LAIA: Programming the Radio Environment with Large Arrays of Inexpensive Antennas

Speaker: Yaxiong Xie

Zhuqi Li, Yaxiong Xie, Longfei Shangguan, Rotman Ivan Zelaya, Jeremy Gummeson, Wenjun Hu, Kyle Jamieson
Wireless communication

• We have witnessed the huge success of wireless communication

• Wireless communication still faces significant challenge
  • High throughput and dense deployment
Fundamental problem

• Wireless channel is unreliable and noisy
Fundamental problem

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Previous solutions

➤ Channel coding: Spinal code, LDPC
Fundamental problem

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Previous solutions

- Channel coding: Spinal code, LDPC
- Leveraging diversity
  - Link diversity: MRD [Miu+05]
Fundamental problem

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- Channel coding: Spinal code, LDPC
- Leveraging diversity
  - Link diversity: MRD
  - Frequency diversity: OFDM
Fundamental problem

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Previous solutions
- Channel coding: Spinal code, LDPC
- Leveraging diversity
  - Link diversity: MRD
  - Frequency diversity: OFDM
  - Path diversity: MIMO
Fundamental problem

- Wireless channel is unreliable and noisy

Leveraging diversity
- Link diversity: MRD
- Frequency diversity: OFDM
- Path diversity: MIMO

Previous solutions
- Previous work focuses on end-points!
Wouldn’t it be nice to change the channel itself?

*Not* physically

Electronically and programmatically
Large array of inexpensive antennas (LAIA)

- Many inexpensive, passive electronic elements
- One point in the design space
LAIA architecture

- Best phase configuration depends on the end-point channel measurements
- **Lightweight server** configures **phase shifter** setting of each element
How does LAIA program the wireless channel?

- Deconstructive superposition VS. constructive superposition
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• Deconstructive superposition VS. constructive superposition

One goal: align the environmental paths
Align the LAIA path with environmental path
Align the LAIA path with environmental path
Challenges

• How to measure the effect of **LAIA element channels**?

• How to measure the effect of **environmental channel**?
  • The channel for environmental path and LAIA paths are superposed

• How to **configure** the phase of LAIA elements?
  • Searching the best phase combination for LAIA array is an exponentially complex problem.
Two-probe channel decomposition algorithm

Shift the phase by $0^\circ$

LAIA path

Environmental paths

Measure: $h$ Superposed channel

LAIA channel $h_p$

Environmental channel $h_{env}$
Two-probe channel decomposition algorithm

Shift the phase by 180°

LAIA path

Environmental paths

AP

Measure: \( h \) Superposed channel

LAIA channel \( h_p \)

\( h_{env} \) Environmental channel

Measure: \( h' \) Superposed channel

LAIA channel \(-h_p\)

22
Two-probe channel decomposition algorithm

Shift the phase by 180°

LAIA path

Environmental paths

Measure: \( h \) Superposed channel

LAIA channel \( h_p \)

Measure: \( h' \) Superposed channel

LAIA channel \(-h_p\)

Environmental channel

\[ h_{env} = \frac{h + h'}{2} \]
Two-probe channel decomposition algorithm

- Shift the phase by 180°
- LAIA channel
- Environmental paths
- AP
- LAIA path

Measure: $h$ Superposed channel

LAIA channel $h_p$

Measure: $h'$ Superposed channel

$-h_p$

Environmental channel $h_{env}$
Two-probe channel decomposition algorithm

Measure: \( h \) Superimposed channel

Measure: \( h \) Superposed channel

\(-h'\) Superposed channel

LAIA channel \( h_p \)

Environmental channel \( h_{env} \)

Shift the phase by 180°
Two-probe channel decomposition algorithm

Shift the phase by 180°

Measure: \(-h'\)
Superposed channel

Measure: \(h\) Superposed channel

\(h_p = \frac{h-h'}{2}\)
Two-probe channel decomposition algorithm

- Shift the phase by 180°

Environmental channel:

\[ h_{env} = \frac{h + h'}{2} \]

LAIA channel:

\[ h_p = \frac{h - h'}{2} \]

Two channel probes can factor the environmental channel and a LAIA element channel.
Multi-element case: how to decompose?
Multi-element case: how to decompose?

2 probes
Multi-element case: how to decompose?

2 probes
Multi-element case: how to decompose?

2 probes
Multi-element case: how to decompose?

![Diagram](image-url)
Multi-element case: how to decompose?

2 probes
Multi-element case: how to decompose?

2 probes
Channel alignment

\[ Q \]

\[ I \]
Channel alignment

\[ Q \]

\[ h_{p1} \]

\[ h_{p2} \]

\[ h_{env} \]

\[ I \]
Phase shifter rotate the same amount of phase for channels of different frequencies!
Channel alignment

Narrowband channel $I$ vs $Q$

- $h_{env}$
- $h_{p1}$
- $h_{p2}$

Frequency $f_1$, $f_2$, $f_3$, $f_4$

Environmental channel

LAIA channel
Channel alignment

Narrowband channel

\( I \)

\( Q \)

\( h_{env} \)

\( h_{p1} \)

\( h_{p2} \)

Frequency

Environmental channel

LAIA channel

\( f_1 \)

\( f_2 \)

\( f_3 \)

\( f_4 \)
Channel alignment

Narrowband channel

\[ Q \]
\[ h_{\text{env}} \]
\[ h_{p_1} \]
\[ h_{p_2} \]
\[ I \]

Frequency

Spatial

Antenna 1

Antenna 2

Environmental channel

LAIA channel

\( f_1 \)

\( f_2 \)

\( f_3 \)

\( f_4 \)
Channel alignment

Narrowband channel

I

Spatial

Antenna 1

Environmental channel

LAIA channel

Antenna 2

Environmental channel

LAIA channel

Frequency

h_{env}

h_{p1}

h_{p2}

f_1

f_2

f_3

f_4

X

✓

X

X
Channel alignment

Narrowband channel

Environmental channel

LAIA channel

Spatial

Antenna 1

Antenna 2

Frequency

$h_{p1}$

$h_{p2}$

$h_{env}$

$f_1$

$f_2$

$f_3$

$f_4$
Channel alignment

Narrowband channel $I$ vs. $Q$

$MIMO$-OFDM channel

Antenna 1

Antenna 2

$f_1$ $f_2$ $f_3$ $f_4$
Channel alignment

Problem: simultaneously align across multiple frequencies and antennas
Strawman solution: exhaustive search

- **Example**: 2-element LAIA array, MIMO wideband channel, 3-bit phase shifter (8 possible phase)

![Diagram of signal phases for Antenna 1 and Antenna 2, showing different channel scenarios](image)
Strawman solution: exhaustive search

- *Example*: 2-element LAIA array, MIMO wideband channel, 3-bit phase shifter (8 possible phase)
Strawman solution: exhaustive search

- **Example**: 2-element LAIA array, MIMO wideband channel, 3-bit phase shifter (8 possible phase)

\[ 8^2 \text{ possible combinations} \]
Strawman solution: exhaustive search

• **Example**: 2-element LAIA array, MIMO wideband channel, 3-bit phase shifter (8 possible phase)

Search space is $N^L$ where $N$ is the number of phase shifts and $L$ is the number of LAIA elements!
Our solution: iterative search

• Example: 2-element LAIA array, MIMO wideband channel, 3-bit phase shifter (8 possible phase)
Our solution: iterative search

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Multiple links

- Multiple links share the wireless medium via CSMA
- LAIA elements must be configured before working
Multiple links

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Goal: maximize the total throughput without decreasing the throughput of any individual link
Multiple links

Phase configuration of all LAIA elements
\[ \theta = [\theta_1, \theta_2, ..., \theta_L] \]

**Optimization problem**

Objective function:  \[ \max_{\theta} C_1(\theta) + C_2(\theta) \]

Subject to:
- \[ C_1(\theta) > C_1(\text{off}) \]
- \[ C_2(\theta) > C_2(\text{off}) \]

where \( C_1(\text{off}) \) and \( C_2(\text{off}) \) is the channel capacities of link 1 and 2 when all LAIA elements are turned off.
Implementation and deployment

- 36 LAIA elements are implemented in Princeton IoT house
- 4-bit phase shifters (16 phase shifts)
Micro-benchmark: controllability

• **Definition**: subcarrier controllability
Micro-benchmark: controllability

• **Definition**: subcarrier controllability

![Diagram](image-url)
Micro-benchmark: controllability

• **Definition**: subcarrier controllability

Subcarrier controllability  **5 dBm**
Micro-benchmark: controllability

- **Definition**: subcarrier controllability

![Graph showing subcarrier controllability](image)

- Subcarrier controllability: $5 \text{ dBm}$
Micro-benchmark: controllability

- **Definition**: subcarrier controllability

Subcarrier controllability \( 5 \text{ dBm} \)
Micro-benchmark: controllability

Greater controllability for weaker subcarriers
Baseline: Environmental SISO channel capacity

![Graph showing CDF over links and channel capacity (bps/Hz)]

All LAIA elements are turned OFF
LAIA improves SISO channel capacity

Channel capacity (bps/Hz)

CDF over links

- Environment
- LAIA

All LAIA elements are turned **ON**
Link diversity also improves SISO channel capacity

![Graph showing CDF over links for different channel capacities with labels for Environment, MRD, and LAIA. The graph illustrates the improvement in channel capacity with link diversity. A note states: All LAIA elements are turned OFF.](image-url)
LAIA improves capacity with or without link diversity

- LAIA provides a **51% channel capacity improvement** compared to the environment alone (**25% over MRD alone**)
LAIA increases 2x2 MIMO channel capacity

- Max: 49%
- Med: 18.95%
- Min: 3.4%
LAIA increases 3x3 MIMO channel capacity

- **Max:** 36%
- **Med:** 15.68%
- **Min:** 5.3%

CDF over links:

- MIMO 2x2
- MIMO 3x3
LAIA increases 4x4 MIMO channel capacity

- Where the improvement comes from, total channel SNR or channel condition improvement?
Why does LAIA help MIMO links?

![Graph showing CDF over links for different channel conditions and SNRs.](image)
2x2: LAIA helps both channel conditioning and SNR
3x3: LAIA helps channel conditioning more than SNR

![Diagram showing CDF over links for different channel conditions: LAIA 2x2, Env 2x2, LAIA 3x3, Env 3x3, LAIA 4x4, Env 4x4. The CDF plots for condition number (dB) and total channel SNR (dB) are compared, highlighting that LAIA 3x3 provides better channel conditioning compared to SNR.](image-url)
4x4: LAIA helps channel conditioning but not SNR

- Majority of the MIMO capacity gain is achieved by decreasing the condition number of the MIMO channel
The programmable environment may damage non-targeted links

**Capacity of Link 1**

**Capacity of Link 2**
The programmable environment may damage non-targeted links

Capacity of Link 1

Capacity of Link 2
The programmable environment may damage non-targeted links

**Capacity of Link 1**

**Capacity of Link 2**
LAIA helps multiple links simultaneously

![Graph showing CDF over locations for different environments and links.

**Capacity of Link 1**

**Capacity of Link 2**

Legend:
- Environment
- Max link 1
- Max link 2
- Max 2 links LAIA
LAIA helps multiple links simultaneously

LAIA achieves performance close to a programmable environment targeting one link in isolation
Conclusion

• The first step towards programming the radio environment
  • A qualitatively different approach to the conventional strategy of optimizing the endpoints

• We implement a prototype that reconfigures the radio environment in real time

• Extensive evaluation demonstrating communications throughput enhancement that complement many other state of the art methods