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

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ACKs

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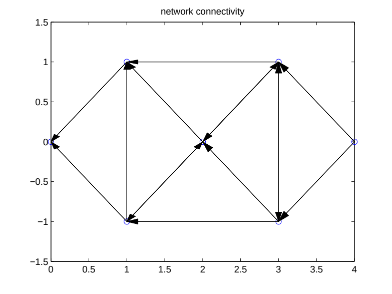
Outline

- 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

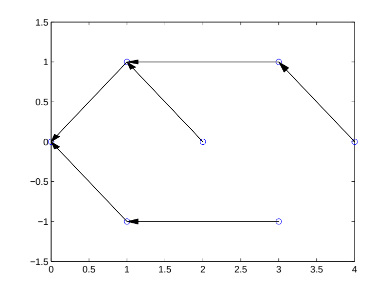
Multi-hop routing: shortest path

Connectivity



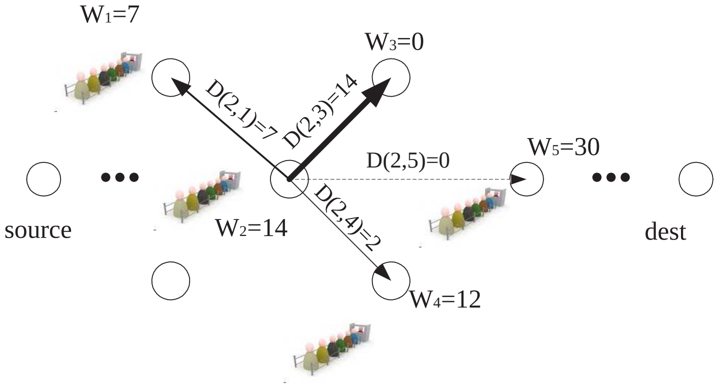
- weights $\sim$ load, delay, “cost”

Shortest paths



- 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

SP

- DP: BF, FW, ...
- Distributed $\checkmark$
- Must know arrival rate
- Quasi-static, slow to adapt to
  - changing arrivals/load
  - availability/failure
  - fading/interference patterns
- Claim: Low delay (shortest path)
- ... but only at low system loads

BP [Tassiulas '92]

- One-hop differential backlog
- Distributed $\checkmark$ Lightweight $\checkmark$
- Auto-adapts $\checkmark$
- Highly dynamic, agile $\checkmark$
- Claim: maximal stable throughput (all paths)
- ... but delay can be large - U(load), $\emptyset \rightarrow$ rand walk!

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

$$D_\ell(t) := \max\left\{0, W_i(t) - W_j(t)\right\}$$

BPPC

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

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

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

Back-pressure power control

BPPC

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

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

$$p_\ell \le P^{(\ell)}, \ell \in \mathcal{L}$$

Link activation / scheduling:

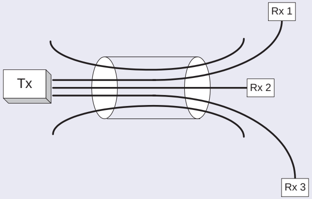
$$p_\ell \in \left\{0, P^{(\ell)}\right\}, \ell \in \mathcal{L}$$

[Tassiulas *et al*, '92 $\rightarrow$]

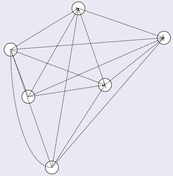
- Max stable throughput $\checkmark$
- Countable control actions: random, adopt if > current
- Still throughput-opt! [Tass'98] - but D $\uparrow$
- Continuous opt vars? - non-convex due to $c_\ell \sim \log(1+\gamma_\ell)$ - diff of concave

Reminiscent of ...

DSL: sum-rate maximization



BPPC



Single-hop DSL

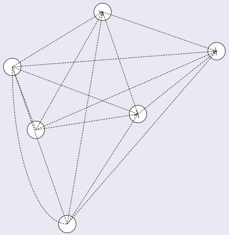
- Listen-while-talk ✓
- Dedicated (Tx,Rx)
- Free choice of $G_{k,\ell}$'s
- NP-hard [Luo, Zhang]

Multi-hop network

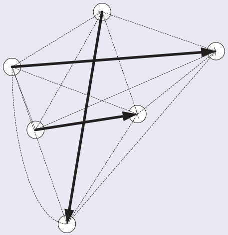
- No listen-while-talk X
- Shared Tx, Rx $\Rightarrow$
- Restricted $G_{k,\ell}$'s
- NP-hard?

Peel off

Generic backlogs



Choosing backlogs



- 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]

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

- 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 $\checkmark$
- Monotonic WSR improvement $\checkmark$, stationary point $\checkmark$
- No global opt in general $\boxtimes$

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

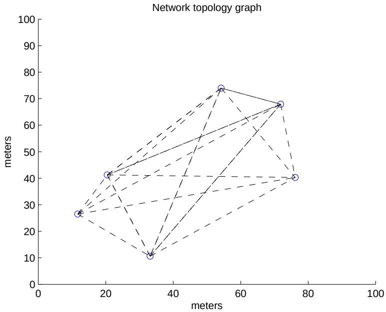
Proper warm-start

- (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?

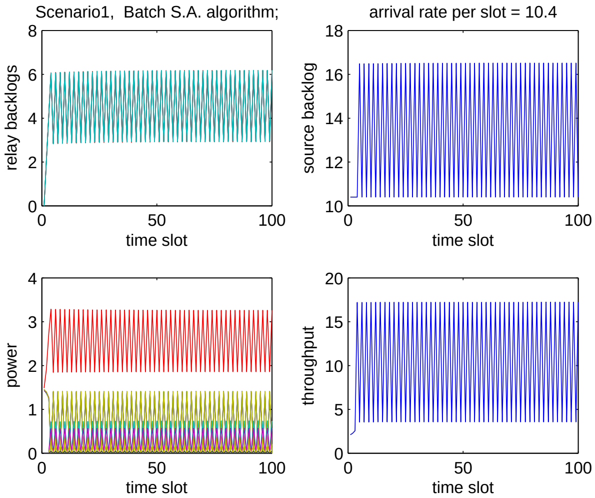
- Max lower bound $\Rightarrow$ link rates attainable
- Sims indicate solutions far outperform prior art in networking in terms of key network metrics: throughput, delay, stability margin
- OK, but upper bound?
- Normally, dual problem
- Here computing dual function is also NP-hard :-(

Simulation setup

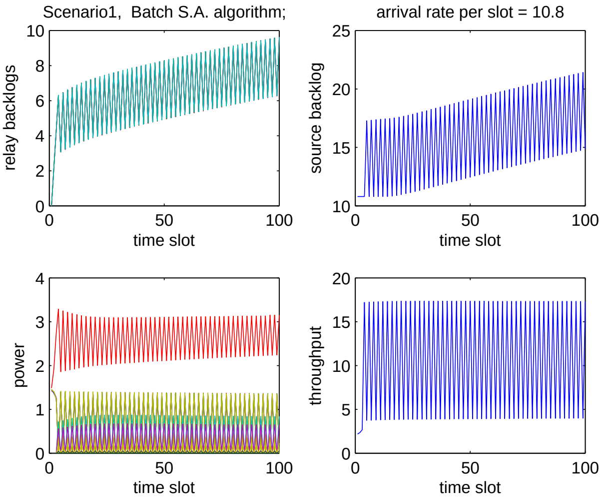


- $N = 6$ nodes, low-left = s, top-right = d, $L = 21$ links
- $G_{\ell,k} \sim 1/d^4$, $G = 128$, no-listen-while-talk $1/\text{eps}$
- $V_\ell = 10^{-12}$, $P^{(\ell)} = 5$, $\forall \ell$
- Deterministic (periodic) arrivals

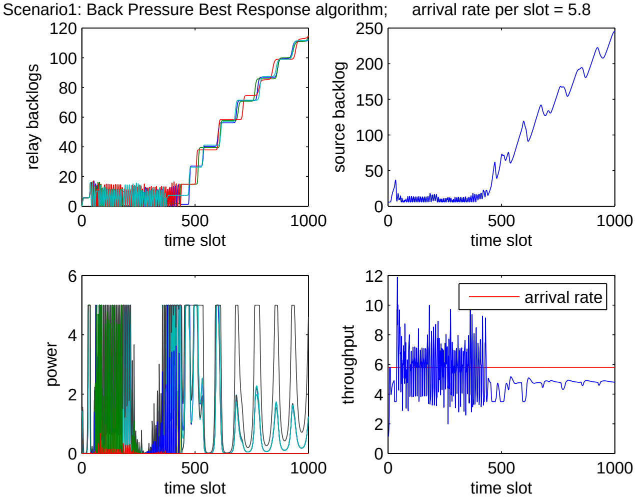
Successive Approximation



Successive Approximation



Best Response



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!
- $\Longrightarrow$ PC and IC problems intertwined
- Consider *joint* BPPC-IC problem

System Model

- SINR at Rx of link ℓ when decoding data from link k is

$$\Gamma_{\ell k} = \frac{G_{\ell k} p_k}{\frac{1}{G_{sg}} \sum_{\substack{m=1 \\ m \neq k}}^{L} G_{\ell m} p_m + \sigma_\ell^2} \quad \forall k \in \mathcal{L} \backslash \{\ell\}, \forall \ell \in \mathcal{L}$$

- $\Gamma_{\ell k} \geq T \implies$ Rx of link ℓ can reliably decode Tx of link k.
- Define $\mathcal{L}_{\ell-} = \{0\} \bigcup \{\mathcal{L} \backslash \{\ell\}\}$
- $\{\{c_{\ell k}\}_{k \in \mathcal{L}_{\ell-}}\}_{\ell \in \mathcal{L}}$ = 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 $k = 0$,

$$c_{\ell 0} = \begin{cases} 1, & \text{if } c_{\ell k} = 0, \ \forall \ k \in \mathcal{L}_{\ell-} \backslash \{0\}, \ \forall \ \ell \ \in \ \mathcal{L} \\ 0, & \text{otherwise} \end{cases}$$

System Model

- Rx of link $\ell \in \mathcal{L}$ can cancel at most one interfering link

$$\sum_{\substack{k=0 \\ k \neq \ell}}^{L} c_{\ell k} = 1, \quad \forall\, \ell \in \mathcal{L}$$

- Maximum achievable rate for link $\ell \in \mathcal{L}$ is

$$R_\ell = \sum_{\substack{m=0 \\ m \neq \ell}}^{L} \log\left(1 + c_{\ell m}\gamma_{\ell m}\right)$$

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

  - $\gamma_{\ell m}$ = SINR at Rx of link ℓ after cancelling link m

Joint BPPC-IC Problem Formulation

$$
\Pi_1 \quad \max_{\substack{\{p_\ell\}_{\ell\in\mathcal{L}} \\ \{\{c_{\ell m}\}_{m\in\mathcal{L}_{\ell-}}\}_{\ell\in\mathcal{L}}}} \sum_{\ell=1}^{L} D_\ell^{(t)} \sum_{\substack{m=0 \\ m\neq\ell}}^{L} \log\left(1 + c_{\ell m}\gamma_{\ell m}\right)
$$

$$
\begin{aligned}
\text{s.t.} \quad & 0 \le p_\ell \le P \quad \forall \ell \in \mathcal{L}, \\
& c_{\ell k} \in \{0,1\} \quad \forall k \in \mathcal{L}_{\ell-} \ \forall \ell \in \mathcal{L}, \\
& \sum_{\substack{k=0 \\ k\neq\ell}}^{L} c_{\ell k} = 1 \quad \forall \ell \in \mathcal{L} \\
& \Gamma_{\ell k} \ge T c_{\ell k} \quad \forall k \in \mathcal{L}_{\ell-} \setminus \{0\},\ \forall \ell \in \mathcal{L}
\end{aligned}
$$

- NP-hard - contains BPPC [BG & NS, IEEE TWC, '13]

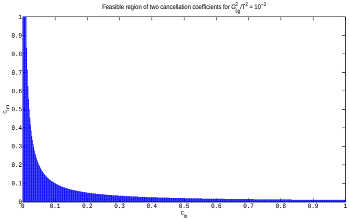
Interval Relaxation

- Consider IC constraints in Π_1 for $\ell \in \mathcal{L}$ and candidates $m, n \in \mathcal{L}_{\ell-}, m \neq n$

$$\frac{G_{\ell m} p_m}{\frac{1}{G_{sg}} \sum_{\substack{j=1 \\ j \neq m}}^{L} G_{\ell j} p_j + \sigma_\ell^2} \geq T c_{\ell m}, \quad \frac{G_{\ell n} p_n}{\frac{1}{G_{sg}} \sum_{\substack{j=1 \\ j \neq n}}^{L} G_{\ell j} p_j + \sigma_\ell^2} \geq T c_{\ell n}$$

$$\Rightarrow \frac{T c_{\ell m}}{G_{sg}} \leq \frac{G_{\ell m} p_m}{G_{\ell n} p_n} \leq \frac{G_{sg}}{T c_{\ell n}} \quad \therefore \boxed{c_{\ell m}\, c_{\ell n} \leq \frac{G_{sg}^2}{T^2}} \tag{1}$$

- If $c_{\ell m} > 0$, $c_{\ell n} \leq \frac{G_{sg}^2}{T^2 c_{\ell m}} \ \forall n \in \mathcal{L}_{\ell-} \setminus \{0, m\}$
- 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.
- 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

Π_3

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

$$\text{s.t.} \quad 0 \le v_\ell^2 \le P \quad \forall \ell \in \mathcal{L}, \tag{2a}$$

$$c_{\ell k} \in [0,1] \quad \forall k \in \mathcal{L}_{\ell -}, \ \forall \ell \in \mathcal{L}, \tag{2b}$$

$$\sum_{k \in \mathcal{L}_{\ell -}} c_{\ell k} = 1 \quad \forall \ell \in \mathcal{L}, \tag{2c}$$

$$\frac{H_{\ell k}^2 v_k^2}{\frac{1}{G_{sg}} \sum_{\substack{m=1 \\ m \neq k}}^{L} H_{\ell m}^2 v_m^2 + \sigma_\ell^2} \ge T c_{\ell k} \quad \forall k \in \mathcal{L}_{\ell -} \setminus \{0\}, \ \forall \ell \in \mathcal{L}. \tag{2d}$$

E- WMMSE Problem Formulation cont'd...

- Here

$$e_{\ell m}(u_{\ell m}, c_{\ell m}, \mathbf{v}) = \left(u_{\ell m} H_{\ell\ell} \sqrt{c_{\ell m}} v_\ell - 1\right)^2 + \frac{1}{G_{sg}} \sum_{\substack{k=1 \\ k \neq l,m}}^{L} (u_{\ell m} H_{\ell k} v_k)^2 + \sigma_\ell^2 u_{\ell m}^2, \; \forall m \in \mathcal{L}_{\ell-} \; \forall \ell \in \mathcal{L} \tag{3}$$

- $w_{\ell m} \in \mathcal{R}^+$ and $u_{\ell m} \in \mathcal{R}^1$ - auxiliary variables.
- $\mathbf{u} = \{\{u_{\ell m}\}_{m \in \mathcal{L}_{\ell-}}\}_{\ell \in \mathcal{L}}$, $\mathbf{w} = \{\{w_{\ell m}\}_{m \in \mathcal{L}_{\ell-}}\}_{\ell \in \mathcal{L}}$ and $\mathbf{c} = \{\{c_{\ell m}\}_{m \in \mathcal{L}_{\ell-}}\}_{\ell \in \mathcal{L}}$
- 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

$$f_{wmmse}(\ell) = \sum_{m \in \mathcal{L}_{\ell-}} \left(w_{\ell m}\, e_{\ell m}(u_{\ell m}, c_{\ell m}, \mathbf{v}) - \log w_{\ell m}\right)$$

Equivalence of E-WMMSE formulation and BPPC-IC

- $\frac{\partial f_{wmmse}}{\partial u_{\ell m}} = 0$, $\frac{\partial f_{wmmse}}{\partial w_{\ell m}} = 0 \Rightarrow$

$$\begin{aligned} u^*_{\ell m} &= \frac{H_{\ell\ell}\sqrt{c_{\ell m}}v_\ell}{(H_{\ell\ell}\sqrt{c_{\ell m}}v_\ell)^2 + \frac{1}{G_{sg}}\sum_{\substack{k=1 \\ k\neq \ell,m}}^{L} (H_{\ell k}v_k)^2 + \sigma_\ell^2}, \qquad (4) \\ w^*_{\ell m} &= (e_{\ell m}(u^*_{\ell m}, c_{\ell m}, \mathbf{v}))^{-1} = \left(1 - u^*_{\ell m}H_{\ell\ell}\sqrt{c_{\ell m}}v_\ell\right)^{-1} \end{aligned}$$

$$\begin{aligned} e_{\ell m}(u^*_{\ell m}, c_{\ell m}, \mathbf{v}) &= \left(1 + \frac{H^2_{\ell\ell}v^2_\ell c_{\ell m}}{\frac{1}{G_{sg}}\sum_{\substack{k=1 \\ k\neq l,m}}^{L} H^2_{\ell k}v^2_k + \sigma^2_\ell}\right)^{-1} \\ &= \left(1 - u^*_{\ell m}H_{\ell\ell}\sqrt{c_{\ell m}}v_\ell\right) = (w^*_{\ell m})^{-1} \qquad (5) \end{aligned}$$

- Substituting (4) and (5) into (3) and Π_3, we get the BPPC-IC problem

Block Coordinate Descent: v-update

- Treating **w**, **u** and **c** as constants in Π_3, we get

$$\Pi_5 \qquad \min_{\mathbf{v}} \sum_{\ell=1}^{L} D_\ell^{(t)} \sum_{m \in \mathcal{L}_{\ell-}} \left(w_{\ell m}^* e_{\ell m}(u_{\ell m}^*, c_{\ell m}, \mathbf{v}) \right)$$

$$\text{s.t.} \quad v_\ell^2 \leq P \quad \forall \ell \in \mathcal{L}, \tag{6a}$$

$$\frac{G_{\ell k} v_k^2}{\frac{1}{G_{sg}} \sum_{j \neq k, j=1}^{L} G_{\ell j} v_j^2 + \sigma_\ell^2} \geq T c_{\ell k} \quad \forall k \in \mathcal{L}_{\ell -}, \forall \ell \in \mathcal{L}. \tag{6b}$$

- Π_5 - non-convex formulation ((6b) - non-convex in **v**)
- But $e_{\ell m}(u_{\ell m}^*, c_{\ell m}, \mathbf{v})$ and constraints - functions of $\{v_\ell^2\}_{\ell \in \mathcal{L}}$
- Hence can introduce restriction $v_\ell \geq 0, \forall \ell \in \mathcal{L}$

v-update cont'd.

$$\Pi_6 \qquad \min_{\mathbf{v}} \sum_{\ell=1}^{L} D_\ell^{(t)} \sum_{m \in \mathcal{L}_{\ell-}} w_{\ell m} e_{\ell m}(u^*_{\ell m}, c_{\ell m}, \mathbf{v})$$

$$\text{s.t.} \quad v_\ell^2 \leq P \quad \forall \ell \in \mathcal{L}, \tag{7a}$$

$$v_\ell \geq 0 \quad \forall \ell \in \mathcal{L}, \tag{7b}$$

$$\|\mathbf{v}_{\mathbf{t}}^{\ell \mathbf{k}}\| \leq \left(\sqrt{G_{\ell k} + \frac{T G_{\ell k} c_{\ell k}}{G_{sg}}}\right) v_k \quad \forall k \in \mathcal{L}_{\ell -} \ \forall \ell \in \mathcal{L}. \tag{7c}$$

where $\mathbf{v}_{\mathbf{t}}^{\ell \mathbf{k}} = \left[\{ \sqrt{\frac{G_{\ell m} T c_{\ell k}}{G_{sg}}} v_m \}_{m \in \mathcal{L}}, \ \sqrt{\sigma_\ell^2 T c_{\ell k}} \right]^T$

- Π_6 is convex in $\mathbf{v}$ - quadratic obj. with cone constraints.

Block Coordinate Descent: c-update

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

Π_7

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

$$\text{s.t.} \quad c_{\ell m} \in [0,1] \quad \forall m \in \mathcal{L}_{\ell-} \quad \forall \ell \in \mathcal{L}, \tag{8a}$$

$$\sum_{m\in\mathcal{L}_{\ell-}} c_{\ell m} = 1 \quad \forall \ell \in \mathcal{L}, \tag{8b}$$

$$c_{\ell k} \leq \frac{1}{T}\frac{G_{\ell k}p_k}{\frac{1}{G_{sg}}\sum_{j\neq k, j=1}^{L} G_{\ell j}p_j + \sigma_\ell^2}, \quad \forall k \in \mathcal{L}_{\ell-}, \forall \ell \in \mathcal{L}. \tag{8c}$$

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

$$c^*_{\ell 0} = \left[\frac{1}{\mu^*_\ell} - \frac{1}{\gamma_{\ell 0}}\right]_0^1, \forall \ell \in \mathcal{L} \tag{9}$$

$$c^*_{\ell m} = \left[\frac{1}{\mu^*_\ell} - \frac{1}{\gamma_{\ell m}}\right]_0^{\min\left(\frac{\Gamma_{\ell m}}{T},1\right)}, \forall m \in \mathcal{L}_{\ell -}, \; \forall \ell \in \mathcal{L} \tag{10}$$

- where μ^*_ℓ can be found using bisection to ensure that $\sum_{m\in_{\ell -}} c^*_{\ell m} = \min\left(1, \sum_{m\in_{\ell -}\setminus\{0\}} \min\left(\frac{\Gamma_{\ell m}}{T}, 1\right)\right)$

E-WMMSE Algorithm

1. *Initialization* - For each time slot t, calculate the differential backlogs, reset iteration counter $n = 1$, and set $v_\ell^{(n)} = \sqrt{P}$, $\forall \ell \in \mathcal{L}$, $c_{\ell 0}^{(n)} = 1$, $c_{\ell m}^{(n)} = 0\ \forall m \in \mathcal{L}_{\ell -}$, $\forall \ell \in \mathcal{L}$.
2. repeat
3. **u**-*update and* **w**-*update* - using (4)
4. **v**-*update* - Solve Π_6 to obtain the updated $\{p_\ell\}_{\ell \in \mathcal{L}}$.
5. **c**-*update* - Solve Π_7 to obtain the updated $\{\{c_{\ell m}\}_{m \in \mathcal{L}_{\ell -}}\}_{\ell \in \mathcal{L}}$.
6. n = n+1
7. until $|\log(w_{\ell m}^{(n)}) - \log(w_{\ell m}^{(n-1)})| \leq \epsilon$, $\forall m \in \mathcal{L}_{\ell -}$, $\forall \ell \in \mathcal{L}$.

Simulation Results

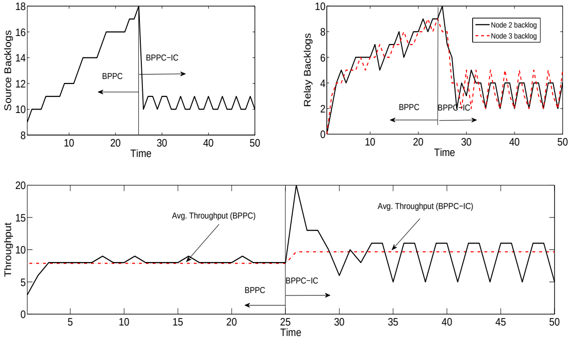
- Channel: path-loss only, $G_{ij} = d_{ij}^{-\alpha}$, d_{ij} - distance between node $Rx(i)$ and node $Tx(j)$, α - path-loss exponent
- Deterministic periodic input traffic λ pkts/slot into source node at the beginning of each time slot.

Table : Simulation Parameters

Symbol	Description	Value
N	Number of nodes	4 / 5
P	Max. power per link	5 W
V	Noise variance	10^{-12} W
G_{sg}	Spreading / Beam-forming gain	128
T	SINR threshold for decoding	1000(30 dB)
ε	Tolerance parameter	0.1

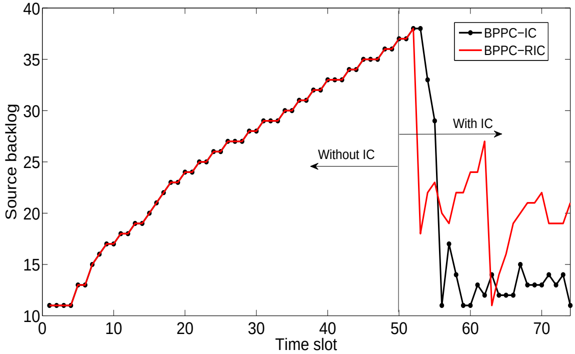
- Performance Metrics: throughput, backlogs (delays)

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.

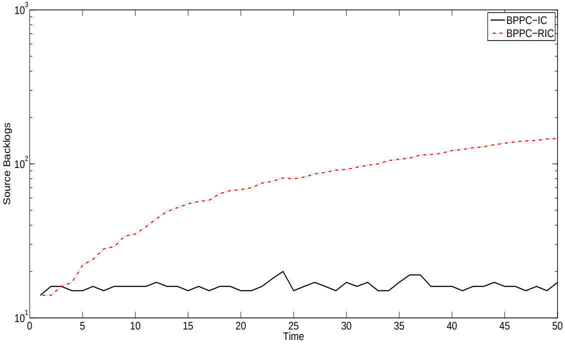
Max. Stable-Throughput Comparison

Table : Maximum Stable-Throughput

IC policy	4-node network	5-node network
BPPC	7	8
BPPC-RIC	9	12
BPPC-IC	10	14

- 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
- $\exists$ simple randomized back-pressure policy attaining max stable throughput for finite control spaces
- $\nexists$ 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?