How Much Training is Needed in Reciprocal Multiple Antenna Systems?

A Diversity Multiplexing Gain Tradeoff Perspective

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Outline

Introduction

- Two fundamental quantities of interest in any communication system: reliability and throughput
  - Diversity-multiplexing gain tradeoff
- Wireless fading channel: time-varying
  - Severe loss of reliability/throughput compared to AWGN
  - Can improve performance by channel estimation at rx/tx using a *known training* signal
- What are the implications of training?
  - Imperfect CSI due to estimation error: leads to outages
  - Training duration overhead: leads to loss of throughput

Key Question

What is the effect of imperfect CSI on the DMT performance?

Introduction

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System Model

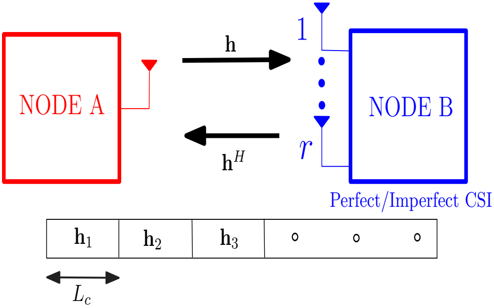

Figure: Quasi-Static SIMO Channel with coherence time L_c. The entries of **h** are $\sim \mathcal{CN}(0, 1)$ and i.i.d. across coherence times.

Performance Metric

- Reliability/probability of error
- Throughput/Data rate

- Proxy: outage probability
- Proxy: degrees of freedom

These proxies are good at high SNR[1]

[1] [ZhengTse2003, TavildarViswanathTITJul2006, EliaKumarPawarKumarLuTITSep2006]

Basic Definitions

- The multiplexing gain g_m and the diversity order d are defined as [ZhengTse2003]:

$$g_m \triangleq \lim_{\bar{P}\to\infty} \frac{R_{\bar{P}}}{\log \bar{P}}$$

$$d \triangleq -\lim_{\bar{P}\to\infty} \frac{\log P_{out}}{\log \bar{P}}$$

where $P_{out} \triangleq \Pr\{\text{capacity} < R_{\bar{P}}\}$.

- We say $f(\bar{P}) \doteq \bar{P}^k$ to mean $\lim_{\bar{P}\to\infty} \frac{\log f(\bar{P})}{\log \bar{P}} = k$

A Motivating Example

- Consider a SISO Rayleigh fading channel
- Assume perfect CSIR and no CSIT
  - Tx power constraint $\bar{P}$
  - Rayleigh channel h, hence, $|h|^2$ is exponentially distributed
- Can show that

$$P_{out} = \Pr\left\{\log\left(1 + |h|^2\,\bar{P}\right) < g_m \log \bar{P}\right\} \doteq \frac{1}{\bar{P}^{1-g_m}}$$

- Thus, the diversity order is $d(g_m) = 1 - g_m$

Can we do better?

- Consider the following power control:

$$\mathcal{P}(h) \triangleq \beta \begin{cases} \bar{P} & |h|^2 \geq \frac{1}{\bar{P}}, \\ \bar{P}^2 & |h|^2 < \frac{1}{\bar{P}} \end{cases}$$

Here β is chosen such that $\mathbb{E}\{\mathcal{P}(h)\} = \bar{P}$

- Requires 1 bit CSI feedback from rx
- In this case, the diversity order is $d(g_m) = 2 - g_m$!
- *Thus, with just* 1 *bit feedback, the diversity order doubles*

Key take-home message # 1

CSI at the transmitter improves the DMT!

But this is not new!

- [KhoshnevisSabharwal2004, RaghavaSharma2005]
  Benefits of CSIT to achievable DMT/error exponents
- [SharmaPremkumarSwamy2008]
  Exponential diversity at low SNR, even w/ imperfect CSIT
- [KimSkoglund2007, AggarwalSabharwal2010]
  Quantized feedback of the CSI *needed* at the tx
- [StegerSabharwal2008]
  Orthogonal RCT, accounting for training duration overhead
- [KimCaire2009]
  Improvement in DMT using power-controlled training
- [ZhangGongLetaief2011]
  Source- or destination-initiated training, joint rate and power control

How can one acquire CSI at *Node A*?

1. Sending the quantized CSI through a feedback link (digital feedback)
   - Typically used in Frequency Division Duplex (FDD) systems
2. Training in the reverse link (analog feedback)
   - Typically used in Time Division Duplex (TDD) systems

- Digital and analog feedback are fundamentally different, e.g., in terms of the channel uncertainty interval
- We will focus on reverse channel training

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Acquiring CSI at *Node A* in a TDD-SIMO Channel

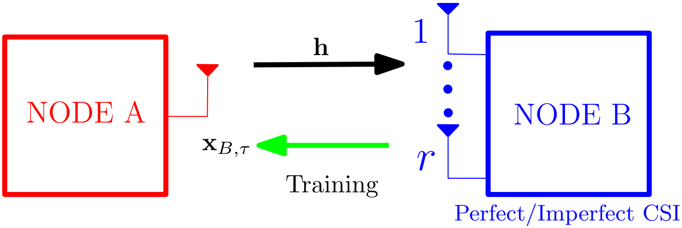
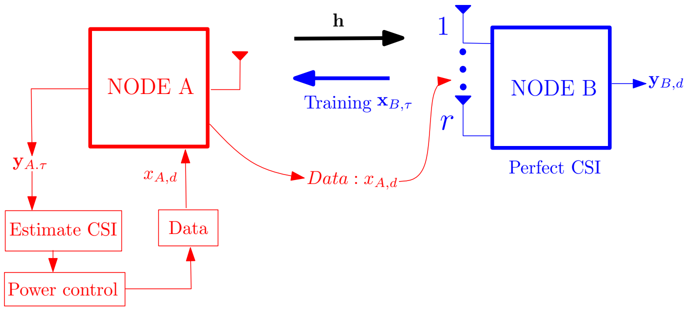


Figure: Training from *node B* to *node A* in a reciprocal SIMO channel

Training and Power Control in a SIMO Channel



Description	Input-Output Equation
Training: *Node B* → *Node A*	$y_{A,\tau} = \mathbf{h}^H \mathbf{x}_{B,\tau} + w_{A,\tau}$
Data : *Node A* → *Node B*	$\mathbf{y}_{B,d} = \mathbf{h} x_{A,d} + \mathbf{w}_{B,d}$

Table: Two-Way Training in a TDD-SIMO System

SIMO Channel with Perfect CSIR and CSIT

- Let $\mathbf{h} = \sigma \mathbf{v}$, where $\sigma \triangleq \|\mathbf{h}\|_2$ and $\mathbf{v} \triangleq \frac{\mathbf{h}}{\|\mathbf{h}\|_2}$
- With a target data rate of R, can achieve an infinite diversity order via the following data power control:

$$\mathcal{P}(\sigma) = C\Phi(\sigma^2)$$

where

$$\Phi(\sigma^2) \triangleq \frac{\exp\left(\frac{RL_c}{L_c - L_{B,\tau}} - 1\right)}{\sigma^2}$$

Here C is chosen to satisfy an average power constraint

- Need the value of σ at *Node A*

Key take-home message # 2

Channel-inversion power control using CSIT improves diversity!

Conventional Orthogonal Reverse Channel Training

- Orthogonal training sequence, e.g., $r \times r$ identity matrix
  - Minimum training duration: r symbols
- Channel estimation
  - MMSE estimator: $\hat{\mathbf{h}} = \mathbf{h} - \tilde{\mathbf{h}}$, where $\tilde{\mathbf{h}}$ is estimation error
  - Estimate σ: $\hat{\sigma} = \|\hat{\mathbf{h}}\|_2$
- Use the estimated σ to set the data transmit power:

$$\mathcal{P}(\hat{\sigma}) = \bar{P}\frac{C}{\hat{\sigma}^{2s}}$$

  - We will consider two cases: $s = 1$ and $s = r$
  - C is the power normalization constant, as before

Achievable DMT w/ Conventional/Orthogonal Training

Theorem (StegerSabharwal2008)

$$d(g_m) \geq r\left(\delta - \frac{g_m}{\alpha}\right), \quad 0 \leq g_m \leq \alpha$$

- $\alpha \triangleq \frac{L_c - r L_{B,\tau}}{L_c}$: the fractional loss due to training overhead
- $\delta = 2$ for $s = 1$ and $\delta = r + 1$ for $s = r$
- Assumes a *genie-aided receiver:* $\mathcal{P}(\hat{\sigma})$ is known at rx

Observation

The training overhead reduces the achievable DMT! Cannot achieve nonzero g_m if $r > L_c/L_{B,\tau}$. Might need to switch off antennas.

Proposed Training Scheme

- We propose the training sequence[2]

$$\mathbf{x}_{B,\tau} = \sqrt{\bar{P} L_{B,\tau}}\,\mathbf{v}$$

- Estimated singular value at *Node A*

$$\hat{\sigma} = \frac{1}{\sqrt{\bar{P} L_{B,\tau}}} \Re\left\{ \sqrt{\bar{P} L_{B,\tau}}\,\sigma + w_{A,\tau} \right\} = \sigma + \bar{w}_{A,\tau}$$

- Note: The min. training duration required is just one symbol, whereas conventional training scheme requires at least r training symbols.

[2] [BharathMurthyICASSP2009]

Power Control Scheme with Imperfect CSIT $\hat{\sigma}$

- Recall that the power control with perfect CSIT was

$$\mathcal{P}(\sigma) = C\Phi(\sigma^2) \triangleq C \frac{\exp\left(\frac{RL_c}{L_c - L_{B,\tau}} - 1\right)}{\sigma^2}$$

- Natural extension:

$$\mathcal{P}(\hat{\sigma}) = C\Phi(\hat{\sigma}^2)$$

- Problem! The avg. power constraint cannot be satisfied:

$$\mathbb{E}[\mathcal{P}(\hat{\sigma})] = \infty$$

Solution, Try 1

- Truncated channel inversion:

$$\mathcal{P}(\hat{\sigma}) \triangleq \kappa_{\bar{P}} \begin{cases} \Phi(\hat{\sigma}^2) & \hat{\sigma} > \theta, \\ 0 & \hat{\sigma} \leq \theta \end{cases}$$

  where $\theta > 0$ is some threshold.
- Choose $\theta > 0$ & $\kappa_{\bar{P}}$ to satisfy the avg. power constraint
- Still a problem: Diversity order is zero
  - $P_{out} = 1$ whenever $\hat{\sigma} \leq \theta$

Solution, Try 2 (Proposed Power Control Scheme)

- Consider

$$\mathcal{P}(\hat{\sigma}) \triangleq \begin{cases} \kappa_{\bar{P}} \Phi(\hat{\sigma}^{2s}) & \hat{\sigma} > \frac{1}{\sqrt{\bar{P}}}, \\ \bar{P}^{l} & \hat{\sigma} \leq \frac{1}{\sqrt{\bar{P}}} \end{cases}$$

  for some $0 \leq l \leq r + 1$.
- Can show that for both $s = 1$ and $s = r$, there exists $\kappa_{\bar{P}}$ such that avg. power constraint is satisfied!
- Moreover, $\kappa_{\bar{P}} \doteq \bar{P}^{1-\frac{gm}{\alpha}}$, where $\alpha \triangleq \frac{L_c - L_{B,\tau}}{L_c}$

Achievable DMT Result

- We have chosen
  - A new reverse channel training scheme
  - A new power control scheme
  - So, question: what is its DMT performance?

Theorem (BharathMurthyICASSP2010)

$$d(g_m) \geq r\left(\delta - \frac{g_m}{\alpha}\right), \quad 0 \leq g_m \leq \alpha,$$

- $\alpha \triangleq \frac{L_c - L_{B,\tau}}{L_c}$
- $\delta = 2$ *for* $s = 1$ *and* $\delta = r + 1$ *for* $s = r$
- *Assumes a genie-aided receiver*

Are we better off?

- Conventional:

$$d(g_m) = r\left(r+1-\frac{g_m(L_c - rL_{B,\tau})}{L_c}\right), \quad 0 \leq g_m \leq \frac{L_c - rL_{B,\tau}}{L_c}$$

- Proposed:

$$d(g_m) = r\left(r+1-\frac{g_m(L_c - L_{B,\tau})}{L_c}\right), \quad 0 \leq g_m \leq \frac{L_c - L_{B,\tau}}{L_c}$$

Key take-home message #3

With training power $= \bar{P}$, the proposed training (beamforming) and power control (modified TCI) scheme significantly improves the DMT. Moreover, having larger r is always better!

Schematic Plot

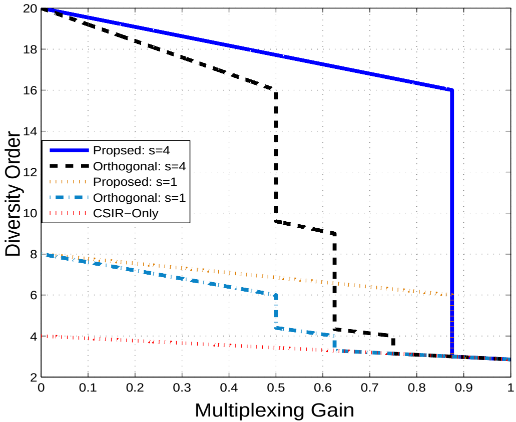


Figure: SIMO system with $r = 4$ antennas, coherence time $L_c = 40$ symbols reverse training duration of $L_{B,\tau} = 5$ symbols per antenna.

Simulation Result

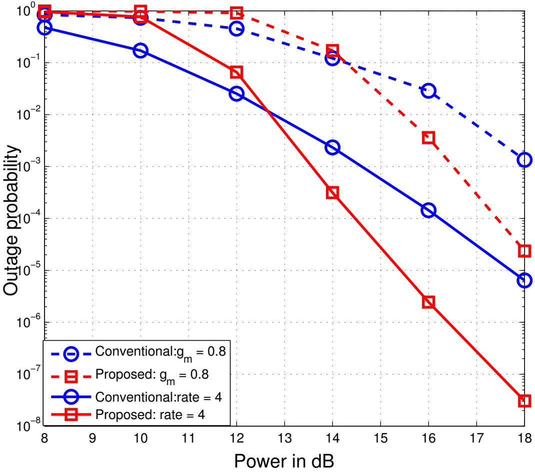


Figure: $r = 3$, $L_c = 40$, $L_{B,\tau} = 1$, $s = 1$ and perfect CSIR

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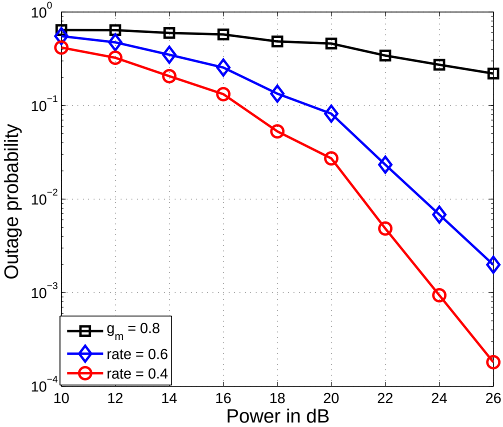

Figure: $r = 3$, $L_c = 40$, $L_{B,\tau} = 1$, $s = r$, and perfect CSIR

Can we do better?

- We actually need $\mathcal{P}(\sigma)$ for data transmission, *not* σ!
  - Error amplification in computing tx power from $\hat{\sigma}$
- Can we directly estimate $\mathcal{P}(\sigma)$ at *node A*?
- Yes! Choose the training sequence sequence such that

$$y_{A,\tau} = \sqrt{\mathcal{P}(\sigma)} + noise$$

  - Where $\mathcal{P}(\sigma)$ is the data power that achieves an infinite diversity order with perfect CSIR and CSIT
  - Note: this necessitates *power controlled training.*

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Power Controlled Training

- Proposed training sequence from *node B*:

$$\mathbf{x}_{B,\tau} = \frac{\sqrt{\bar{P}}\sqrt{(r-1)(r-2)}}{\sigma^2}\mathbf{v}$$

- Note: $\mathbb{E}\{\mathbf{x}_{B,\tau}^H \mathbf{x}_{B,\tau}\} = \bar{P}$ because of the Rayleigh fading
- Corresponding received training signal at *node A*

$$y_{A,\tau} = \underbrace{\frac{\sqrt{\bar{P}}\sqrt{(r-1)(r-2)}}{\sigma}}_{\text{Scaled version of } \sqrt{\mathcal{P}(\sigma)}!} + w_{A,\tau}$$

Data Transmission from *Node A*

- *Node A* sends $g_c x_{A,d}$, where $x_{A,d} \sim \mathcal{CN}(0,1)$, and

$$g_c = \sqrt{\frac{2\bar{P}}{2(r-2)\bar{P}+1}} \left| \Re\{y_{A,\tau}\} \right|$$

- Can show that $\mathbb{E}\{|g_c|^2\} = \bar{P}$
- Received data signal (after pre-multiplying by $\mathbf{v}^H$) is

$$y_{B,d} \triangleq \sigma g_c x_{A,d} + \mathbf{v}^H \mathbf{w}_{B,d}$$

DMT with Power Controlled Training

- We have proposed
  - A new *power controlled* RCT scheme
  - A new data power control scheme
    - The achievable rate is $\alpha \log(1 + \sigma^2 |g_c|^2)$
  - So, question: what is its DMT performance?

Theorem

An infinite diversity order is achievable when $0 \leq g_m < \alpha$.

Proof: See [BharathMurthy, arXiv:1105.2375v1, 2011]

- Note: Assumes a *genie aided* receiver, as before

Key take-home message #4

With power-controlled reverse channel training and direct estimation of the data tx power at *Node A*, can achieve a performance similar to an AWGN channel!

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Story So Far

- We assumed
  1. Perfect CSIR
  2. Genie-aided receiver
- And showed
  1. Diversity order $r\left(r+1-\frac{g_m}{\alpha}\right)$ achievable with constant power training, $0 \leq g_m < \alpha$
  2. Infinite diversity order achievable with power-controlled training, $0 \leq g_m < \alpha$

Next Question

What can we say about the DMT if CSI is estimated at the receiver and the genie stopped helping us?

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Four Phase Protocol

1. Forward training: *node B* estimates $\mathbf{h}$
2. Reverse training: *node A* estimates the singular value σ
3. Forward training, round 2: *node A* sends the power control $\mathcal{P}(\hat{\sigma})$ that will be used during the data transmission
   - *Node B* estimates the composite channel
4. Data transmission: *node A* transmits power controlled data

Phase 1: Forward Training

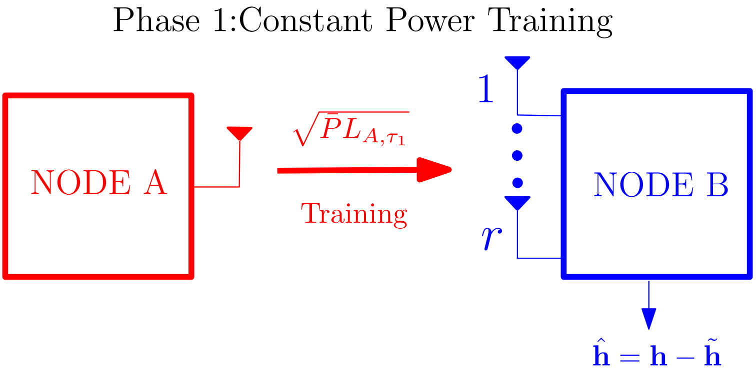
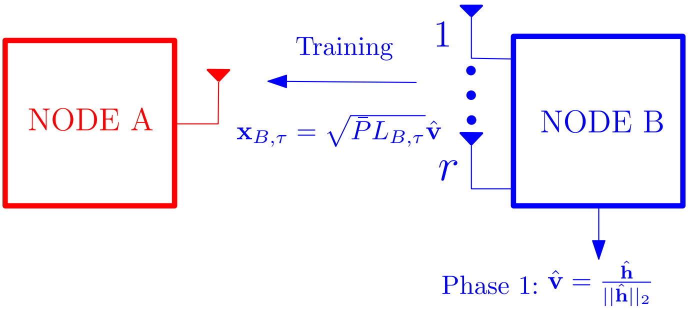


Figure: Here, *node B* obtains an MMSE estimate of $\mathbf{h}$.

Phase 2: Reverse Training



- *Node A* estimates the singular value as

$$\hat{\sigma} \triangleq \frac{\Re\{y_{A,\tau}\}}{\sqrt{\bar{P} L_{B,\tau}}} = \sigma \Re\{\mathbf{v}^H \hat{\mathbf{v}}\} + \bar{w}_{A,\tau}$$

- Note: fixed-power reverse training

Data Power Control Computation at *Node A*

- Using $\hat{\sigma}$, *Node A* computes $\mathcal{P}(\hat{\sigma})$ as

$$\mathcal{P}(\hat{\sigma}) \triangleq \begin{cases} \kappa_{\bar{P}} \Phi(\hat{\sigma}^2) & \hat{\sigma} > \frac{1}{\sqrt{\bar{P}}} \\ \bar{P}^{l} & \hat{\sigma} \leq \frac{1}{\sqrt{\bar{P}}} \end{cases}$$

  for some $0 \leq l \leq r$.
- Can show that there exists a $\kappa_{\bar{P}} \doteq \bar{P}^{-\frac{g m}{\alpha}}$, where $\alpha \triangleq \frac{L_c - L_{B,\tau} - L_{A,\tau_1} - L_{A,\tau_2}}{L_c}$, such that $\mathbb{E}\mathcal{P}(\hat{\sigma}) = 1$
- Problem: *Node B* does not know $\mathcal{P}(\hat{\sigma})$!
  - Solution: use a third round of training

Phase 3: Forward Power-Controlled Training

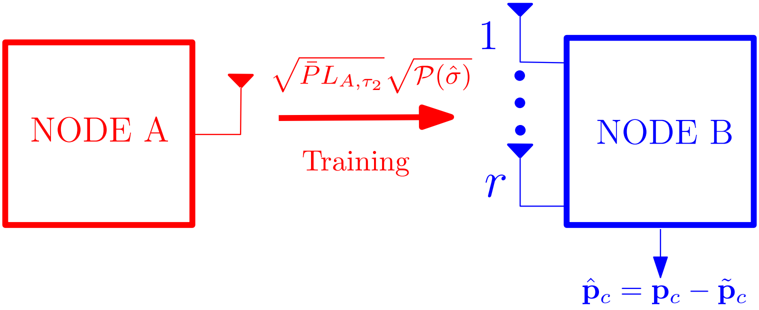


Figure: Here, *node B* obtains an *MMSE estimate* of $\mathbf{p}_c$.

- Received training signal

$$\mathbf{y}_{B,\tau_2} = \sqrt{\bar{P}L_{A,\tau_2}}\underbrace{\sqrt{\mathcal{P}(\hat{\sigma})}\mathbf{h}}_{\triangleq \mathbf{p}_c} + \mathbf{w}_{B,\tau_2},$$

Phase 4: Power-Controlled Data Transmission

- *Node A* sends the data symbol

$$x = \sqrt{\bar{P}\mathcal{P}(\hat{\sigma})}x_{A,d}$$

Where $x_{A,d} \sim \mathcal{CN}(0,1)$

- The corresponding received signal is

$$\begin{aligned} \mathbf{y}_{B,d} &= \sqrt{\bar{P}\mathcal{P}(\hat{\sigma})}\mathbf{h}x + \mathbf{w}_{B,d} \\ &= \sqrt{\bar{P}}\hat{\mathbf{p}}_c x_{A,d} + \underbrace{\sqrt{\bar{P}}\tilde{\mathbf{p}}_c x_{A,d} + \mathbf{w}_{B,d}}_{\text{effective noise}} \end{aligned}$$

Capacity Lower Bound

- Since $\hat{\mathbf{p}}_c$ is an MMSE estimate, using the worst case noise theorem[3], we get a lower bound on the mutual information:

$$I(x_{A,d}; \mathbf{y}_{B,d} | \hat{\mathbf{p}}_c) \geq \alpha \log \left(1 + \frac{\bar{P} \|\hat{\mathbf{p}}_c\|_2^2}{\bar{P}\mathbb{E}[\|\tilde{\mathbf{p}}_c\|_2^2] + r} \right)$$

- $\alpha \triangleq \frac{L_c - L_{B,\tau} - L_{A,\tau_1} - L_{A,\tau_2}}{L_c}$ accounts for total training overhead
- Note: genie-aided assumption is not required here!

[3][HochwaldHassibi2003]

Achievable Diversity Multiplexing Gain Tradeoff

Theorem

The achievable DMT is given by

$$d(g_m) = r\left(2 - \frac{g_m}{\alpha}\right), \quad 0 \leq g_m \leq \alpha$$

where $\alpha \triangleq \frac{L_c - L_{B,\tau} - L_{A,\tau_1} - L_{A,\tau_2}}{L_c}$

Key take-home message #5

Even without the perfect CSIR, and even without the genie, can significantly improve the DMT using reverse channel training!

Proof Outline

- The outage probability can be upper bounded as

$$P_{out} \leq \Pr\left\{\alpha \log\left(1 + \frac{\bar{P}\|\hat{\mathbf{p}}_c\|_2^2}{\bar{P}\mathbb{E}[\|\tilde{\mathbf{p}}_c\|_2^2] + r}\right) < R_{\bar{P}}\right\}$$

where $R_{\bar{P}} \triangleq g_m \log \bar{P}$ is the target data rate

- Let $\bar{R}_{\bar{P}} \triangleq \frac{(\bar{P}\mathbb{E}[\|\tilde{\mathbf{p}}_c\|_2^2]+r)(\exp\{R_{\bar{P}}/\alpha\}-1)}{\bar{P}} \doteq \frac{1}{\bar{P}^{(1-g_m/\alpha)}}$. Then,

$$\begin{aligned} P_{out} &\leq \Pr\left\{\|\hat{\mathbf{p}}_c\|_2^2 < \bar{R}_{\bar{P}}\right\} \\ &\leq \Pr\left\{\left|\|\mathbf{p}_c\|_2 - \|\tilde{\mathbf{p}}_c\|_2\right| < \sqrt{\bar{R}_{\bar{P}}}\right\} \\ &\leq \Pr\left\{\|\tilde{\mathbf{p}}_c\|_2 > \sqrt{\bar{R}_{\bar{P}}}\right\} + \Pr\left\{\|\mathbf{p}_c\|_2^2 < 4\bar{R}_{\bar{P}}\right\} \end{aligned}$$

Proof Outline (continued)

Lemma (Property of MMSE Estimators)

$\mathbb{E}\|\tilde{\mathbf{p}}_c\|_2^{2z} \doteq \frac{1}{\bar{P}^z}$ *for every* $z > 0$.

- Using the lemma with $z = r\frac{\alpha}{g_m}\left(2 - \frac{g_m}{\alpha}\right) > 0$, we have

$$\Pr\left\{\|\tilde{\mathbf{p}}_c\|_2^2 > \bar{R}_{\bar{P}}\right\} \preceq \frac{1}{\bar{P}^{r\left(2-\frac{g_m}{\alpha}\right)}}, \quad 0 \le g_m < \alpha$$

- Can show that the second term is also bounded as

$$\Pr\left\{\|\mathbf{p}_c\|_2^2 > 4\bar{R}_{\bar{P}}\right\} \preceq \frac{1}{\bar{P}^{r\left(2-\frac{g_m}{\alpha}\right)}}, \quad 0 \le g_m < \alpha$$

- Combining the two, we have

$$d(g_m) = -\frac{\log P_{out}}{\log \bar{P}} \ge r\left(2 - \frac{g_m}{\alpha}\right), \quad 0 \le g_m < \alpha. \quad \blacksquare$$

Conclusions

- Even imperfect CSIT helps! Key ingredients:
  1. Exploit CSI at the receiver in reverse channel training
  2. Use power controlled training to convey only the CSI required for data transmission at *node A*
     - Tx does not require knowledge of the entire channel
  3. Use better power control strategies at the transmitter
  4. With imperfect CSIR, use a third round of training
- Advantages
  - Reduction in training overhead
  - Better channel estimate
  - Improvement in diversity-multiplexing gain tradeoff
- Topics studied but not presented today:
  - Training sequence design for a MIMO channel
  - Power controlled training in a spatial multiplexing system

References

- B. N. Bharath and C. R. Murthy, “Reverse channel training for reciprocal MIMO systems with spatial multiplexing,” *IEEE ICASSP* 2009
- B. N. Bharath and C. R. Murthy, “On the improvement of the diversity-multiplexing gain tradeoff in a training based TDD-SIMO system,” *IEEE ICASSP* 2010
- Journal version submitted to the *IEEE Transactions on Wireless Communications* and available at arXiv:1105.2375v1

Thank you!