JMB: Scaling Wireless Capacity with User Demands

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Outline

- Motivation & Contribution
- Design
- Evaluation
- Relate work & Future work
- Conclusion

Chuanyao Nie (Motivation & Contribution, Design)

Xiao Huang (Evaluation, Relate work & Future work, Conclusion)

Motivation

Wireless spectrum is limited, however, wireless demands can grow unlimited.

Busy Wi-Fi networks (in conference rooms, hotels, enterprises) are unable to keep up with user demands.

The iPhone 4 demo failed because of wireless congestion.

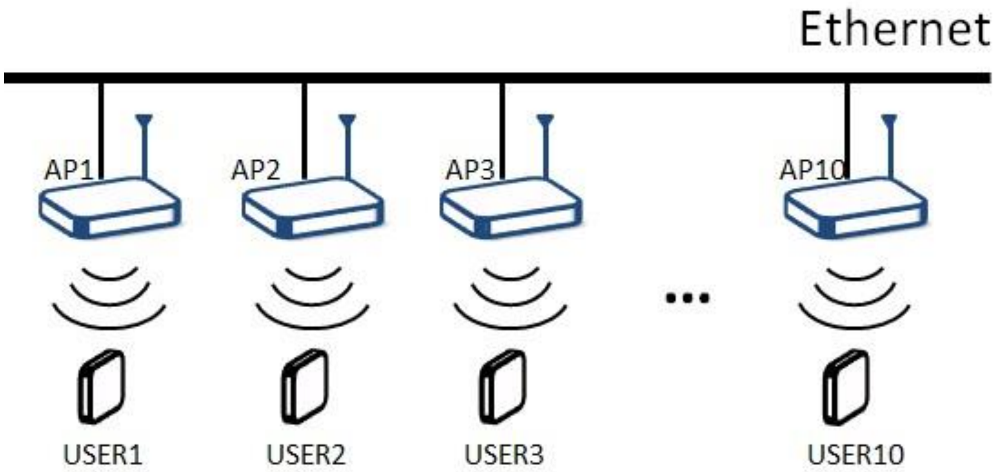
Jobs's reaction:"You know you can help me out; if you on wifi, you can just get off. I appreciate."

Can we make wireless throughput scale with the number of APs???

network throughput does not.

Contribution

Joint multi-user beamforming (JMB) presents a system that can scales wireless throughput by enabling joint beamforming from distributed independent transmitters.



10APs → 10x higher throughput

JMB enables each AP sends packets to its user at the same time, in the same channel, without interference.

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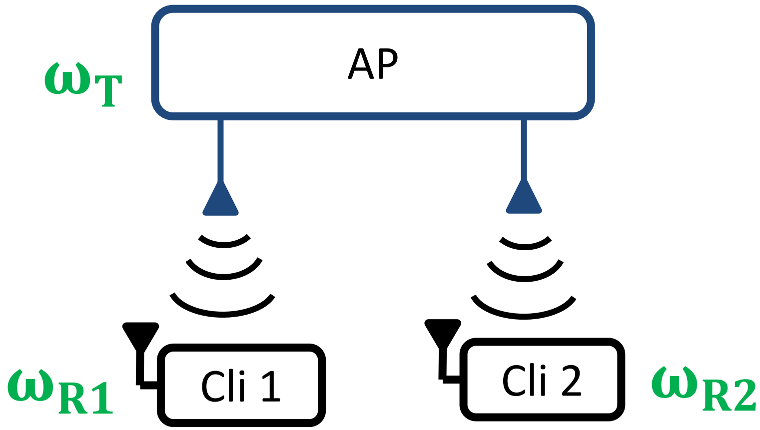
Design

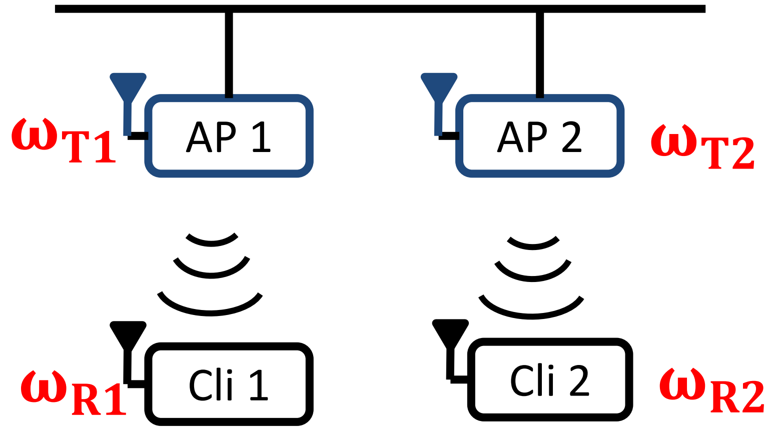
Problem:

1. How to cancel interference ?
2. ???

AP with 2 antennas



Distributed APs



Client 1 synchronize ω_{R1} with ω_T .

Client 2 synchronize ω_{R2} with ω_T .

Client 1 synchronize ω_{R1} with ???

Client 2 synchronize ω_{R2} with ???

Design

Problem:

1. How to cancel interference ?

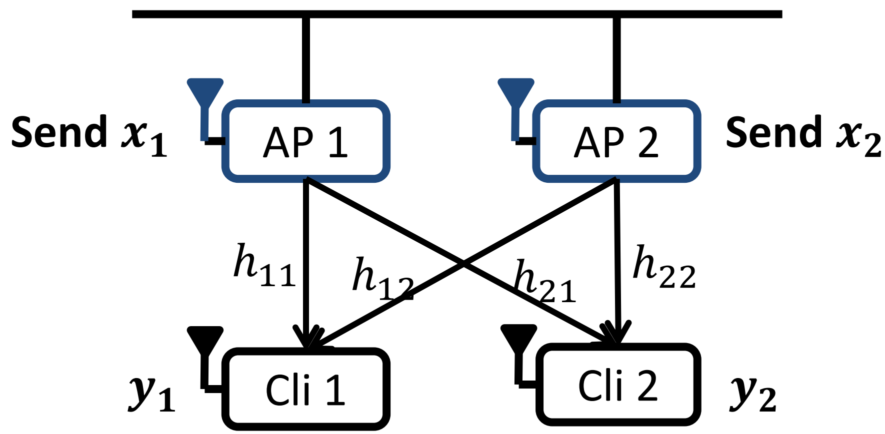
2. ??? How to synchronize oscillators?

Next Slides:

- **Start analysis with no oscillator offset**

- Then take oscillator offset into consideration

- **If no Oscillator Offset:**



Result:

Goal:

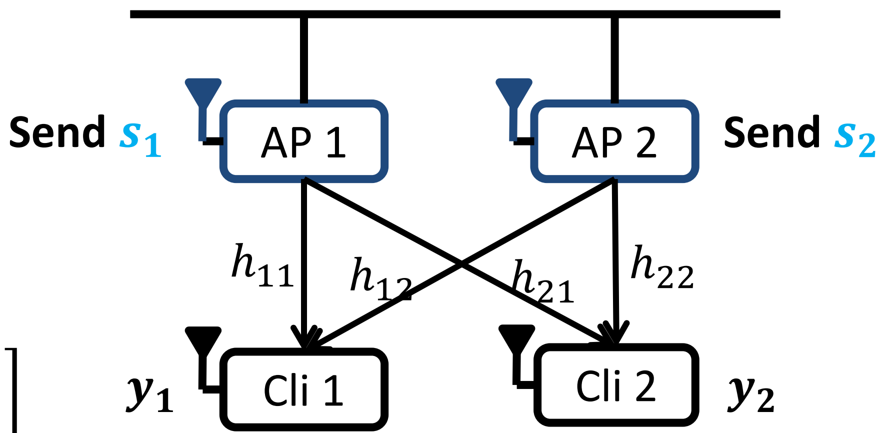
Diagonal Matrix →Non-Interference

Goal: Make the effective channel matrix diagonal

$\mathbf{H}$

Diagonal

- **If no Oscillator Offset:**



$$\mathbf{H} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}$$

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \mathbf{H} \begin{bmatrix} s_1 \\ s_2 \end{bmatrix}$$

$$\begin{bmatrix} s_1 \\ s_2 \end{bmatrix} = \mathbf{H}^{-1} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \mathbf{H}\mathbf{H}^{-1} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

$$\mathrm{HH}^{-1} = \mathrm{I}$$

Effective channel is diagonal

Design

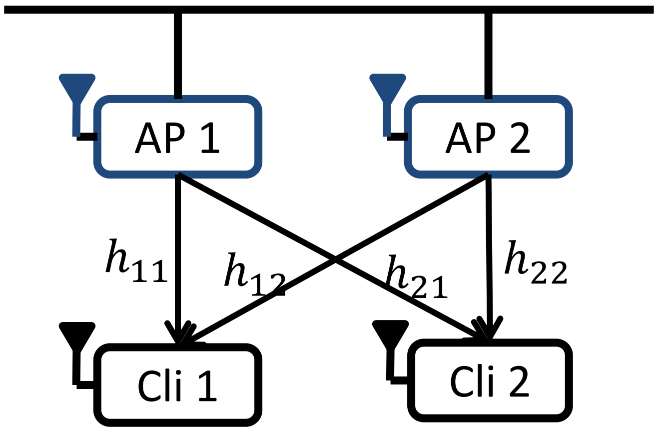
Problem:

1. How to cancel interference ?
2. How to synchronize oscillators?

Next Slides:

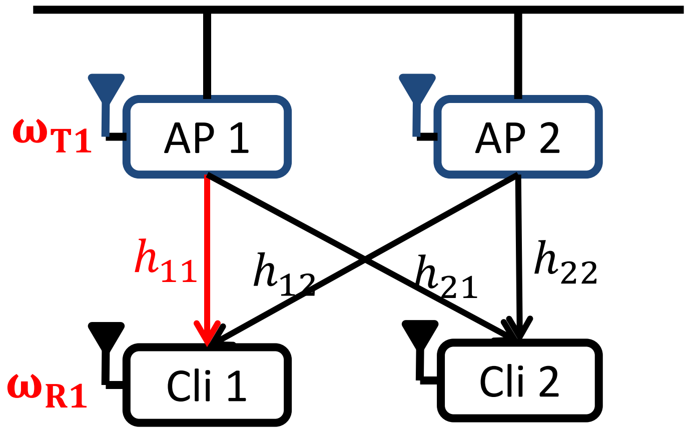
- Start analysis with no oscillator offset
  - → **Diagonal Matrix →Non-Interference**
- **Then take oscillator offset into consideration**
  - → **Need to make Diagonal Matrix under oscillator offset**

- **With Oscillator Offset:**



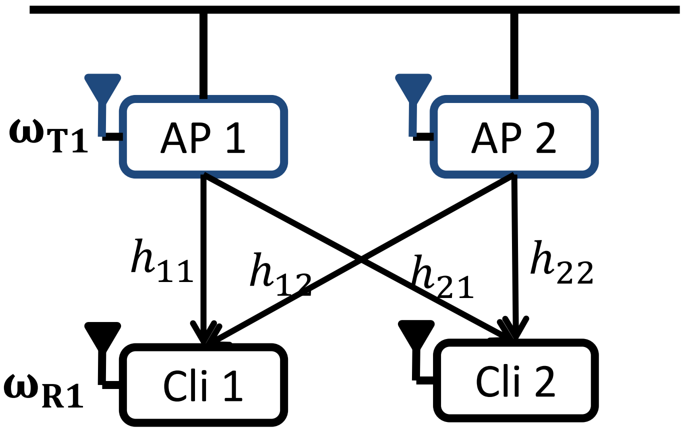
$$\begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}$$

- **With Oscillator Offset:**



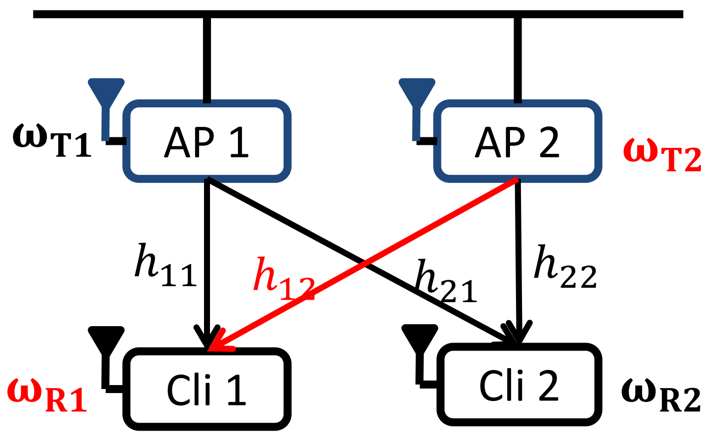
$$\begin{bmatrix} h_{11}e^{j(\omega_{T1}-\omega_{R1})t} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}$$

- **With Oscillator Offset:**



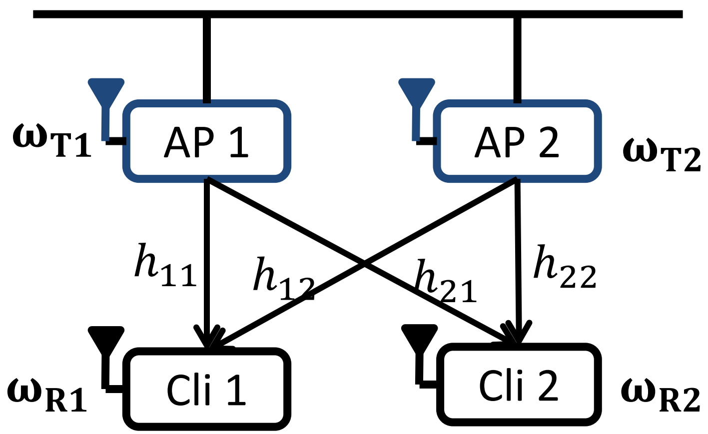
$$\begin{bmatrix} h_{11}e^{j(\omega_{T1}-\omega_{R1})t} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}$$

- **With Oscillator Offset:**



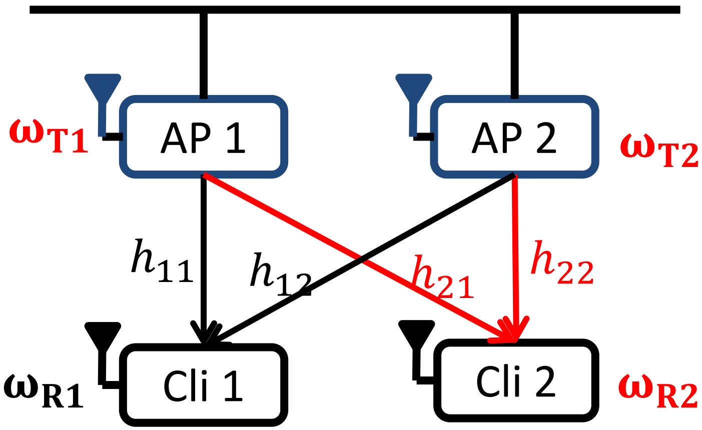
$$\begin{bmatrix} h_{11} e^{j(\omega_{T1}-\omega_{R1})t} & h_{12} e^{j(\omega_{T2}-\omega_{R1})t} \\ h_{21} & h_{22} \end{bmatrix}$$

- **With Oscillator Offset:**



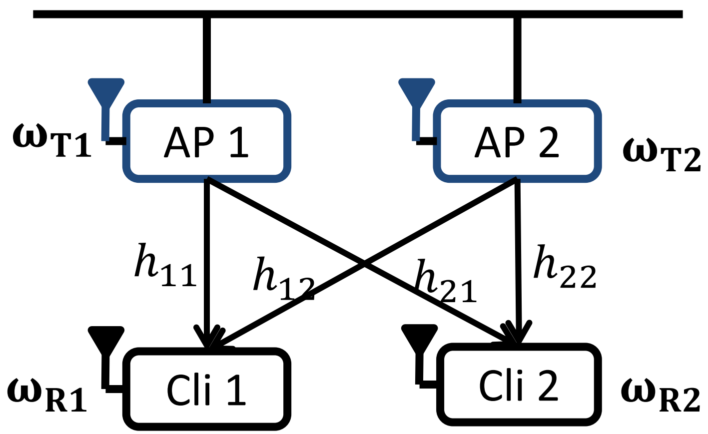
$$\begin{bmatrix} h_{11} e^{j(\omega_{T1}-\omega_{R1})t} & h_{12} e^{j(\omega_{T2}-\omega_{R1})t} \\ h_{21} & h_{22} \end{bmatrix}$$

- **With Oscillator Offset:**



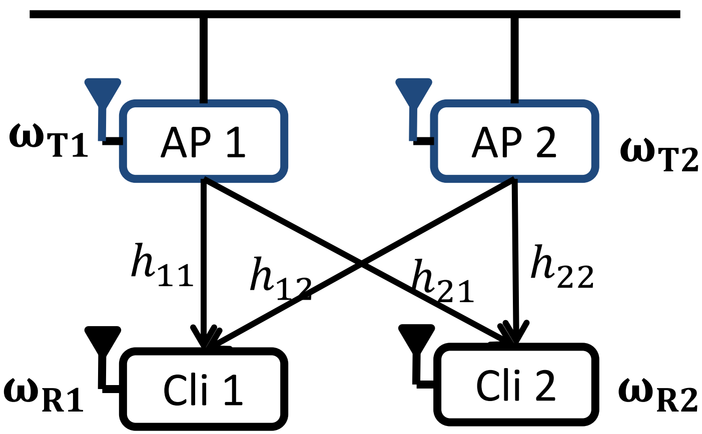
$$\begin{bmatrix} h_{11}e^{j(\omega_{T1}-\omega_{R1})t} & h_{12}e^{j(\omega_{T2}-\omega_{R1})t} \\ h_{21}e^{j(\omega_{T1}-\omega_{R2})t} & h_{22}e^{j(\omega_{T2}-\omega_{R2})t} \end{bmatrix}$$

- **With Oscillator Offset:**



$$\begin{bmatrix} h_{11}e^{j(\omega_{T1}-\omega_{R1})t} & h_{12}e^{j(\omega_{T2}-\omega_{R1})t} \\ h_{21}e^{j(\omega_{T1}-\omega_{R2})t} & h_{22}e^{j(\omega_{T2}-\omega_{R2})t} \end{bmatrix} = H(t)$$

- **With Oscillator Offset:**



$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \mathbf{H}(t) \begin{bmatrix} s_1 \\ s_2 \end{bmatrix} \qquad \begin{bmatrix} s_1 \\ s_2 \end{bmatrix} = \mathbf{H}^{-1} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \mathbf{H(t)H^{-1}} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

Not Diagonal

JMB uses Distributed Phase Synchronization

Distributed Phase Synchronization

High Level Intuition:

- Pick one AP as lead → AP1
- All other APs are slaves → AP2

  --synchronize its oscillator to the lead AP

Distributed Phase Synchronization :

$$H(t) = \begin{bmatrix} h_{11}e^{j(\omega_{T1}-\omega_{R1})t} & h_{12}e^{j(\omega_{T2}-\omega_{R1})t} \\ h_{21}e^{j(\omega_{T1}-\omega_{R2})t} & h_{22}e^{j(\omega_{T2}-\omega_{R2})t} \end{bmatrix}$$

$$= \begin{bmatrix} e^{-j\omega_{R1}t} & 0 \\ 0 & e^{-j\omega_{R2}t} \end{bmatrix} \underbrace{\begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}}_{\mathbf{H}} \begin{bmatrix} e^{j\omega_{T1}t} & 0 \\ 0 & e^{j\omega_{T2}t} \end{bmatrix}$$

Distributed Phase Synchronization :

$$e^{j\omega_{T1}t}\begin{bmatrix} e^{-j\omega_{R1}t} & 0 \\ 0 & e^{-j\omega_{R2}t} \end{bmatrix} \mathbf{H} \begin{bmatrix} e^{j\omega_{T1}t} & 0 \\ 0 & e^{j\omega_{T2}t} \end{bmatrix} e^{-j\omega_{T1}t}$$

$$=$$

$$\underbrace{\begin{bmatrix} e^{j(\omega_{T1}-\omega_{R1})t} & 0 \\ 0 & e^{j(\omega_{T1}-\omega_{R2})t} \end{bmatrix}}_{\mathbf{R(t)}} \mathbf{H} \underbrace{\begin{bmatrix} 1 & 0 \\ 0 & e^{j(\omega_{T2}-\omega_{T1})t} \end{bmatrix}}_{\mathbf{T(t)}}$$

Distributed Phase Synchronization :

$$\begin{bmatrix} e^{j(\omega_{T1}-\omega_{R1})t} & 0 \\ 0 & e^{j(\omega_{T1}-\omega_{R2)}t} \end{bmatrix} \mathbf{H} \begin{bmatrix} 1 & 0 \\ 0 & e^{j(\omega_{T2}-\omega_{T1})t} \end{bmatrix}$$

$$\mathbf{H(t) = R(t)HT(t)}$$

Distributed Phase Synchronization :

$$\mathbf{H}(\mathbf{t}) = \mathbf{R}(\mathbf{t})\mathbf{H}\mathbf{T}(\mathbf{t})$$

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \mathbf{H}(\mathbf{t}) \begin{bmatrix} s_1 \\ s_2 \end{bmatrix} \qquad \begin{bmatrix} s_1 \\ s_2 \end{bmatrix} = \boldsymbol{T}(\boldsymbol{t})^{-1}\boldsymbol{H}^{-1} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \mathbf{R}(\mathbf{t})^{-1}\mathbf{R}(\mathbf{t})\mathbf{H}\mathbf{T}(\mathbf{t})\boldsymbol{T}(\boldsymbol{t})^{-1}\boldsymbol{H}^{-1} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

Result unitary matrix

Diagonal

For transmitters: $\boldsymbol{T}(\boldsymbol{t})^{-1}$

For receivers: $\mathbf{R}(\mathbf{t})^{-1}$

Transmitter Compensation

$$\mathbf{T}(\mathbf{t}) = \begin{bmatrix} 1 & 0 \\ 0 & e^{j(\omega_{T2}-\omega_{T1})t} \end{bmatrix}$$

Transmitter Compensation

$$\mathbf{T}(\mathbf{t})^{-1} = \begin{bmatrix} 1 & 0 \\ 0 & e^{-j(\omega_{T2}-\omega_{T1})t} \end{bmatrix}$$

- Depends only on transmitters
- Slave receives message from lead through Ethernet
- Slave calculates oscillator rotation relative to lead
- Need to keep resynchronizing to avoid error accumulation

Receiver Compensation

$$\mathbf{R(t)} = \begin{bmatrix} e^{j(\omega_{T1}-\omega_{R1})t} & 0 \\ 0 & e^{j(\omega_{T1}-\omega_{R2)}t} \end{bmatrix}$$

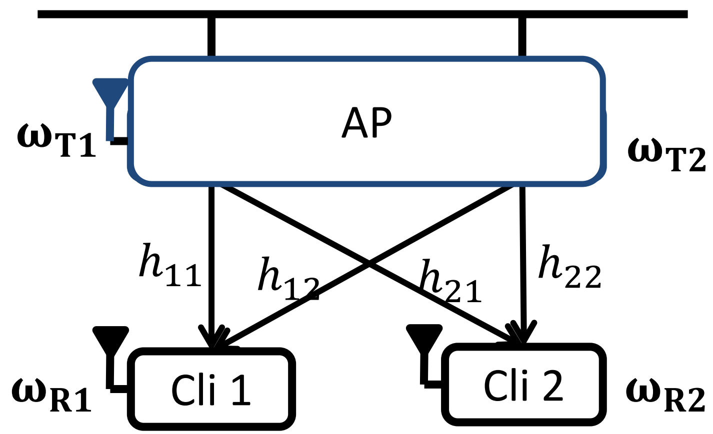
Receiver Compensation

$$\mathbf{R(t)}^{-1} = \begin{bmatrix} e^{-1j(\omega_{T1}-\omega_{R1})t} & 0 \\ 0 & e^{-1j(\omega_{T1}-\omega_{R2})t} \end{bmatrix}$$

Receiver need to synchronize its oscillator offset with lead

-- that is what the receiver does in the regular MIMO

- **With Oscillator Offset:**



- Distributed Phase Synchronization : make all APs run as a single AP with multiple antennas

  → Clients synchronize with lead

- $$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \mathbf{R}(\mathbf{t})^{-1} \mathbf{R}(\mathbf{t}) \; \mathbf{H}\mathbf{T}(\mathbf{t}) \boldsymbol{T}(\boldsymbol{t})^{-1} \boldsymbol{H}^{-1} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

  Diagonal

  → APs can transmit packets to clients without interference

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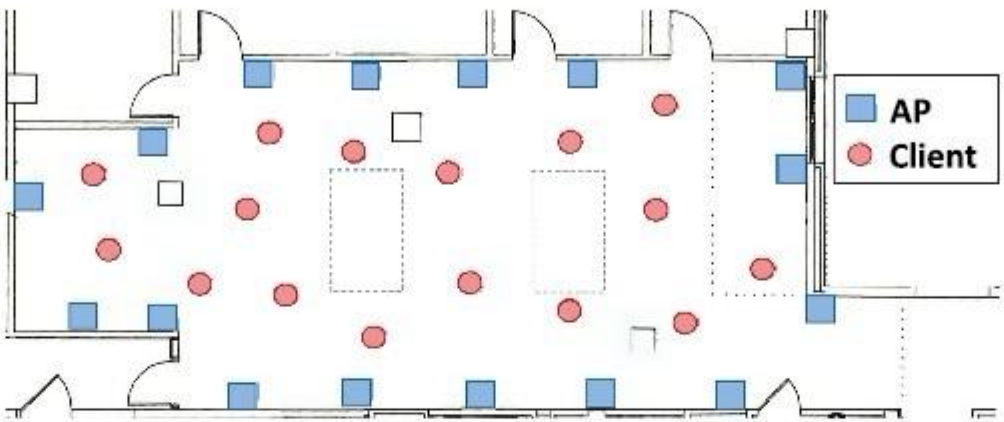
Implementation

- Implemented USRP2 board
- OFDM with 10MHz channel in 2.4GHz range
- Various modulation
- Software radios regarded as APs
- Software radios/off-the-shelf 802.11 cards regarded as clients separately on different testbeds

Testbed topology

- Deployed as a dense congested conference room
- APs and clients are randomly assigned to these locations
- Line-of-sight/non line-of-sight

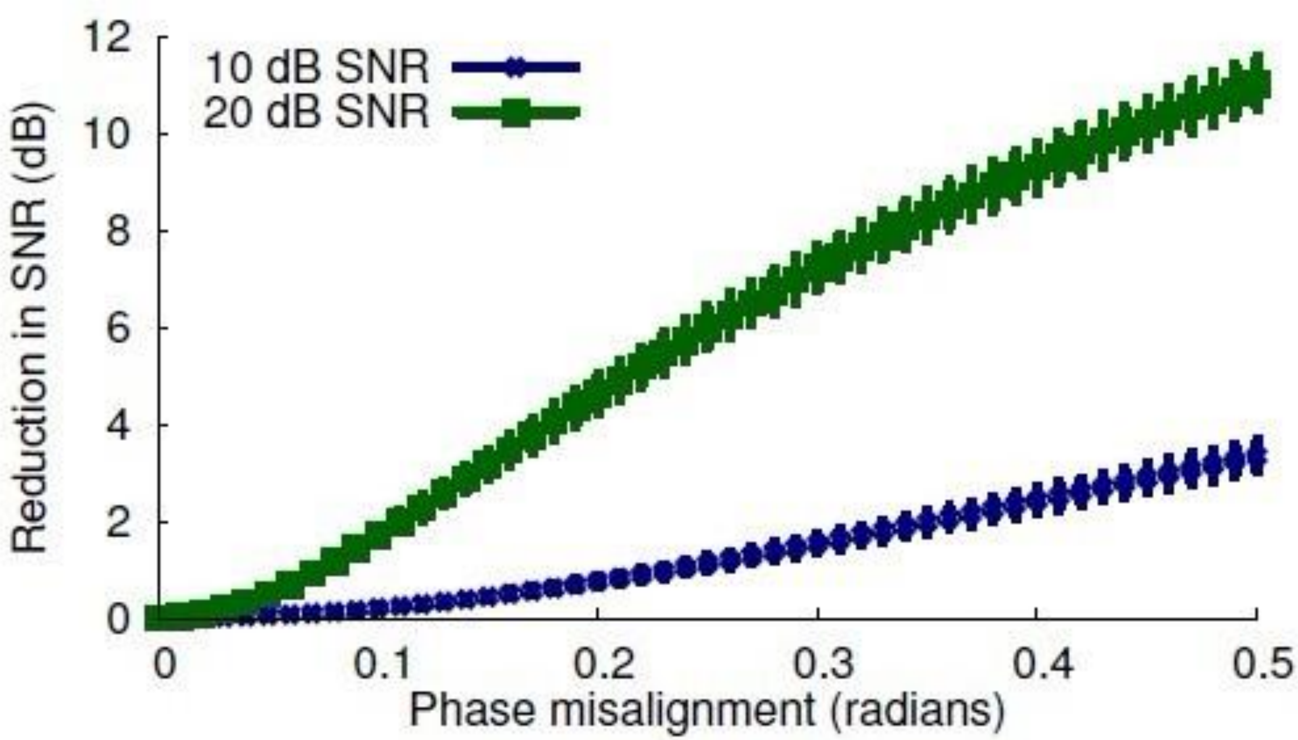


Experimental methodology

- The test of JMB is from the microbenchmarks of its individual component to the integrated system:
  - Misalignment of phase
  - Throughput
  - Fairness
  - Diversity
  - Compatibility with 802.11

Misalignment of phase

- Necessity of phase alignment

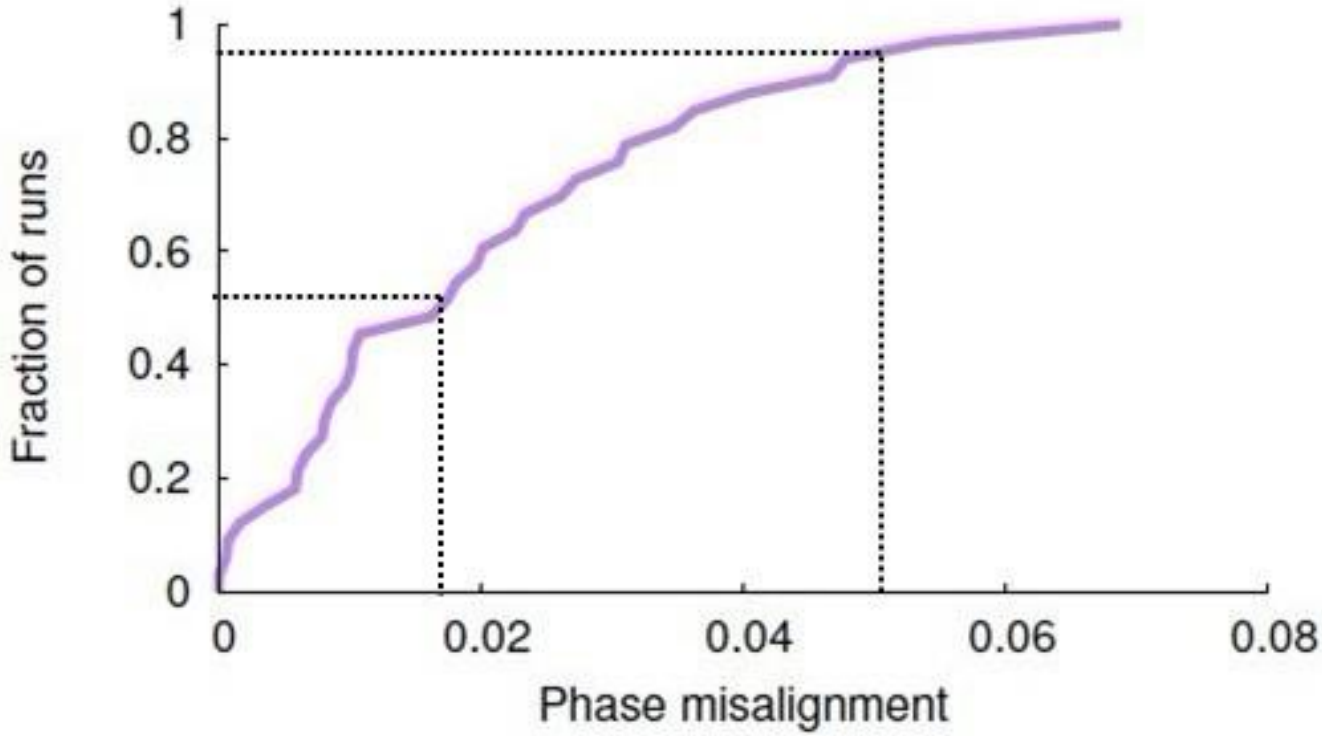


- Cite figure from paper

- Interference increases as phase misalignment increase
- Higher SNR leads to more SNR reduction

Misalignment of phase

- Accuracy of phase alignment

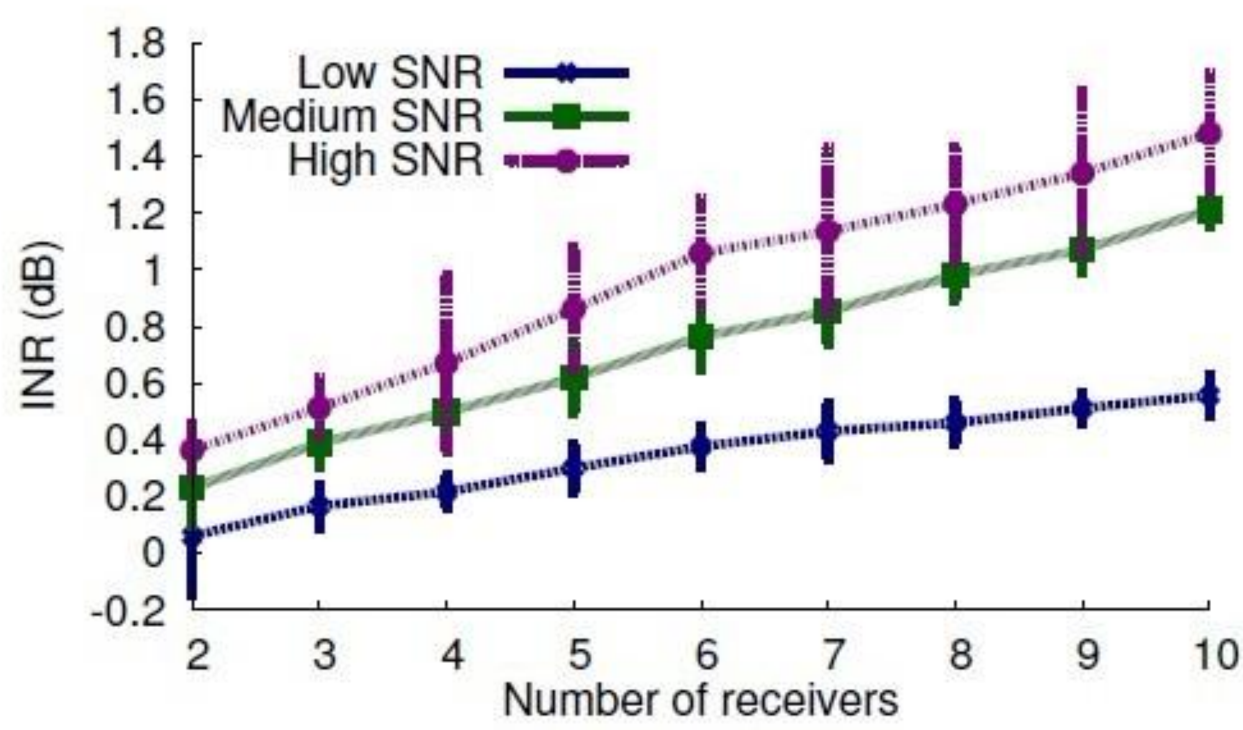


- Cite figure from paper

- Noise
- Delay of slave to measure the lead's channel

Misalignment of phase

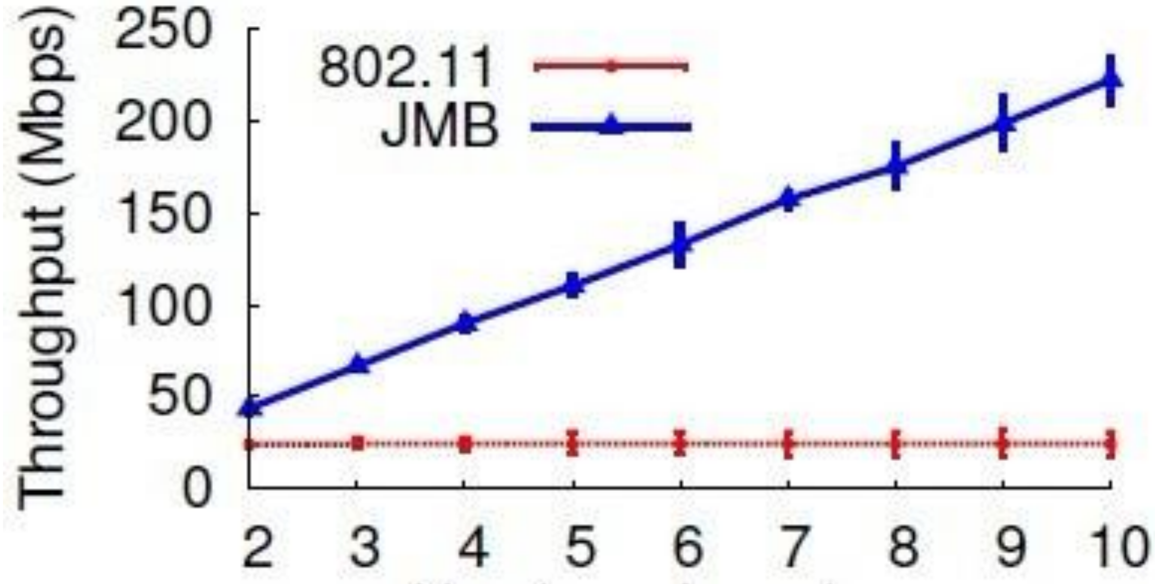
- SNR reduction of multiple receivers



- Cite figure from paper

- INR increases with the number of APs

Throughput



- Cite figure from paper

- 802.11 does not benefit from additional APs because only one AP works at the time
- JMB can transmit packets concurrently, so almost linear increase
- High SNR: ~9.4× medium SNR: ~9.1× low SNR: ~8.1×

Limitation of JMB system

- Beamforming throughput with N APs:

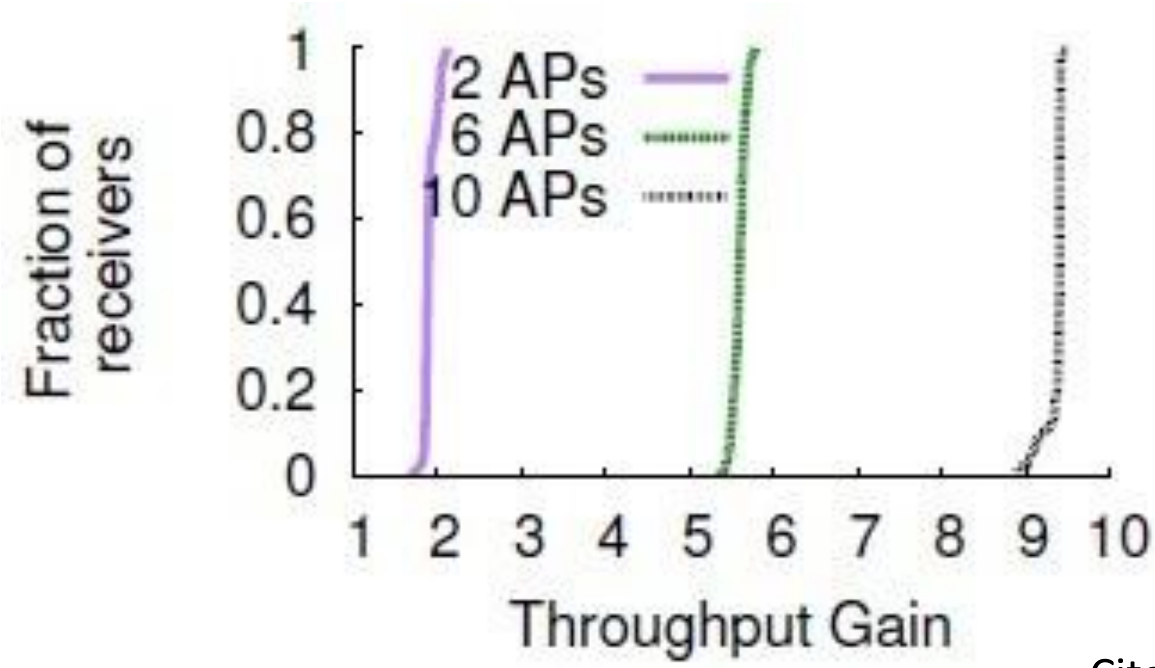
$$Nlog\left(\frac{SNR}{K}\right) = Nlog(SNR) - Nlog(K)$$

where K depends on channel matrix H, can act as constant

- 802.11 throughput is roughly: $\log(SNR)$
- The gain of JMB over 802.11 should be:

$$N(1 - \frac{\log(K)}{\log(SNR)})$$

Fairness

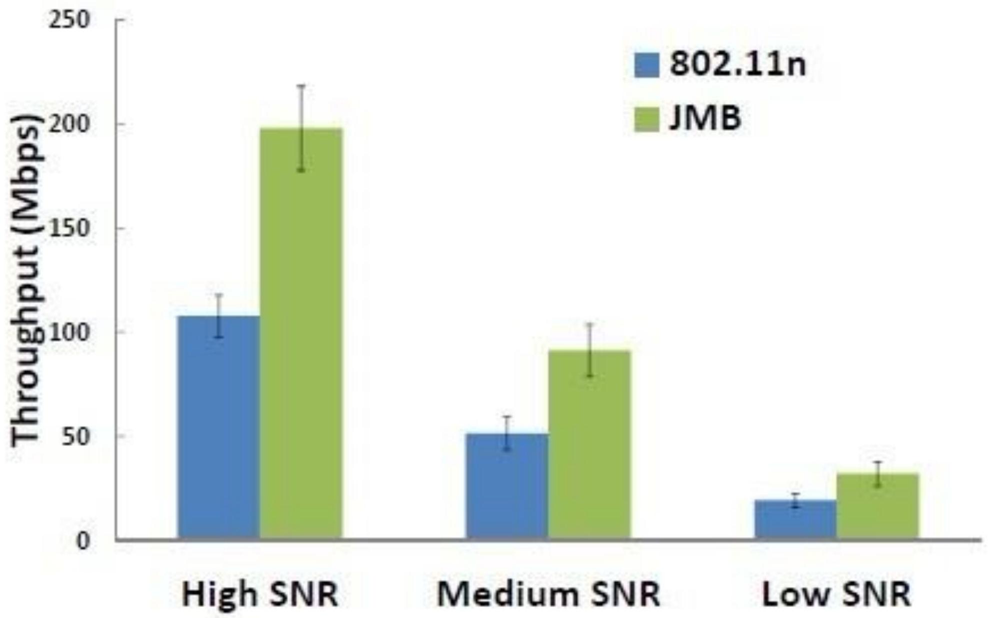


- Cite figure from paper

- All clients almost have the same throughput gain for different APs
- The CDF is wider at lower SNR

Compatibility with 802.11

- 802.11n over 20 MHz bandwidth
- Two 2-antenna USRPs acting as APs
- Two 2-antenna 802.11n clients



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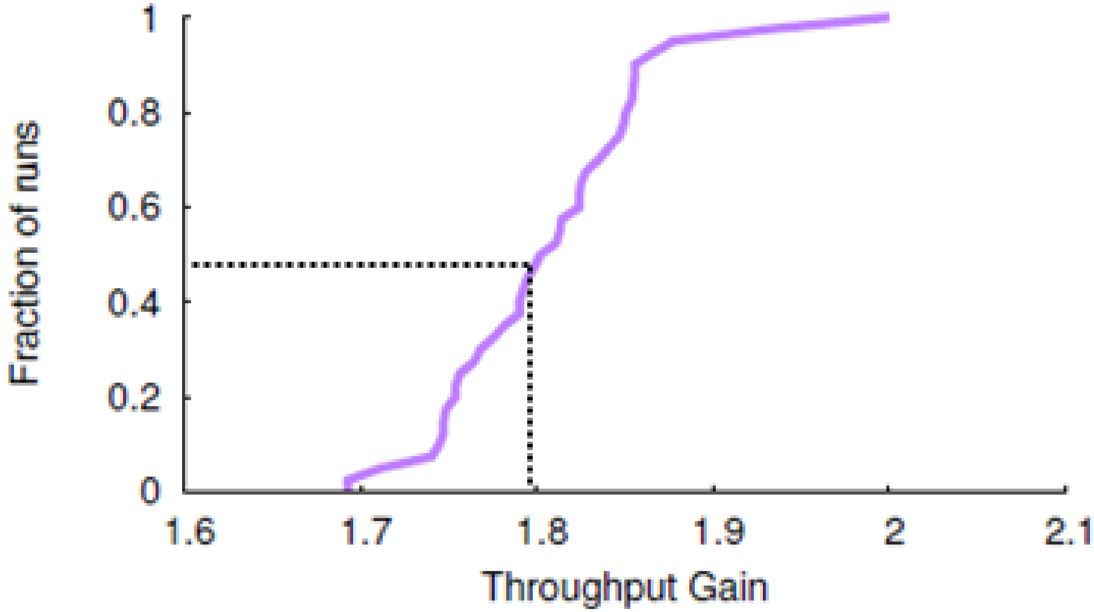
Compatibility with 802.11



- Cite figure from paper

- Median gain is 1.8× with two receivers
- Compatibility with 802.11n clients
- Compatibility with MIMO APs and clients

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Related work

- Distributed multi-user beamforming [Antonio ‘09][D. C. Jenn ‘10]
- Concurrent transmission in the network (MU-MIMO in LTE, WiMAX, SAM)
- Channel diversity gain [Z. MA ‘09] [H. Rahul ‘10]
- Distributed phase synchronization [I. Thibault ’11][S. Berger ‘07]

Future work

- Consider uplink scenario
- Mobility of clients
- Multiple antennas in each AP
- Cellular network

Conclusion

- Network throughput scales with the number of devices
- Distributed and accurate phase synchronization
- JMB enables multiple independent transmitters to transmit to independent receivers concurrently in the same channel without interference
- Strength: repeat experiment several times using random topologies