_{\ell m} = 1 \quad \forall \ell \in \mathcal{L},
\]
\[
(8b)
\]
\[
c_{\ell k} \leq \frac{1}{T} \frac{G_{\ell k} p_k}{\frac{1}{G_{sg}} \sum_{j \neq k, j=1}^{L} G_{\ell j} p_j + \sigma_{\ell}^2}, \quad \forall k \in \mathcal{L}_{\ell^-}, \forall \ell \in \mathcal{L}.
\]
\[
(8c)
\]
Block Coordinate Descent: c-update

- **c-update** - Waterfilling problem with spectral mask constraints [Nguyen et al.'10], with c’s playing the role of powers. Solution is

\[
\begin{align*}
  c_{\ell0}^* &= \left[ \frac{1}{\mu_{\ell}^*} - \frac{1}{\gamma_{\ell0}} \right]_0^1, \quad \forall \ell \in \mathcal{L} \\
  c_{\ell m}^* &= \left[ \frac{1}{\mu_{\ell}^*} - \frac{1}{\gamma_{\ell m}} \right]_0^\min(\frac{\Gamma_{\ell m}}{T},1), \quad \forall m \in \mathcal{L}_{\ell}, \quad \forall \ell \in \mathcal{L}
\end{align*}
\]

(9) (10)

- where \( \mu_{\ell}^* \) can be found using bisection to ensure that

\[
\sum_{m \in \mathcal{L}_{\ell}} c_{\ell m}^* = \min \left( 1, \sum_{m \in \mathcal{L}_{\ell} \setminus \{0\}} \min \left( \frac{\Gamma_{\ell m}}{T}, 1 \right) \right)
\]
E-WMMSE Algorithm

1. **Initialization** - For each time slot $t$, calculate the differential backlogs, reset iteration counter $n = 1$, and set $v_\ell^{(n)} = \sqrt{P}$, $\forall \ell \in \mathcal{L}$, $c_\ell^{(n)} = 1$, $c_{\ell m}^{(n)} = 0$ $\forall m \in \mathcal{L}_\ell^-$, $\forall \ell \in \mathcal{L}$.

2. repeat

3. **u-update and w-update** - using (4)

4. **v-update** - Solve $\Pi_6$ to obtain the updated $\{p_\ell\}_{\ell \in \mathcal{L}}$.

5. **c-update** - Solve $\Pi_7$ to obtain the updated $\{\{c_{\ell m}\}_{m \in \mathcal{L}_\ell^-}\}_{\ell \in \mathcal{L}}$.

6. $n = n + 1$

7. until $|\log(w_{\ell m}^{(n)}) - \log(w_{\ell m}^{(n-1)})| \leq \epsilon$, $\forall m \in \mathcal{L}_\ell^-$, $\forall \ell \in \mathcal{L}$. 

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Simulation Results

- Channel: path-loss only, $G_{ij} = d_{ij}^{-\alpha}$, $d_{ij}$ - distance between node Rx$(i)$ and node Tx$(j)$, $\alpha$ - path-loss exponent
- Deterministic periodic input traffic $\lambda$ pkts/slot into source node at the beginning of each time slot.

Table: Simulation Parameters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$</td>
<td>Number of nodes</td>
<td>4 / 5</td>
</tr>
<tr>
<td>$P$</td>
<td>Max. power per link</td>
<td>5 W</td>
</tr>
<tr>
<td>$V$</td>
<td>Noise variance</td>
<td>$10^{-12}$ W</td>
</tr>
<tr>
<td>$G_{sg}$</td>
<td>Spreading / Beam-forming gain</td>
<td>128</td>
</tr>
<tr>
<td>$T$</td>
<td>SINR threshold for decoding</td>
<td>1000(30 dB)</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>Tolerance parameter</td>
<td>0.1</td>
</tr>
</tbody>
</table>

- Performance Metrics: throughput, backlogs (delays)
Network stabilization property of BPPC-IC policy for $N = 4$ and $\lambda = 10$

- BPPC-IC stabilizes the network (bounded queues) unlike BPPC where the backlogs were increasing with time
- Average network throughput increases when BPPC-IC is introduced
Comparison of Network stabilization property of BPPC-IC and BPPC-RIC policies for $N = 5$ and $\lambda = 11$

- BPPC-IC and BPPC-RIC policies stabilize the network.
- Average source backlog is lower for BPPC-IC.
- BPPC-IC policy takes less time to stabilize the network than BPPC-RIC policy.
**Max. Stable-Throughput Comparison**

<table>
<thead>
<tr>
<th>IC policy</th>
<th>4-node network</th>
<th>5-node network</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPPC</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>BPPC-RIC</td>
<td>9</td>
<td>12</td>
</tr>
<tr>
<td>BPPC-IC</td>
<td>10</td>
<td>14</td>
</tr>
</tbody>
</table>

- Significant gain in maximum stable throughput with interference cancellation
- Up to 42.8% increase for $N = 4$ and 75% increase for $N = 5$
- % increase in maximum stable throughput increases with the number of nodes
- BPPC-IC superior performance compared to BPPC-RIC
Max. stable throughput comparison of BPPC-IC and BPPC-RIC policies for $N = 5$ and $\lambda = 14$

- Source node backlogs increase with time for BPPC-RIC and remains bounded for BPPC-IC
Take-home points & future research

- PHY-layer optimization critical for enhancing NET-layer performance
- ∃ simple randomized back-pressure policy attaining max stable throughput for finite control spaces
- ∄ for continuous control spaces: BPPC is NP-hard
- So (what!) are most problems in cross-layer network operations ...
- ... but take-home point is recent advances in SP and OPT enable much better performance than previously attainable!
- Many challenges remain, such as lightweight distributed implementation, with low signaling overhead ... and how to
- Cross-leverage w/ recent paradigm shifts, e.g., network coding and interference alignment?