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Information Theory and Communications

Harnessing Interaction in Bursty Interference Networks

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Modern Wireless: Grand Challenges

- Global mobile data traffic is expected to increase nearly 11-fold from 2013 – 2018 (source: Cisco VNI mobile forecast)

- What drives this increase?
  - Growing # of users
  - Data-hungrier (smarter) mobile devices

- Grand challenges:

Support higher data rate

Accommodate more users

Increase spectral efficiency

More Users + Growing Demand

⟹ more **interference** along with **intermittence**

Toy example: people talking in a crowded room

Also, more chances for **interaction**

Interference vs. Intermittence

- Interference:
  - Born-nature of wireless medium
  - Limits the throughput of modern wireless networks

- Intermittence:
  - Lack of coordination across distributed terminals
  - Born-nature of data traffic
  - Not a critical issue if users do not interfere with one another

- Major bottleneck: interference

Modern View on Interference

- Traditional techniques: orthogonalization (2G), treating interference as noise (3G, 4G)
- Recent advances in network information theory shed light on how to break the interference barrier:
- Two-user IC: approximate capacity to within 1 bit/s/Hz
  - Partial interference cancellation [Etkin et al IT08]
- K-user IC: total # of degrees of freedom = $K/2$
  - Interference alignment [Maddah-Ali et al IT08] [Cadambe & Jafar IT08]

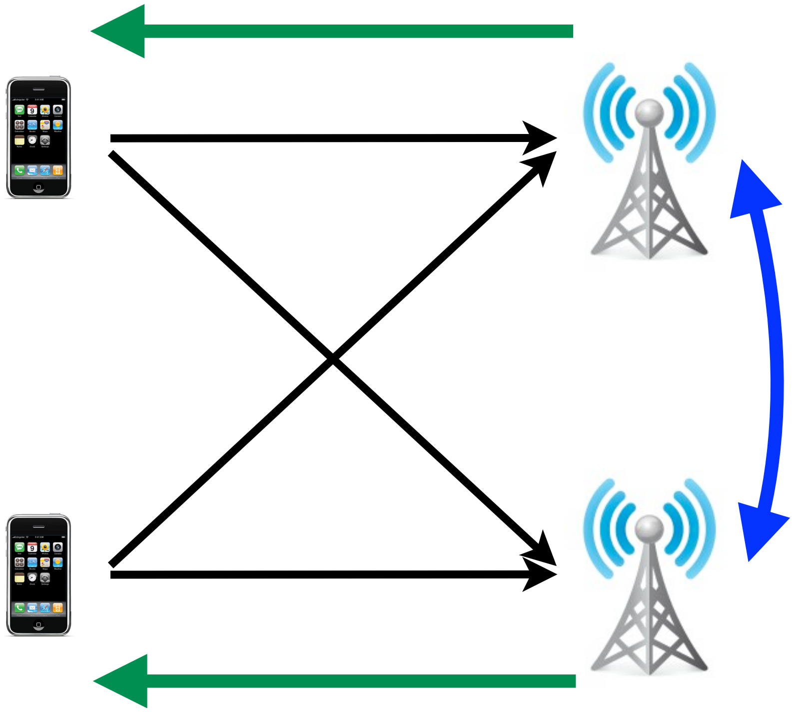
Caveat:

(in most information theoretic literature)

Assume that interference is always present

Interaction Helps Manage Interference

- Cooperation among Tx/Rx terminals
  - Cloud RAN, cooperative MIMO, etc.
  - Capacity increase is bounded by the cooperation capacity [W & Tse IT11]
- Feedback from Rx to Tx
  - With *perfect* output feedback, capacity increase is multiplicative [Suh & Tse IT11]



- However, interaction cannot increase the total **multiplexing gain** (degrees of freedom) [Cadambe & Jafar IT09]

Caveat:

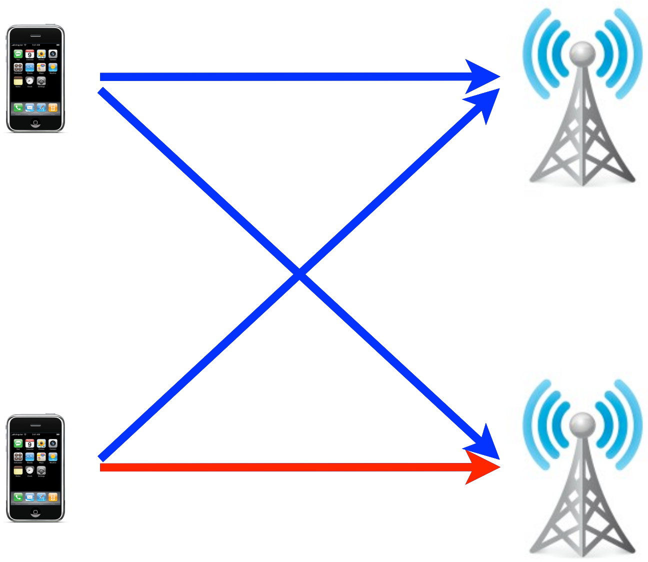
(in most information theoretic literature)

Assume that interference is always present

Interference can be Intermittent

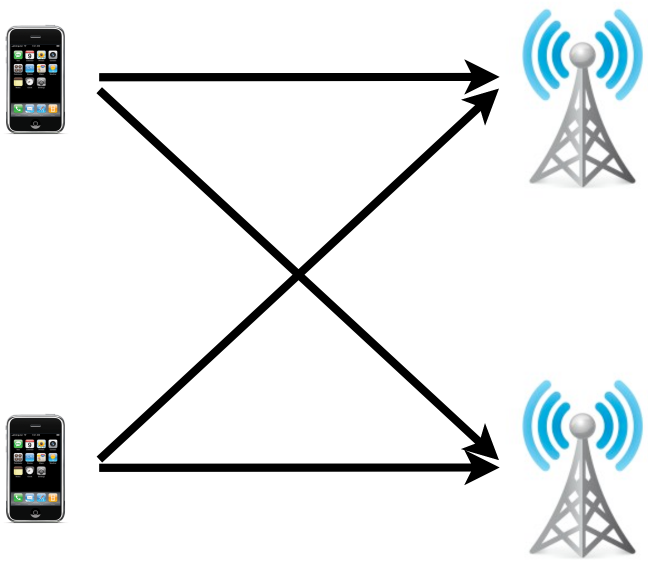
- At PHY, interference may not be always present
- Medium access control mechanism
  - Decentralized resource allocation

	Time 1	Time 2	Time 3
User 1	f_1	f_1	f_1
User 2	f_1	f_2	f_1



- Network layer protocol/demand
  - Bursty network traffic

	Time 1	Time 2	Time 3
User 1	On	Off	On
User 2	Off	On	On



Exploit Intermittence of Interference

- Naive idea: send more when there is no interference

  $\Longrightarrow$ but may not know *if* there is interference *beforehand*

- Not completely hopeless:

  $\Longrightarrow$ we may have *delayed* information about the presence of interference, thanks to **interaction** (feedback/cooperation)

- If interferer's activity can be predicted from the past, then obviously such delayed information can help
- If not (in the extreme case when coherence time = 1 symbol time), it seems such delayed information will not help

Two Major Questions

- Question 1:

  In bursty/intermittent environment, does delayed state information help mitigate interference?

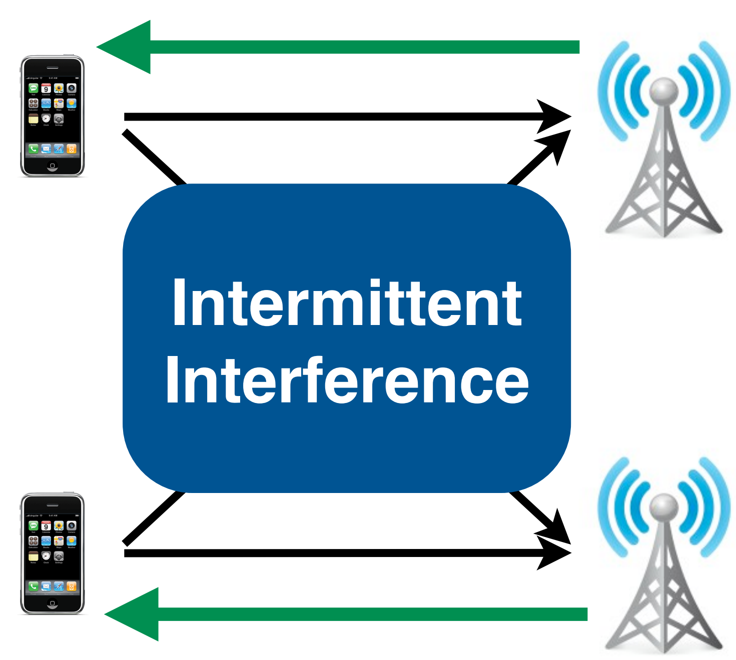
- Question 2:

  In bursty/intermittent environment, does interaction play a more important role in interference management, compared with the static one?

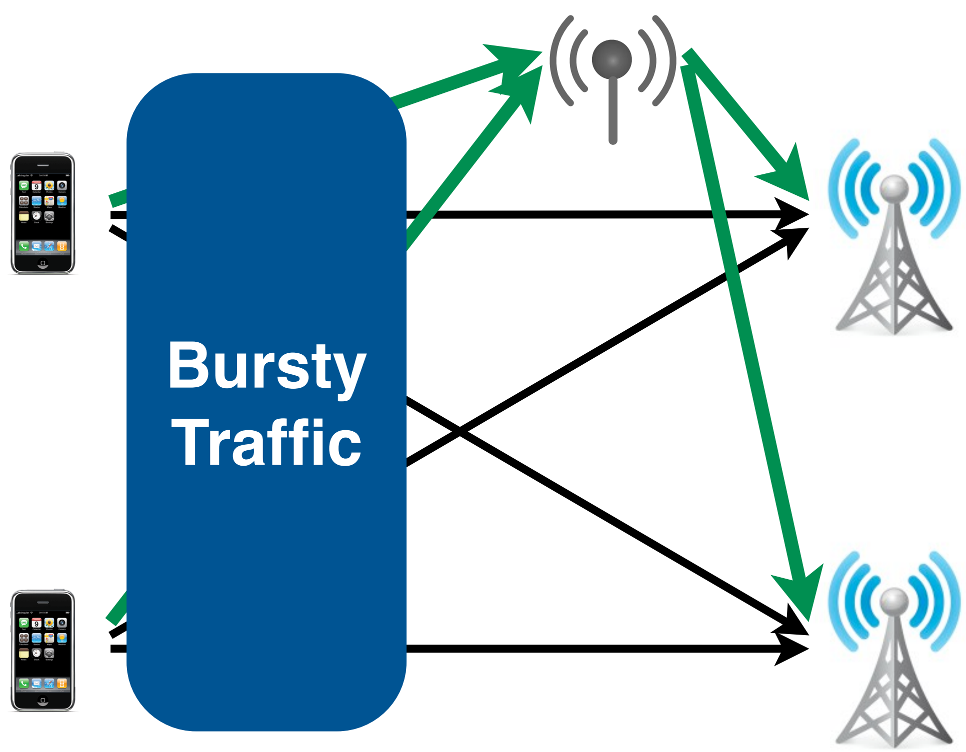
- Both answers are YES.

Two Case Studies in this Talk

Bursty Interference Channel with Feedback



Bursty Interference Channel with a Relay



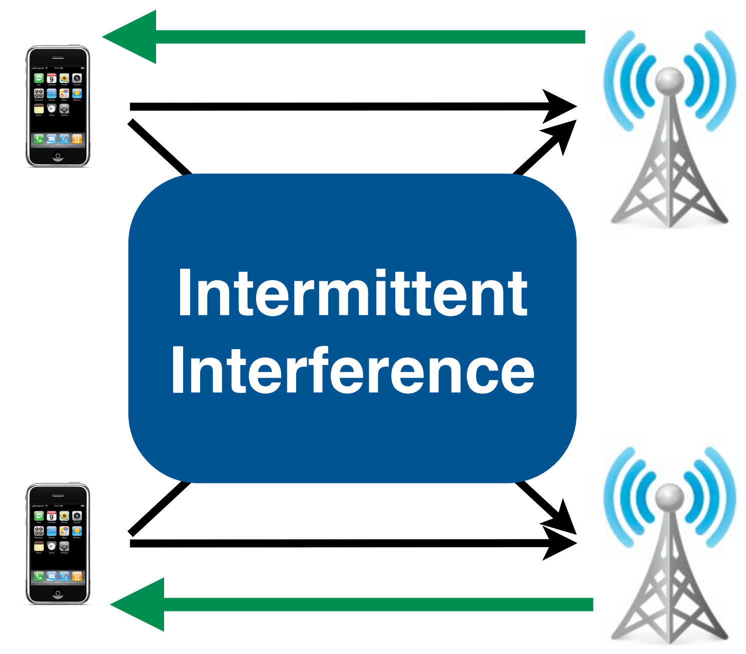
With delayed state information, in both cases

interaction increases the **multiplexing gain**

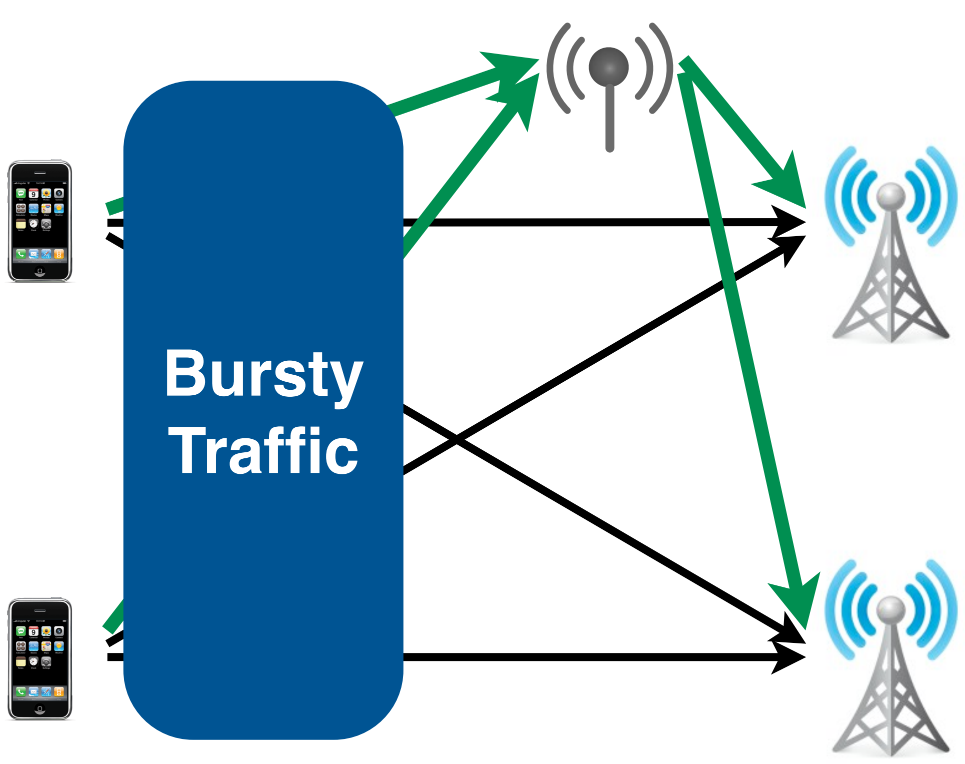
degrees of freedom (DoF)

Major Findings and Contributions

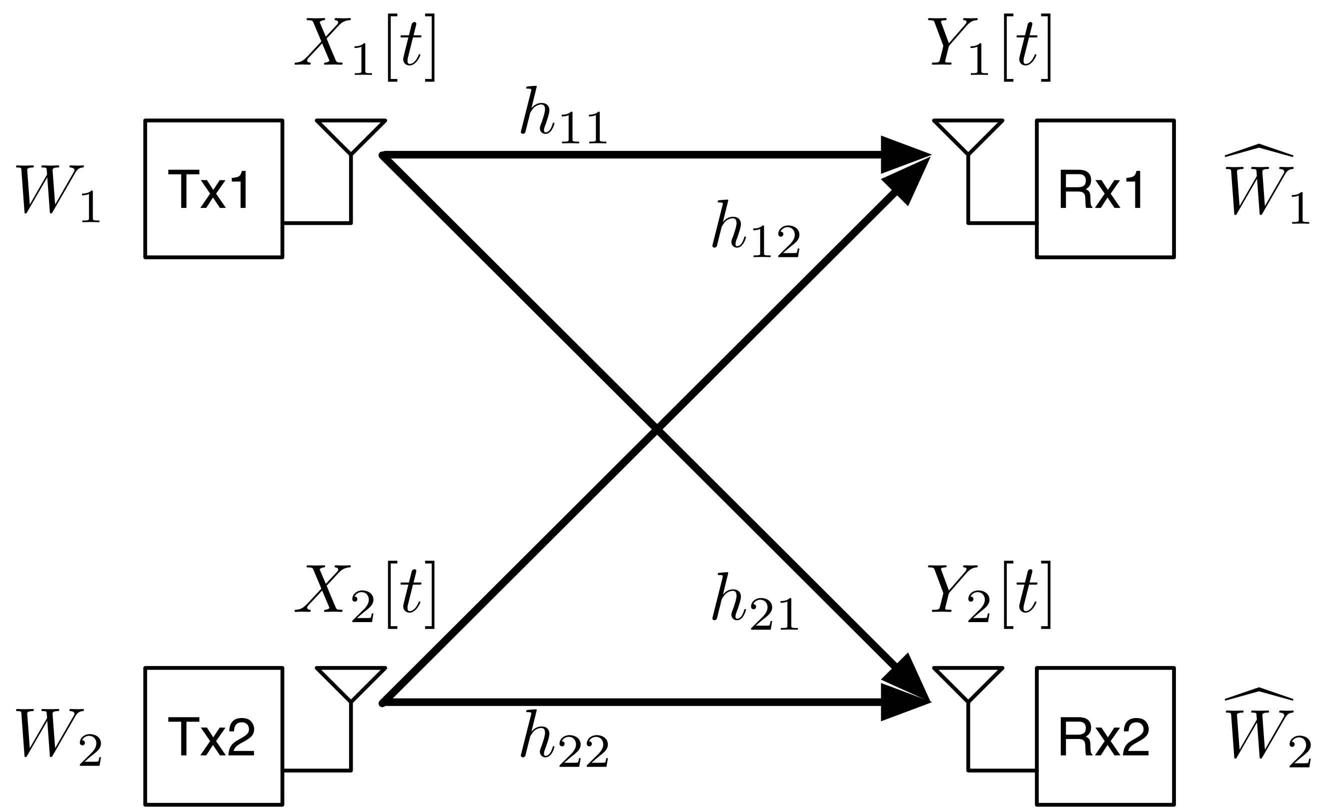
- Bursty IC with feedback:
  - One-bit feedback increases DoF
  - Characterize the approximate capacity
  - An adaptive coding scheme
  - Novel outer bounds



- Bursty (MIMO) IC with a relay:
  - In-band cooperation increases DoF
  - DoF increase linearly with the # of relay antennas
  - Derive conditions for interference-free DoF performances



Gaussian Interference Channel

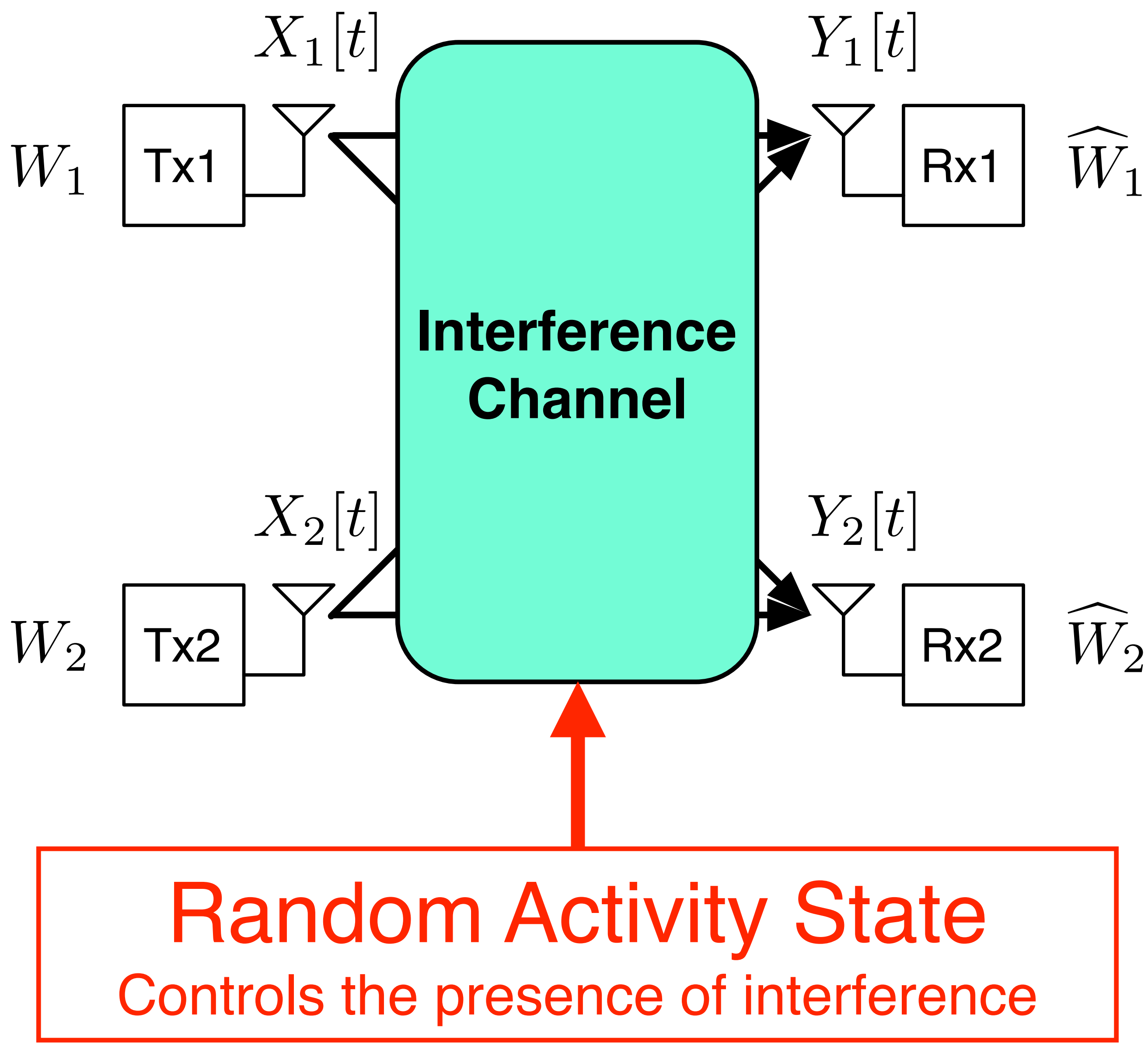


Unit power constraint

$\mathcal{CN}(0,1)$

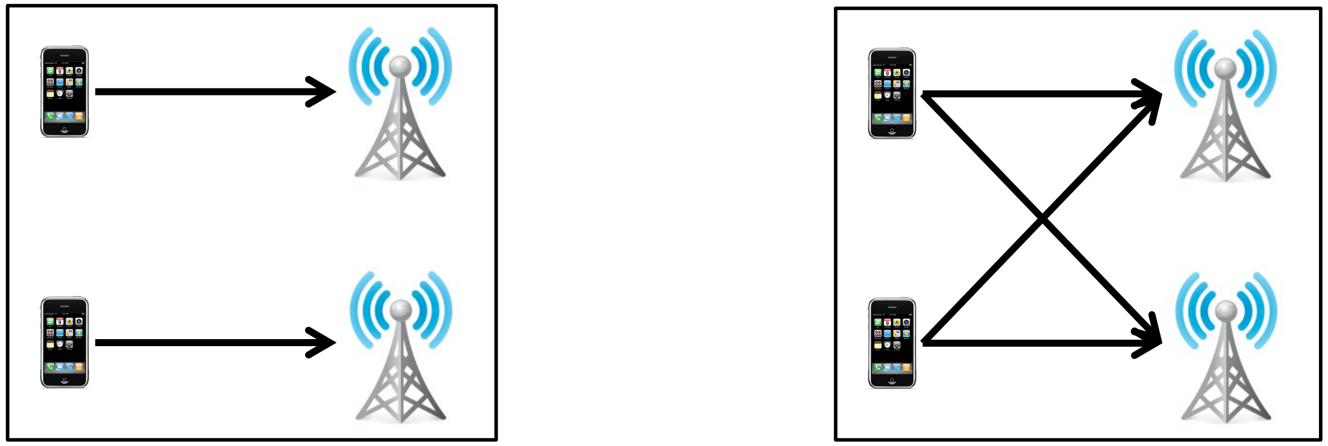
$$Y_1[t] = h_{11}X_1[t] + h_{12}X_2[t] + Z_1[t]$$
$$Y_2[t] = h_{22}X_2[t] + h_{21}X_1[t] + Z_2[t]$$

Modeling Burstiness/Intermittence

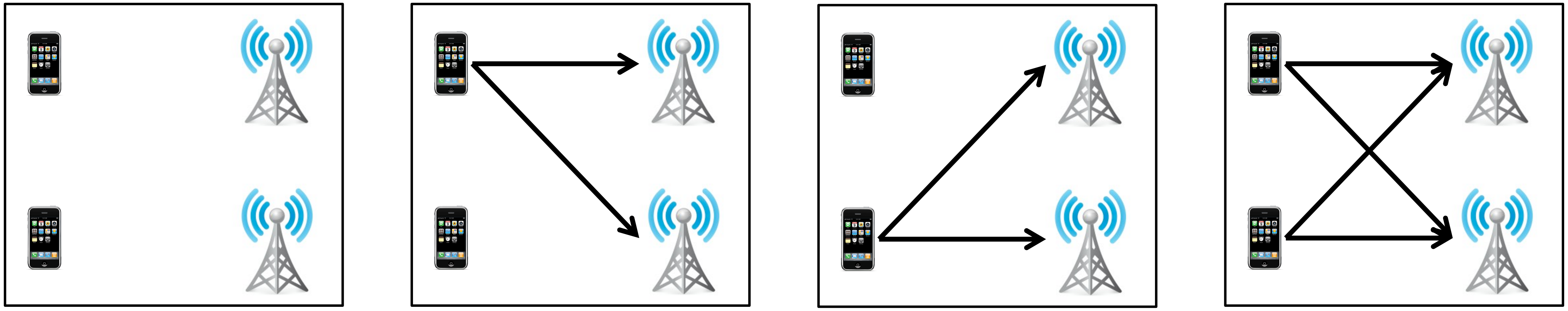


Bursty Interference Channel: Two Models

- Intermittent Interference: motivated by the MAC layer

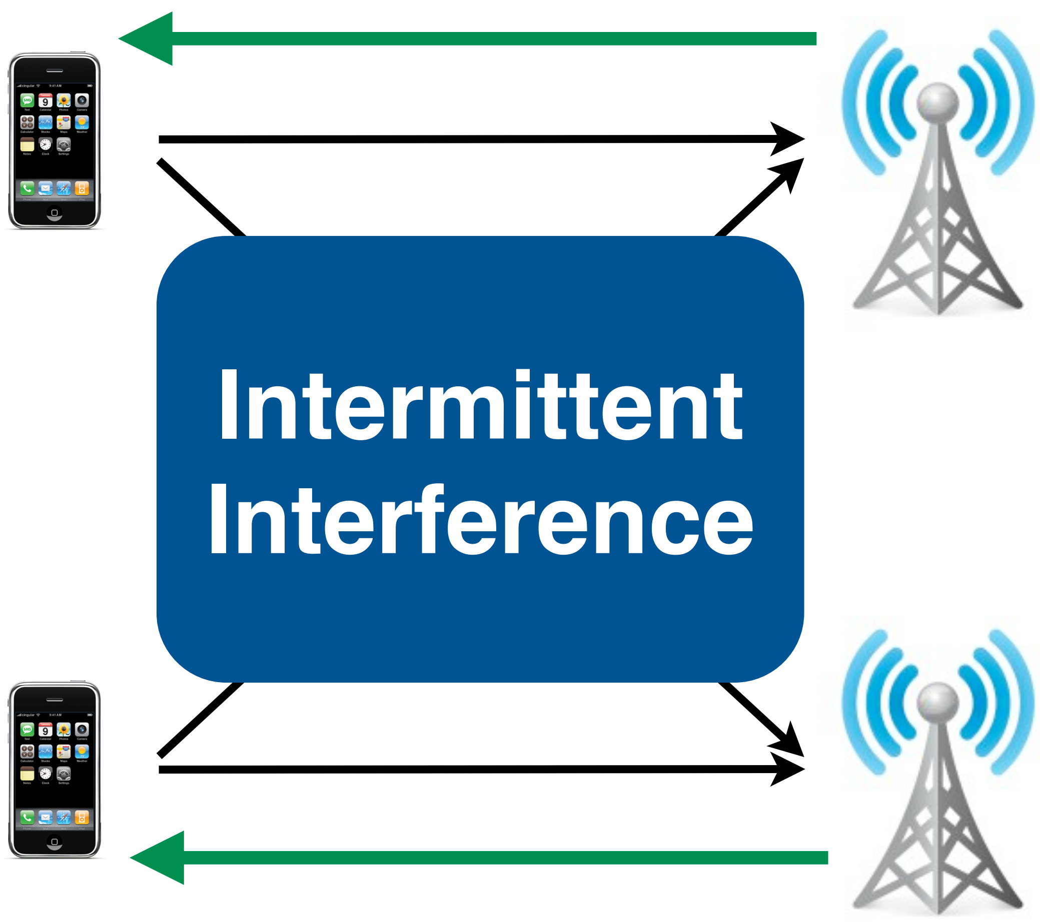


- Bursty Traffic: motivated by the Network layer

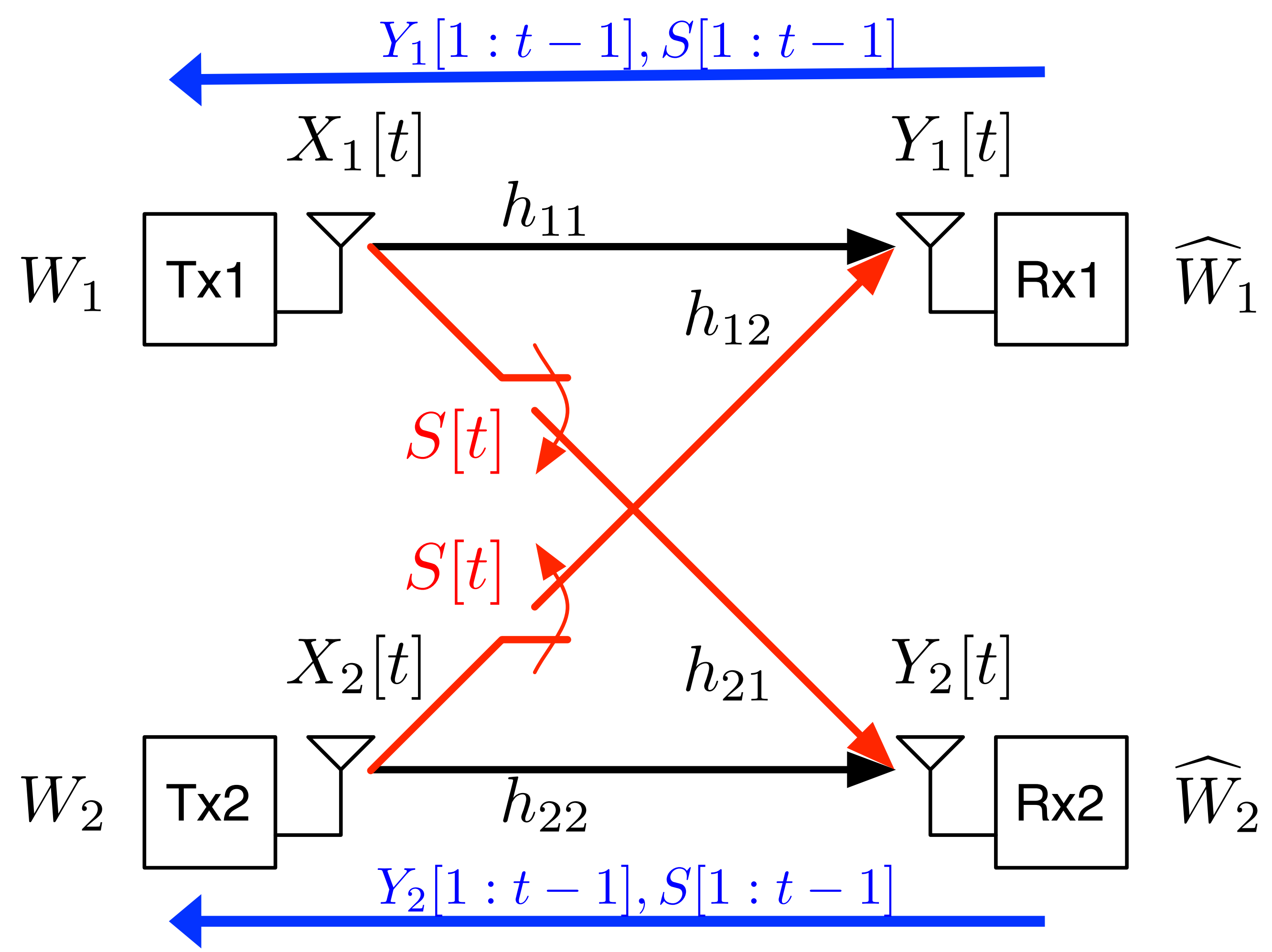


Part I: Bursty Interference Channel with Feedback

Joint work with S. Diggavi, C. Suh, P. Viswanath



Model



$\{S[t]\}$: i.i.d. Bernoulli $\mathrm{Ber}(p)$ process

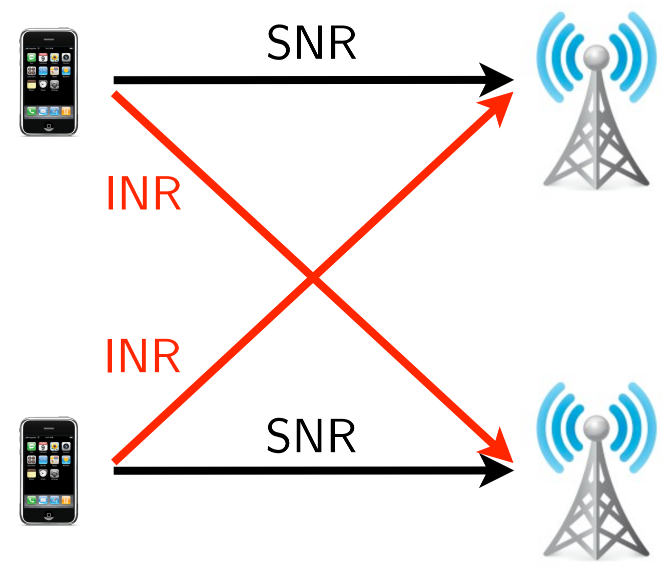
$$Y_1[t] = h_{11}X_1[t] + h_{12}\left(\boxed{S[t]}X_2[t]\right) + Z_1[t]$$
$$Y_2[t] = h_{22}X_2[t] + h_{21}\left(\boxed{S[t]}X_1[t]\right) + Z_2[t]$$

Encoding: $X_i[t] \stackrel{\mathrm{f}}{=} (W_i, Y_i[1:t-1], S[1:t-1])$

Generalized Degrees of Freedom

- For better illustration, let us focus on the symmetric setting:

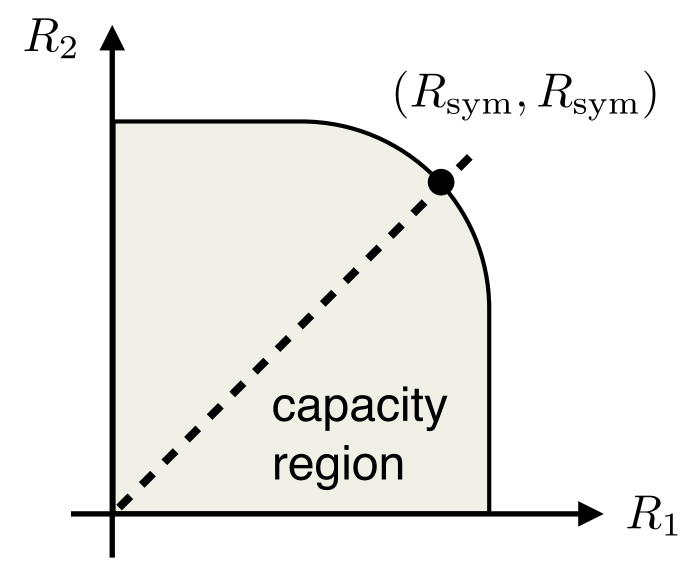
$$|h_{11}|^2 = |h_{22}|^2 = \text{SNR}, \ |h_{21}|^2 = |h_{12}|^2 = \text{INR}$$



- Generalized degrees of freedom:

$$d := \frac{\text{Achievable Rate under Interference}}{\text{Interference Free Capacity}}$$

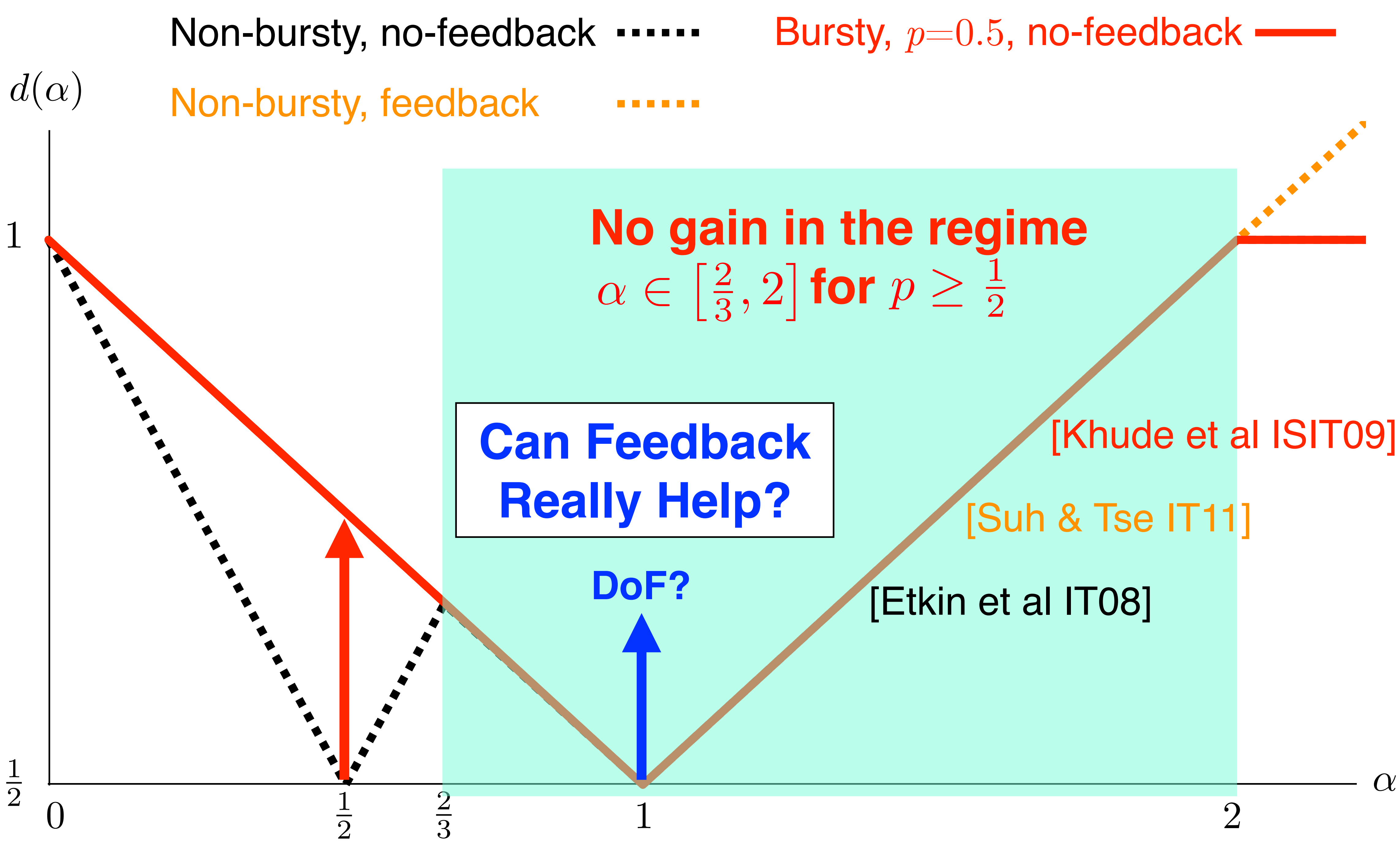
$$d(\alpha) = \lim_{\text{SNR}\to\infty} \frac{R_{\text{sym}}}{\log \text{SNR}}, \ \text{with fixed } \alpha := \frac{\log \text{INR}}{\log \text{SNR}}$$



- GDoF: a function of
  - strength of interference α
  - probability of interference p

Gain in GDoF
$\Longrightarrow$ multiplicative gain in capacity

Baseline



Non-bursty, no-feedback
Bursty, $p=0.5$, no-feedback
Non-bursty, feedback
$d(\alpha)$
1
No gain in the regime
$\alpha \in \left[\frac{2}{3}, 2\right]$ for $p \geq \frac{1}{2}$
Can Feedback Really Help?
[Khude et al ISIT09]
[Suh & Tse IT11]
DoF?
[Etkin et al IT08]
$\frac{1}{2}$
0
$\frac{1}{2}$
$\frac{2}{3}$
1
2
α

In the regime $\alpha \in \left[\frac{2}{3}, 2\right]$

(moderate to strong interference)

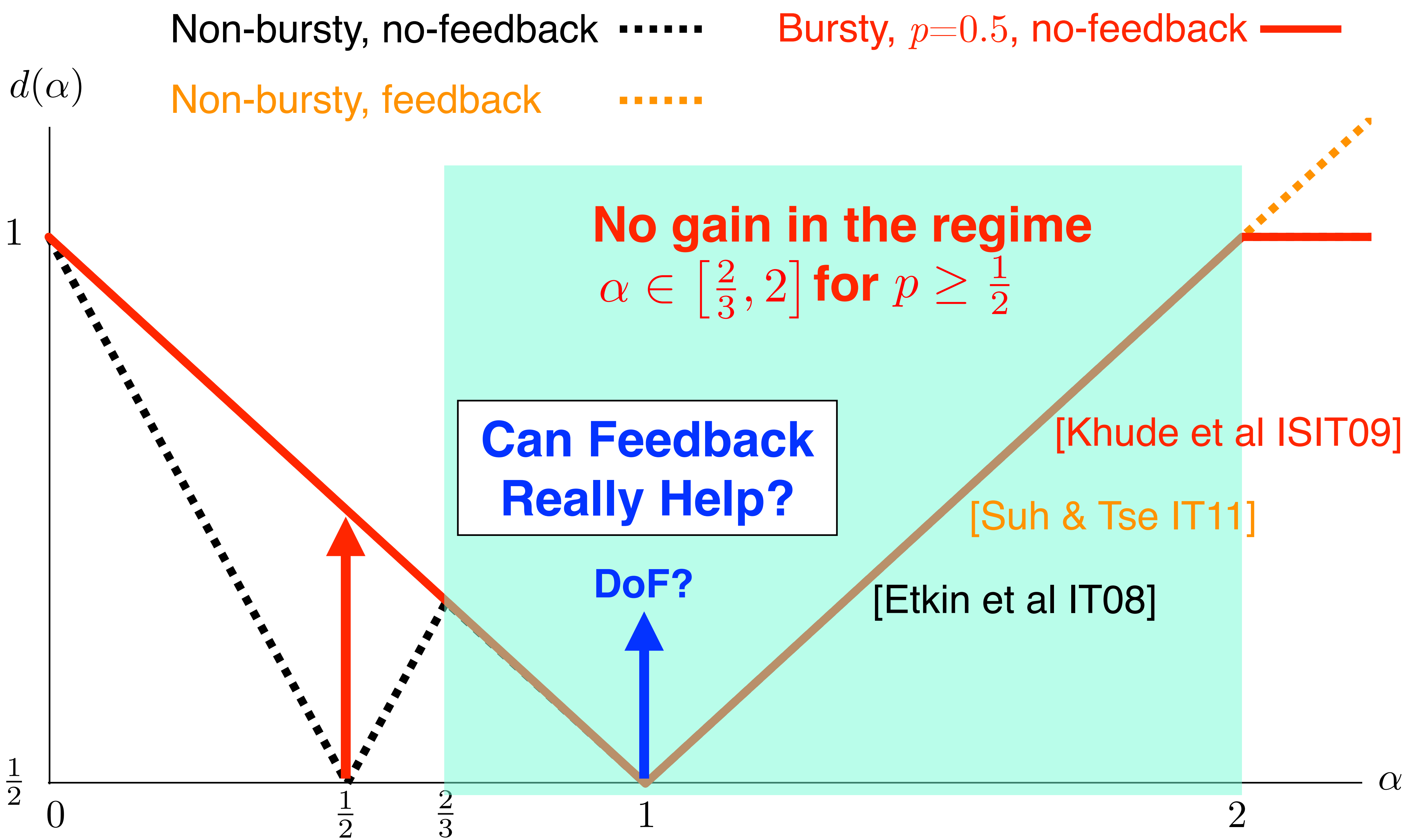
Feedback in non-bursty case

No gain in GDoF and DoF

Exploiting intermittence without feedback

No gain in GDoF and DoF

Baseline



Non-bursty, no-feedback
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$d(\alpha)$
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No gain in the regime
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Can Feedback Really Help?
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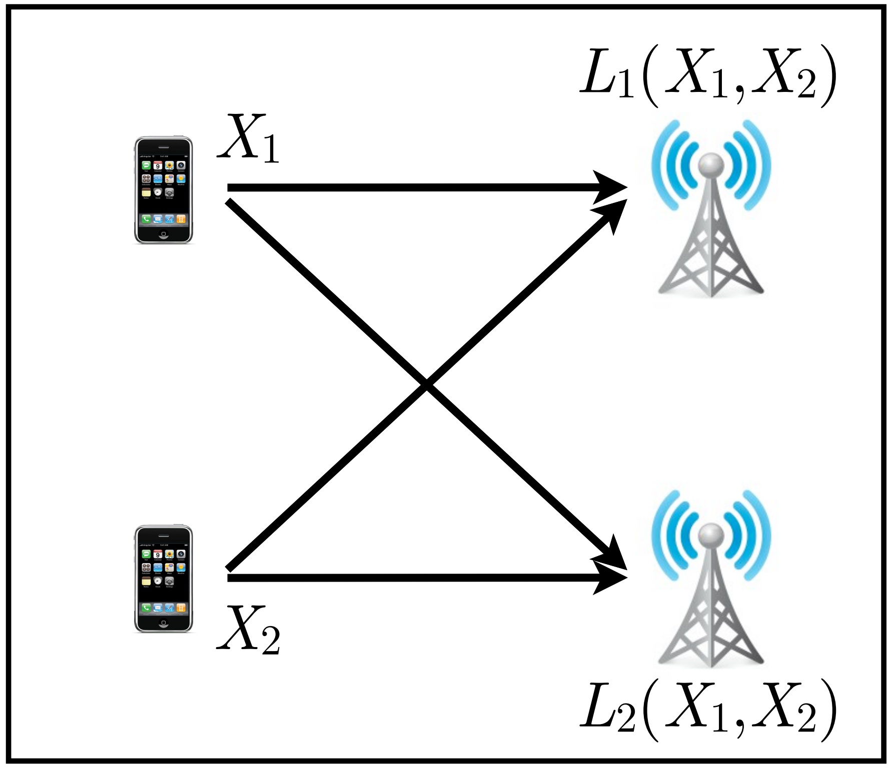
DoF?
[Etkin et al IT08]
$\frac{1}{2}$
0
$\frac{1}{2}$
$\frac{2}{3}$
1
2
α

One-Bit Feedback Increases DoF

Phase **F**resh

Transmit as if there is no interference

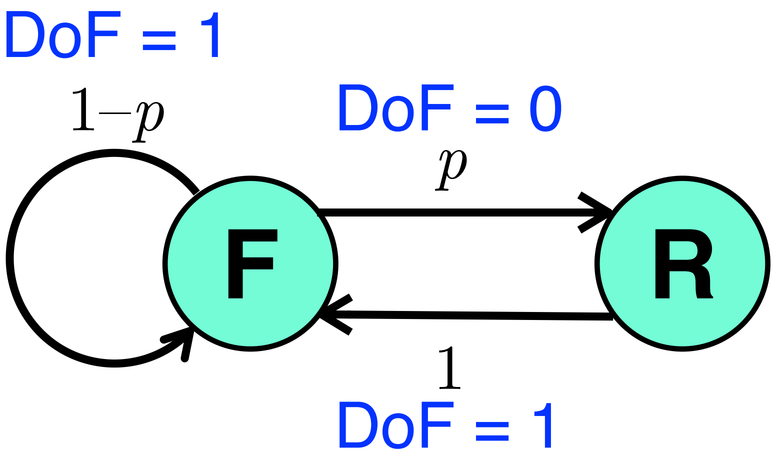
State	Rx Operation	Tx Operation
No interference	Both Decode	Stay in Phase **F**
Interference	Hold	Jump to Phase **R**



Phase **R**etransmit

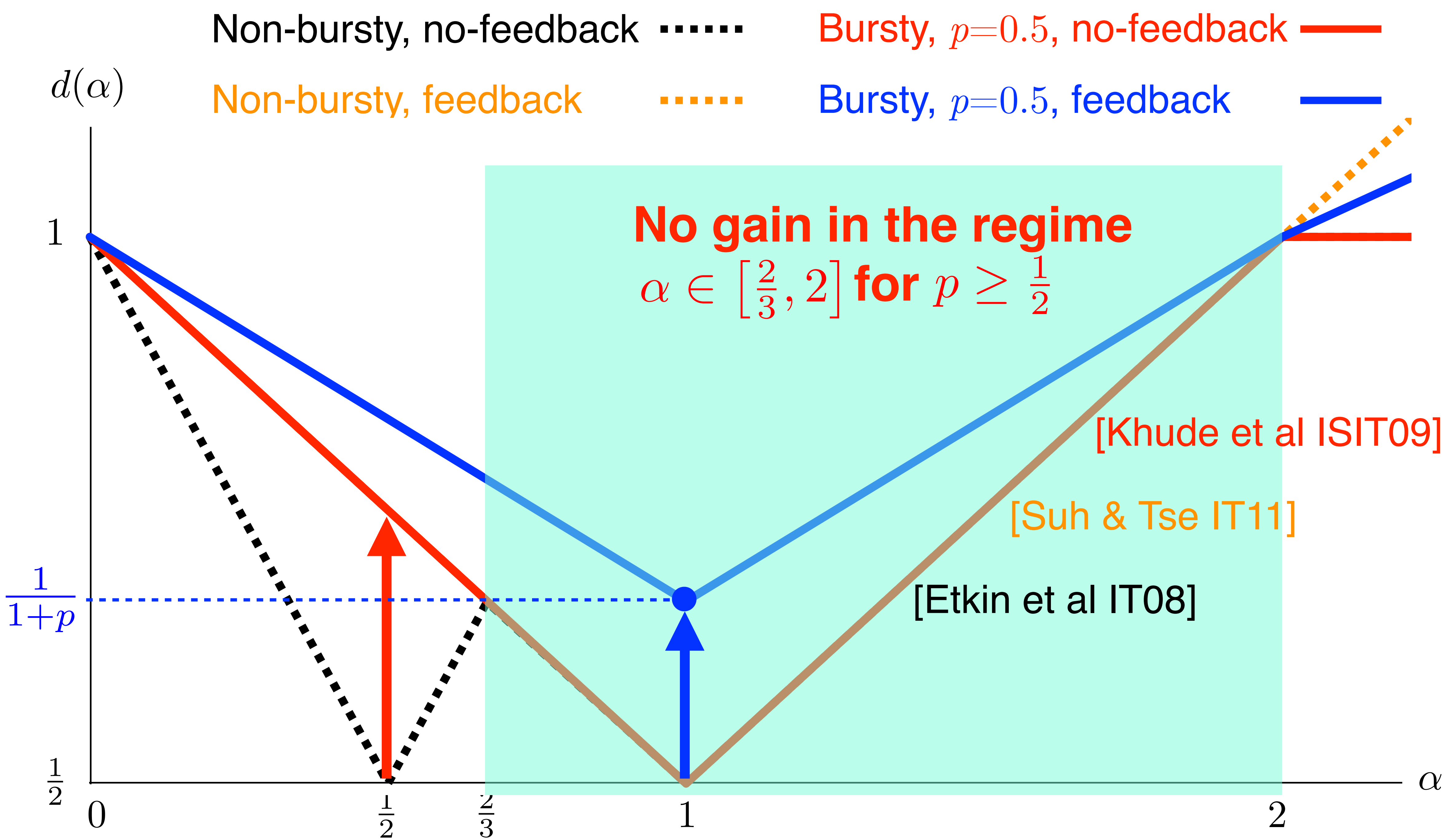
Retransmit the unresolved symbol

State	Rx Operation	Tx Operation
No interference	Both Decode	Back to Phase **F**
Interference	Both Decode (exploit side info.)	Back to Phase **F**



Stationary Distribution: $\pi\,(\mathrm{F}) = \frac{1}{1+p},\ \pi\,(\mathrm{R}) = \frac{p}{1+p} \implies \mathrm{DoF} = \frac{1}{1+p}$

Synergetic Benefit of Feedback



Harnessing Output Feedback

- Weak interference regime

  Analog interference refinement

- Strong interference regime

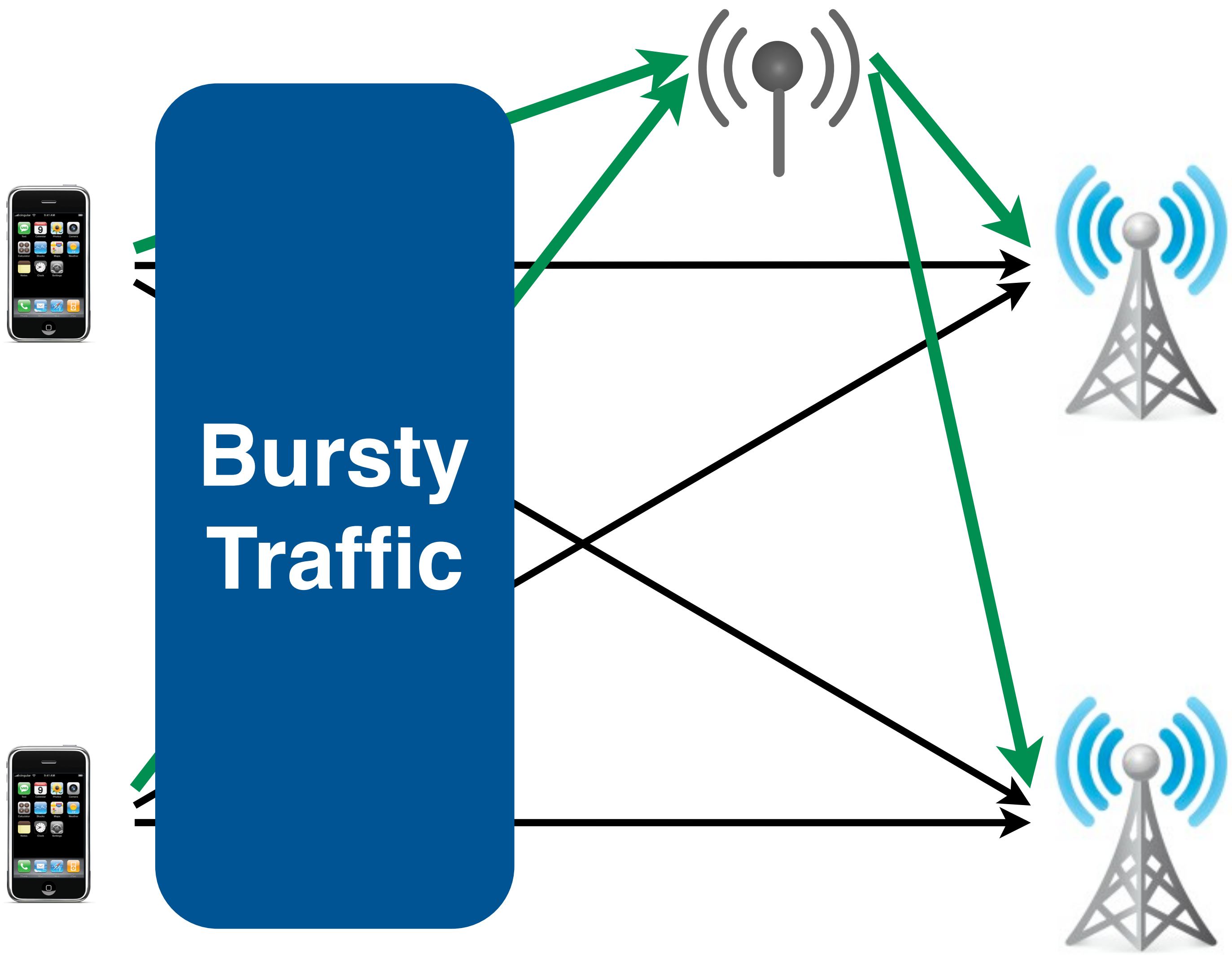
  Interference refinement with structured codes

- Very strong interference regime

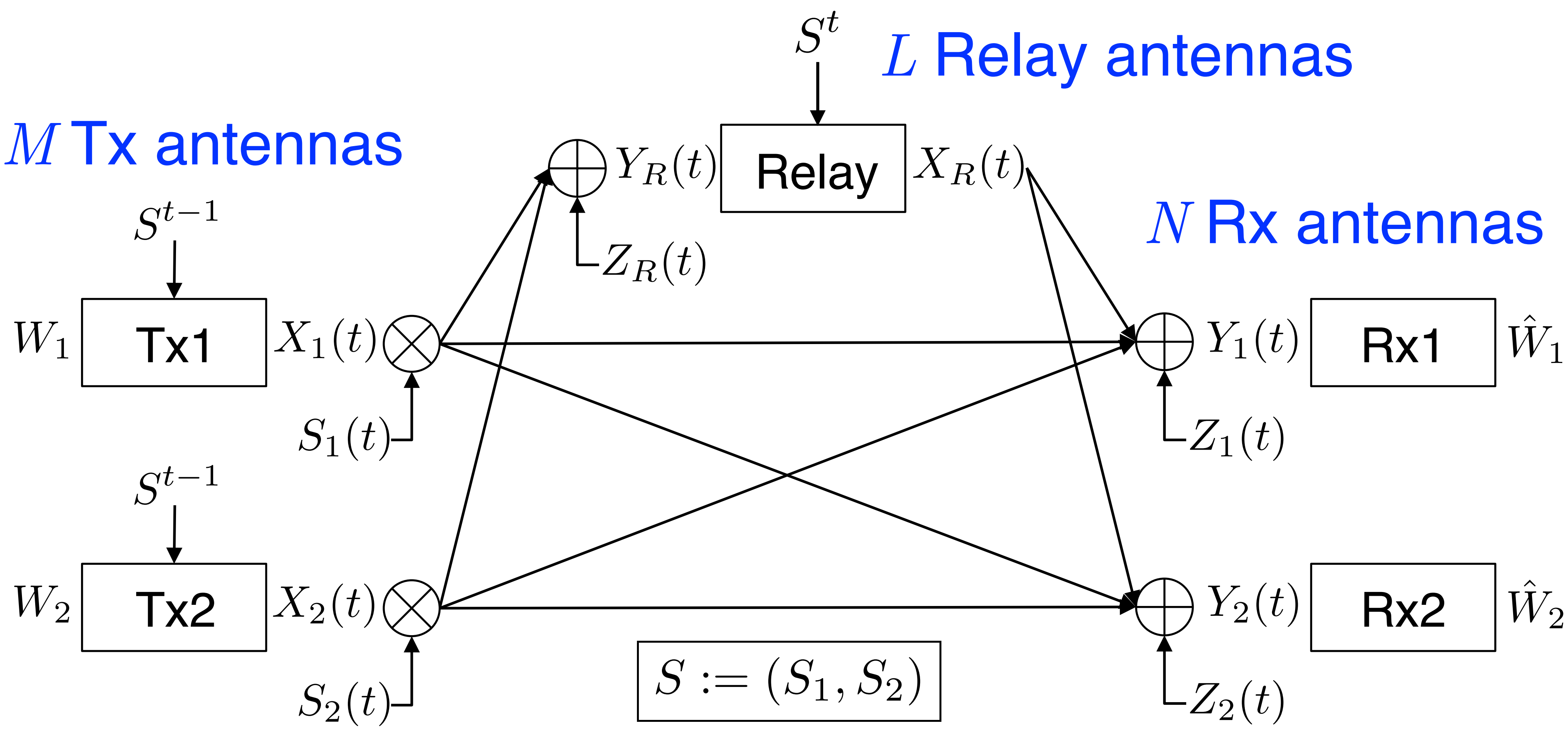
  Opportunistic relaying with structured codes

Part II: Bursty Interference Channel with a Relay

Joint work with S. Kim, C. Suh



Model

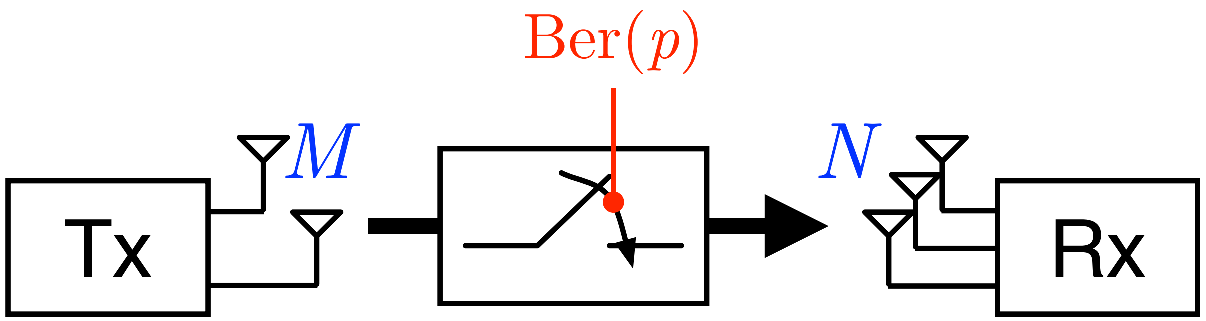


$$Y_1(t) = \mathbf{H}_{11}\left(S_1(t)X_1(t)\right) + \mathbf{H}_{12}\left(S_2(t)X_2(t)\right) + \mathbf{H}_{1R}X_R + Z_1,$$
$$Y_2(t) = \mathbf{H}_{21}\left(S_1(t)X_1(t)\right) + \mathbf{H}_{22}\left(S_2(t)X_2(t)\right) + \mathbf{H}_{2R}X_R + Z_2,$$
$$Y_R(t) = \mathbf{H}_{R1}\left(S_1(t)X_1(t)\right) + \mathbf{H}_{R2}\left(S_2(t)X_2(t)\right) + Z_R.$$

$\{S_1[t]\} \perp\!\!\!\perp \{S_2[t]\}$: i.i.d. Bernoulli $\mathrm{Ber}(p)$ processes

In-Band Relay Increases DoF

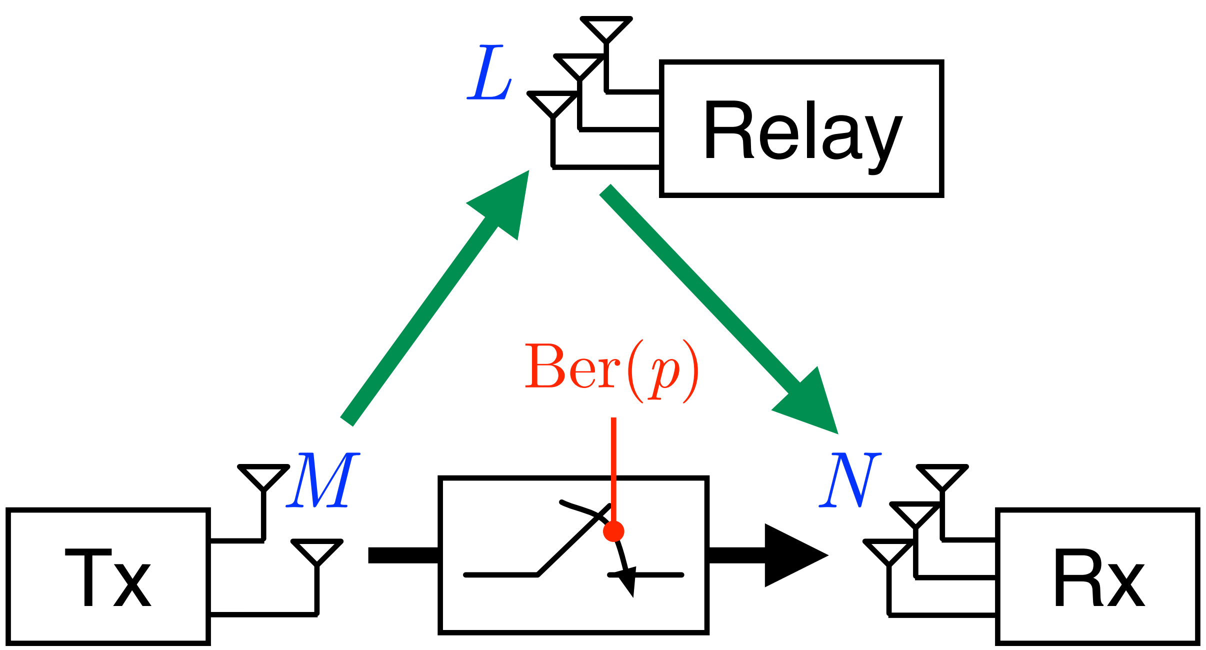
Bursty P2P



$$d = p \min(M, N)$$

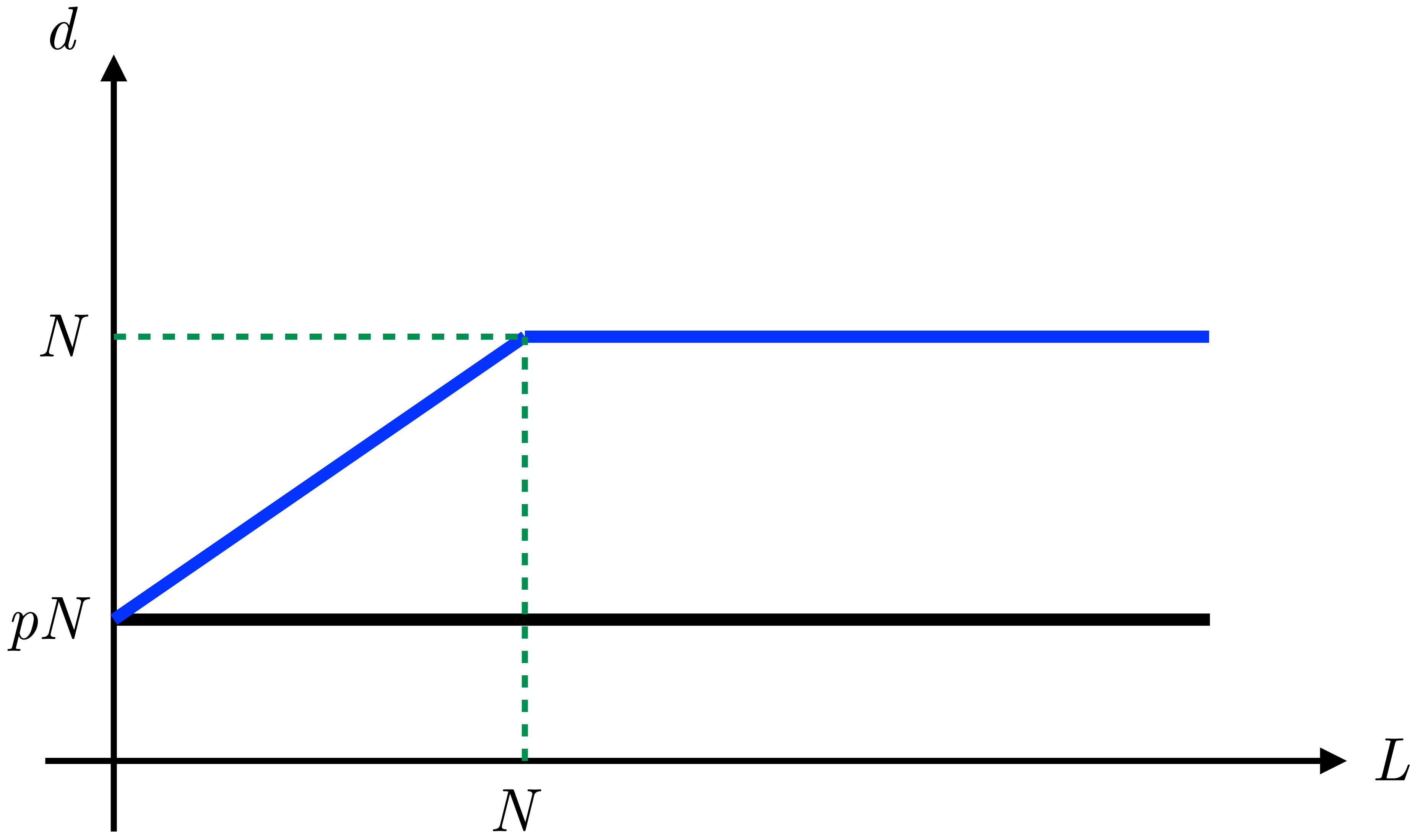
$= pN$ for M sufficiently large

Adding a relay



$$d = \min\{p \min(M, N+L), p \min(M+L, N) + (1-p)\min(L, N)\}$$

$= pN + \min\{pL, (1-p)\min(L, N)\}$ for M sufficiently large



- DoF increase is linear in L, # of relay antennas

- DoF is boost by up to p^{-1} times

Interference-Free Communication

- For two-user bursty interference channel with a relay, main focus is on getting interference-free DoF $\forall p \in [0,1)$

- Sufficient condition

$$2M \leq N$$

or

$$M \geq 2N + L \text{ and } L \geq 2N$$

or

$$M \geq 2N + L \text{ and } 3L \leq N$$

Necessary condition

$$2M \leq N$$

or

$$M \geq 2N + L \text{ and } L \geq 2N$$

or

$$M \geq 2N \text{ and } 3L \leq N$$

Cooperative Zero-Forcing

4	3	2	1	t	1	2	3	4
sent					received			
a_5+b_5	a_1+b_1	a_1+b_1	0	Relay	a_1+b_1	b_5	a_5	0

$L=1$

4	3	2	1		
a_9	a_5	a_5	a_1	Tx 1	
a_{10}	a_6	a_6	a_2		
a_{11}	a_7	a_7	a_3		
a_{12}	a_8	a_8	a_4		
a_9	a_5	a_5	a_1		
0	a_1	a_1	0		
0	0	0	0		
sent					
b_9	b_9	b_5	b_1	Tx 2	
b_9	b_9	b_5	b_1		
0	0	b_1	0		
0	0	0	0		
b_{10}	b_{10}	b_6	b_2		
b_{11}	b_{11}	b_7	b_3		
b_{12}	b_{12}	b_8	b_4		$M=7$

t	(S_1,S_2)
1	$(1,1)$
2	$(0,1)$
3	$(1,0)$
4	$(0,0)$

	1	2	3	4
Rx1	a_2+b_1	$b_5+a_1+b_1$	$a_6+a_1+b_1$	a_5+b_5
	a_3	$b_1+a_1+b_1$	$a_7+a_1+b_1$	a_5+b_5
	a_4	a_1+b_1	$a_8+a_1+b_1$	a_5+b_5
	received			
Rx 2	b_2+a_1	$b_6+a_1+b_1$	$a_5+a_1+b_1$	a_5+b_5
	b_3	$b_7+a_1+b_1$	$a_1+a_1+b_1$	a_5+b_5
	b_4	$b_8+a_1+b_1$	a_1+b_1	a_5+b_5
$N=3$				

Takeaway

1. Interaction (feedback and cooperation) is more helpful in bursty communication

2. Harnessing delayed state information and interaction boost up capacity greatly

Since interaction is so useful, please give us feedback and let us collaborate!

Email: ihwang@ntu.edu.tw
Website: http://cc.ee.ntu.edu.tw/~ihsiangw

Thank You!