Vidyut: Exploiting Power Line Infrastructure for Enterprise Wireless Networks

Vivek Yenamandra and Kannan Srinivasan

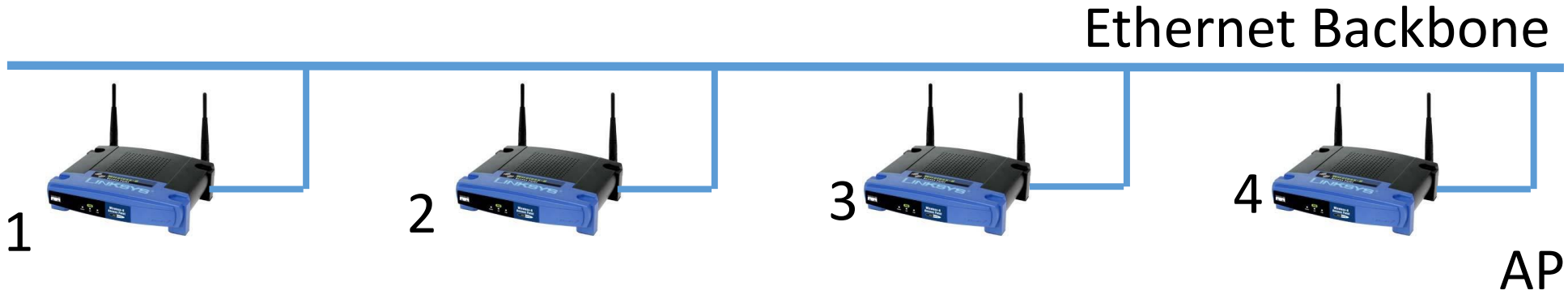
THE OHIO STATE UNIVERSITY

Motivation

- Increasing demand for wireless capacity
  - Proliferation of BYOD in workplaces
  - Data Intensive applications: Video Streaming, Teleconferencing, Surveillance etc.
- Scare spectrum resources

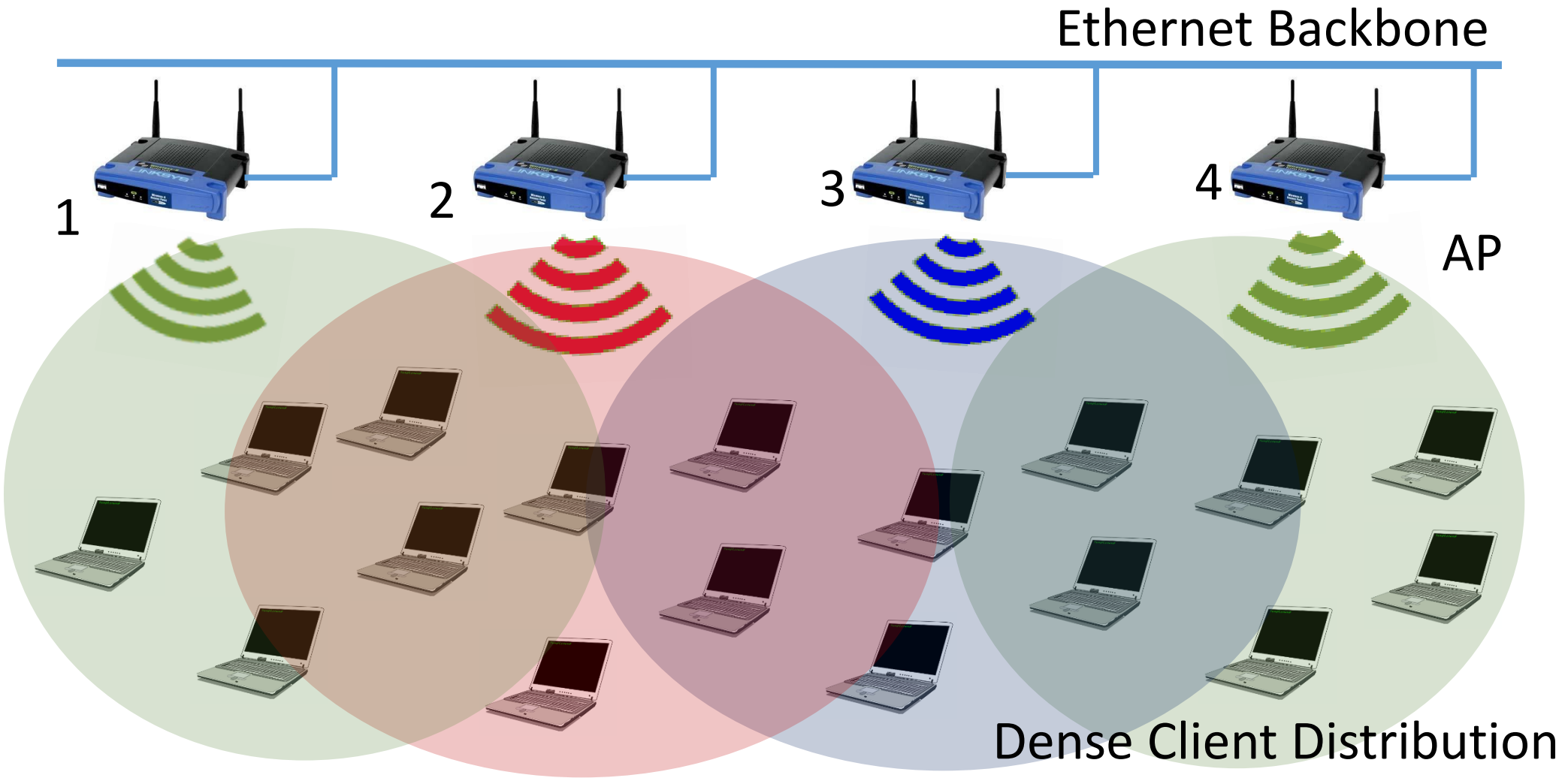
Growing emphasis for spectrally efficient large capacity wireless networks

Enterprise WLAN

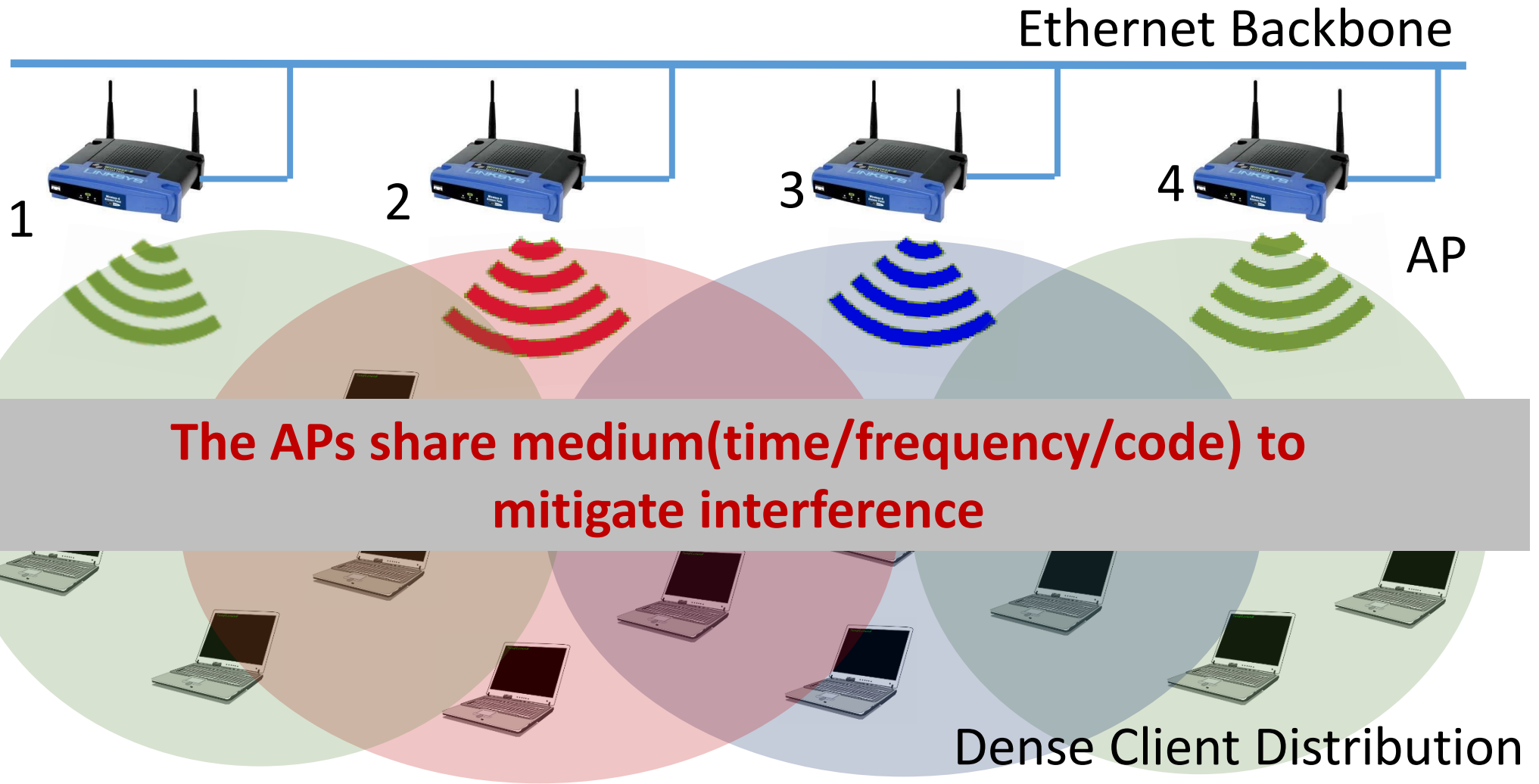


Dense Client Distribution

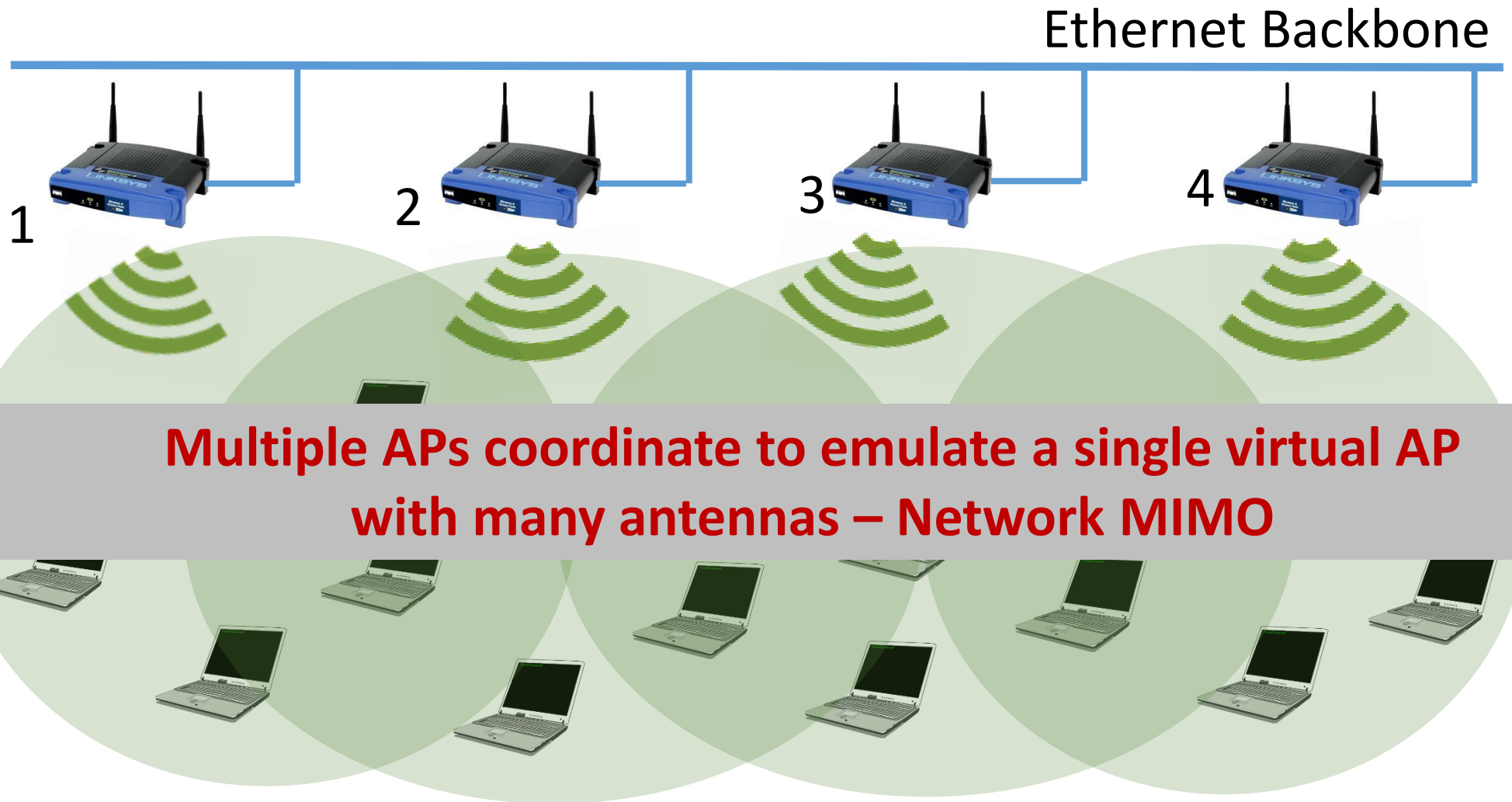
Enterprise WLAN



Enterprise WLAN

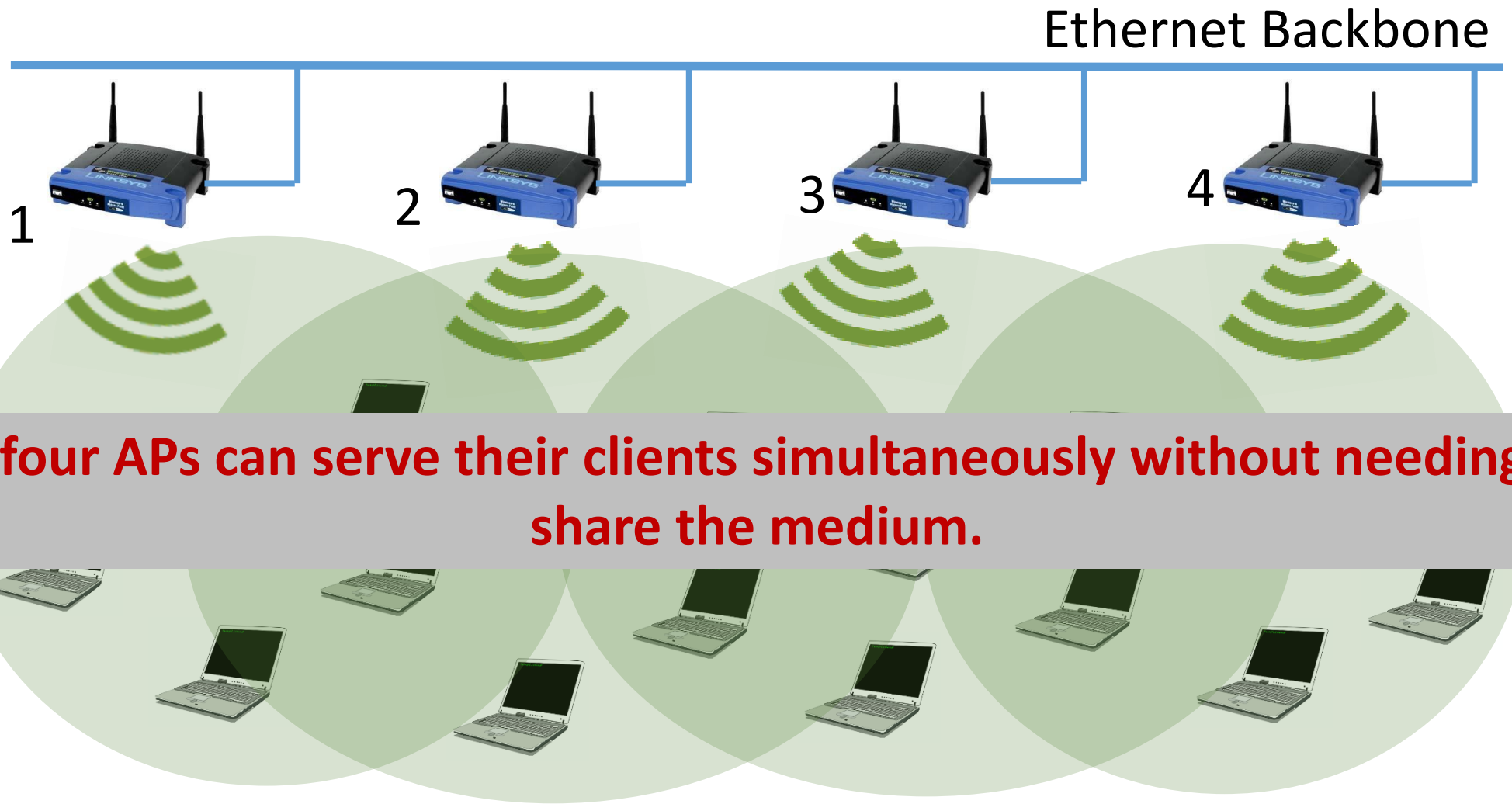


Alternative?



Multiple APs coordinate to emulate a single virtual AP with many antennas – Network MIMO

Why Network MIMO?

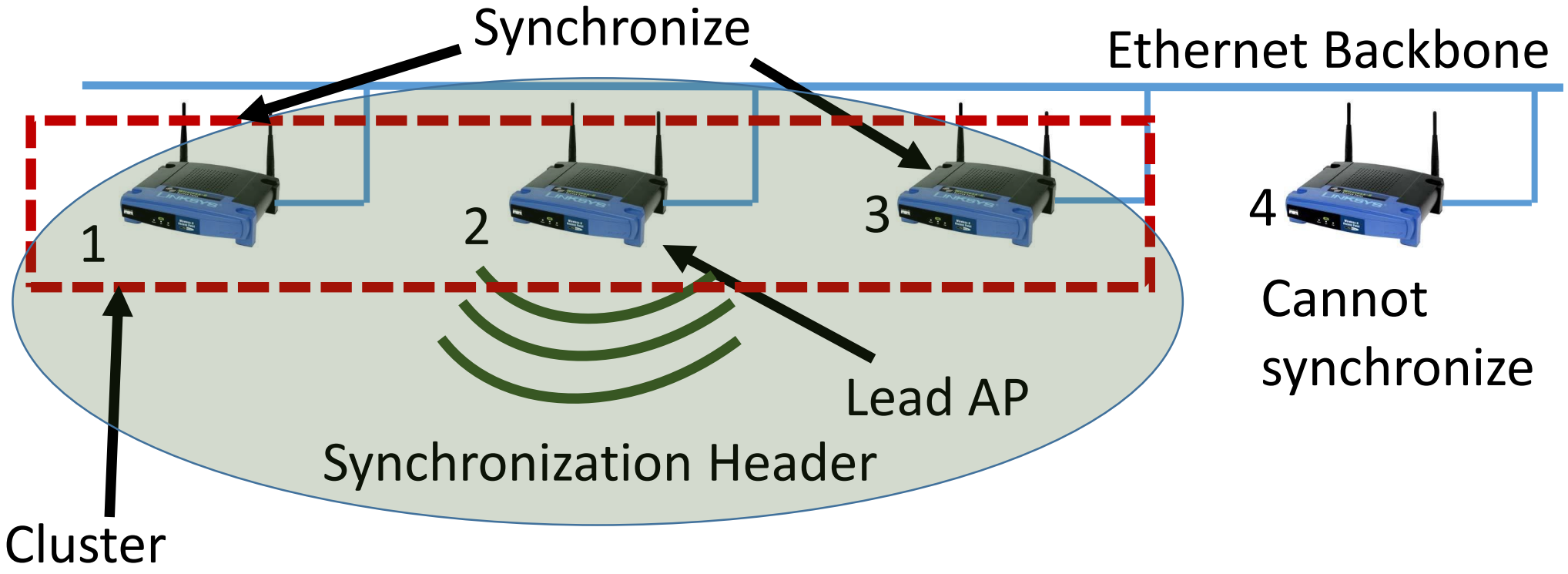


All four APs can serve their clients simultaneously without needing to share the medium.

Network MIMO Prerequisite

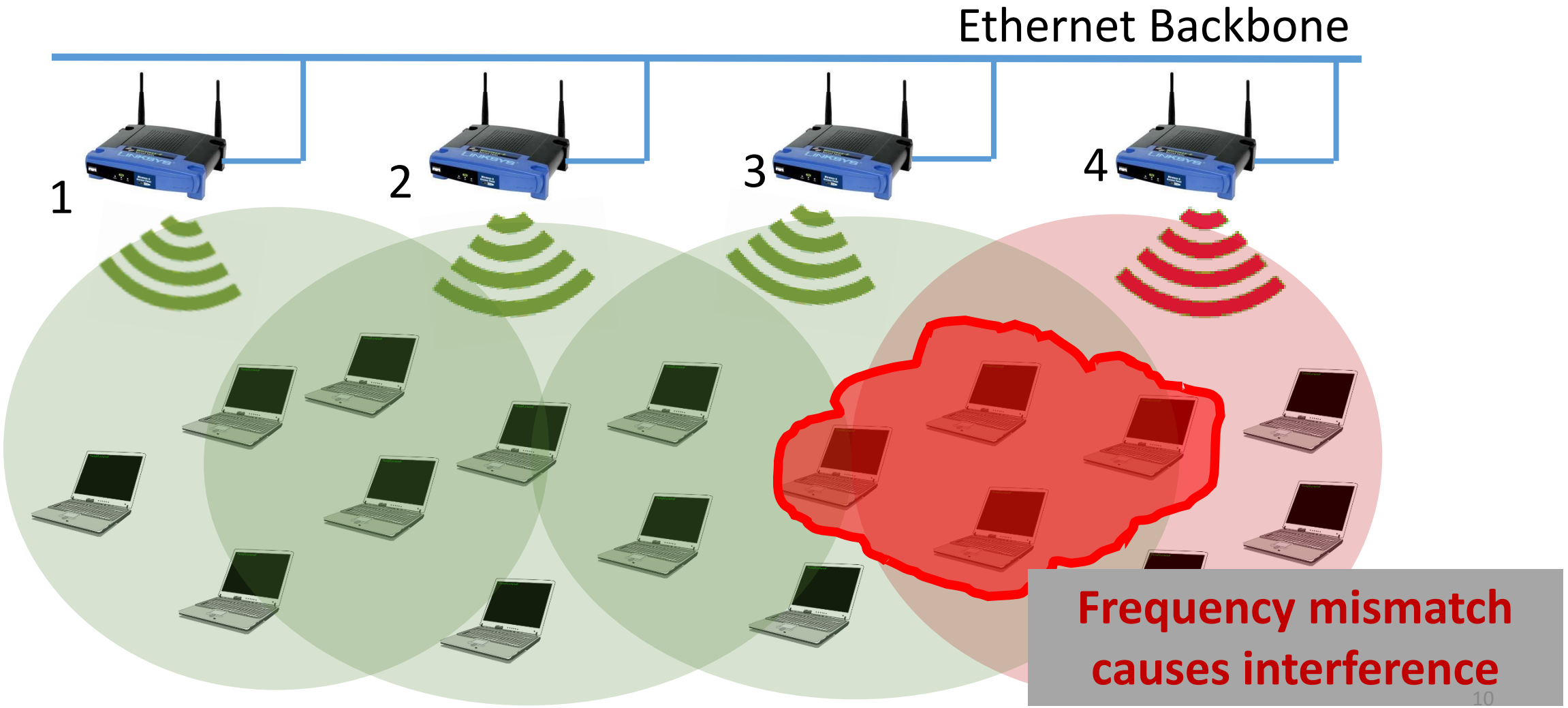
The coordinating APs *need* to be synchronized in frequency and time

Network MIMO Implementation[1]

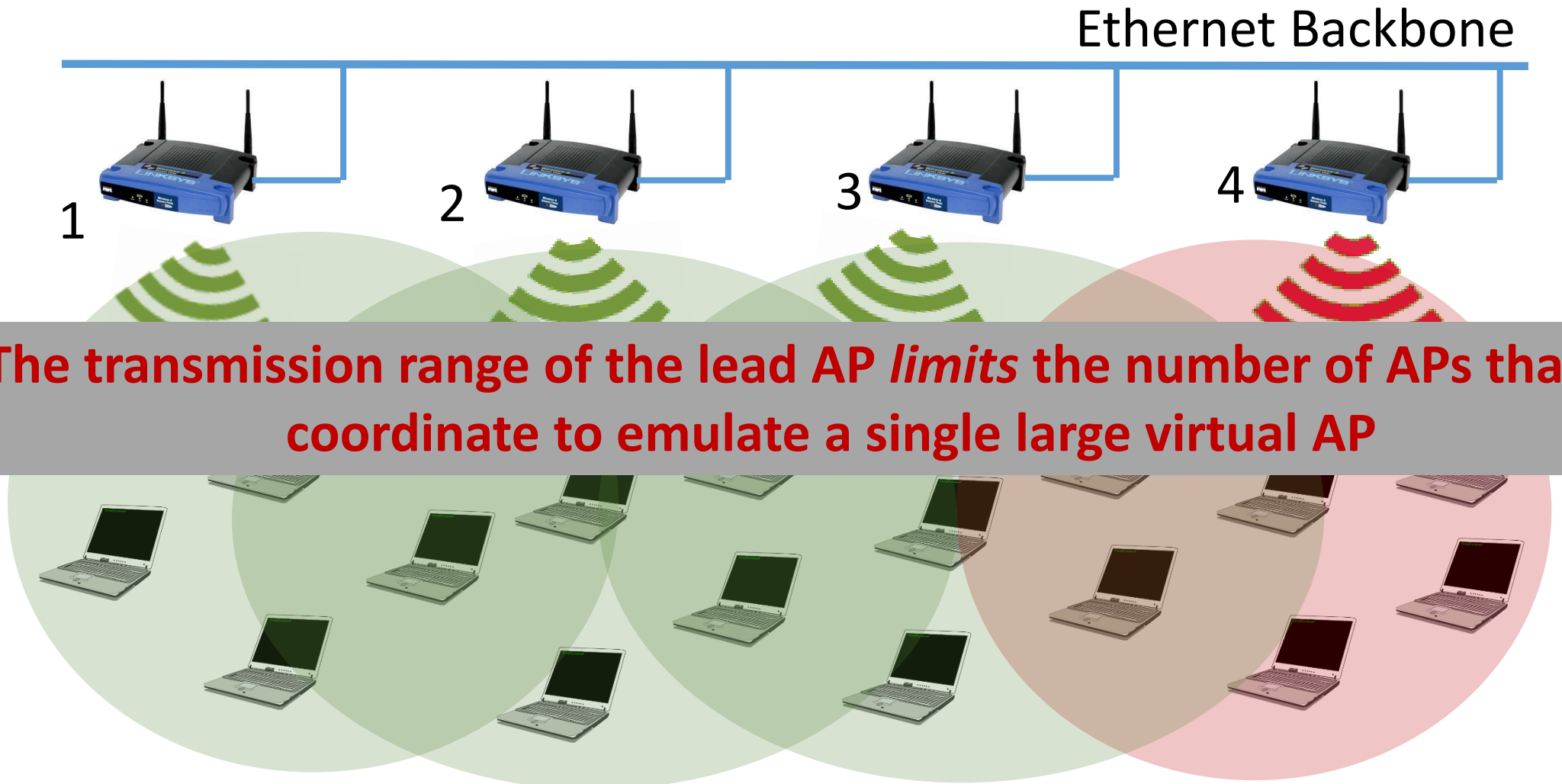


[1]. Hariharan et.al, JMB: Scaling Wireless Capacity with User Demands, SIGCOMM, 2012

Network MIMO Implementation



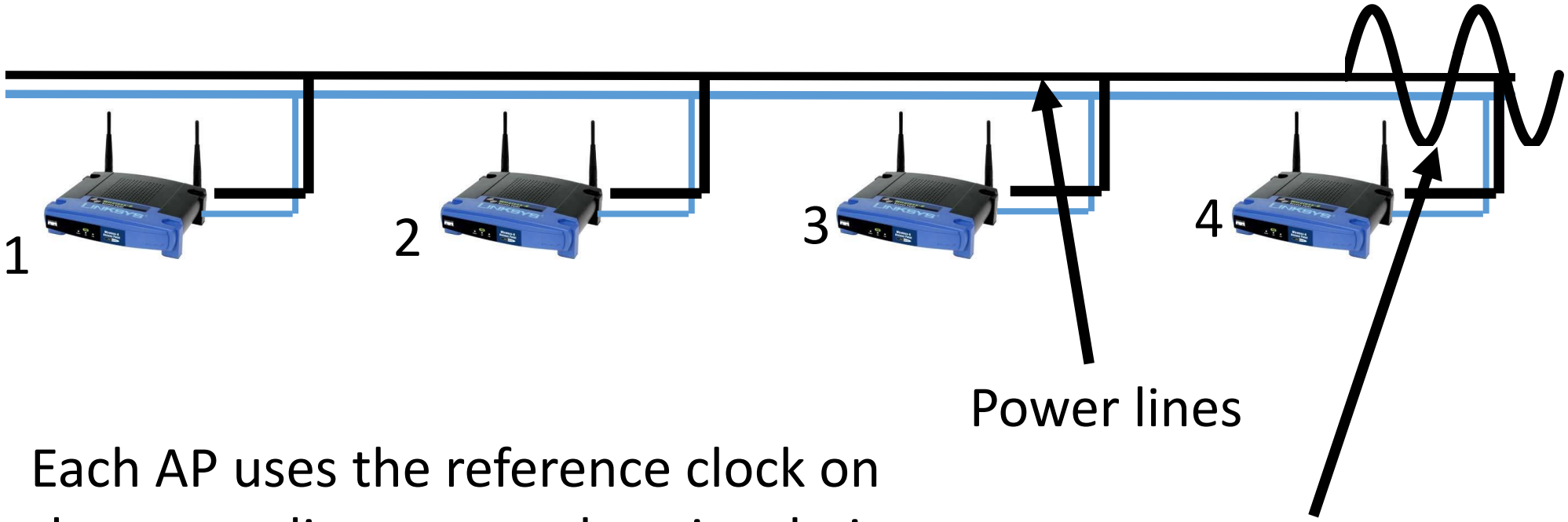
Network MIMO Implementation



The transmission range of the lead AP *limits* the number of APs that can coordinate to emulate a single large virtual AP

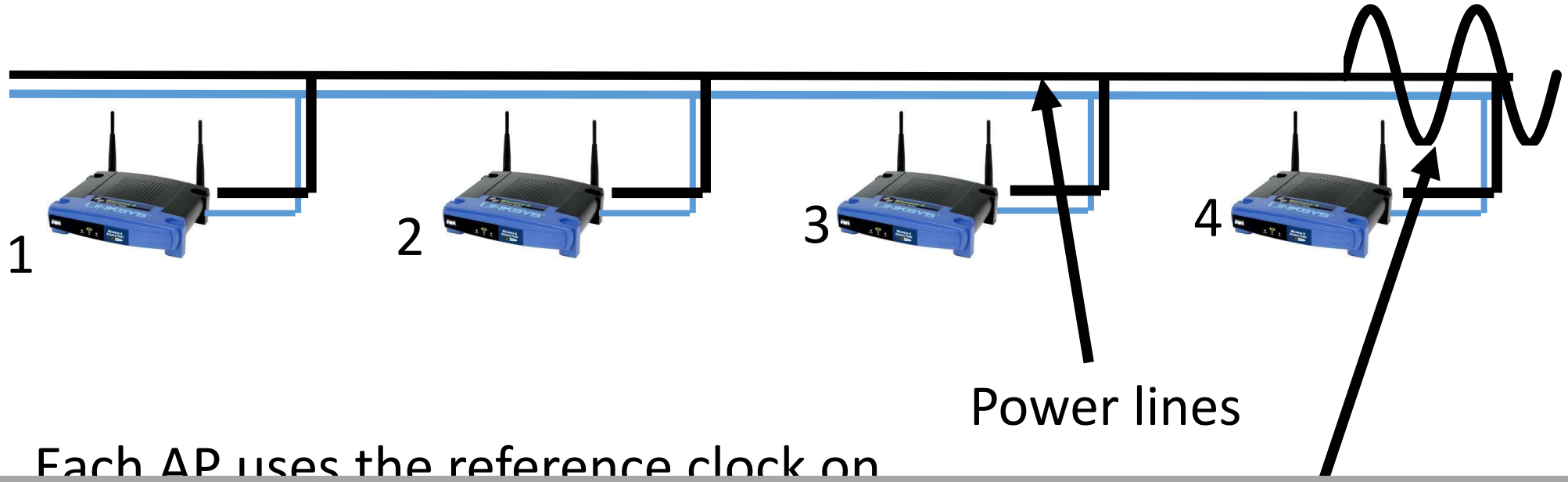
How can we synchronize *across* clusters?

Vidyut



Each AP uses the reference clock on the power lines to synchronize their own carrier clocks using a PLL.

Vidyut



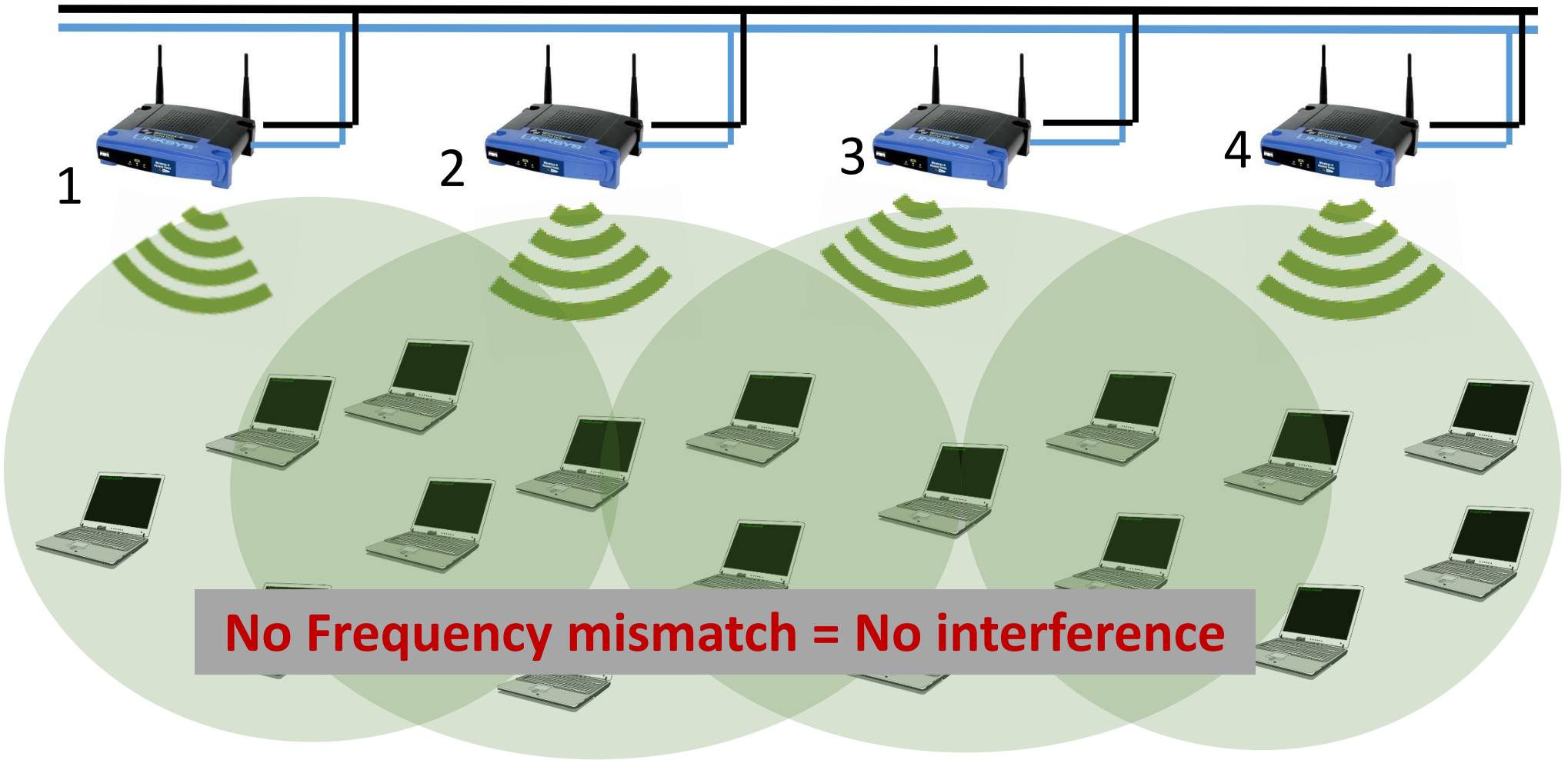
Each AP uses the reference clock on

All APs are synchronized

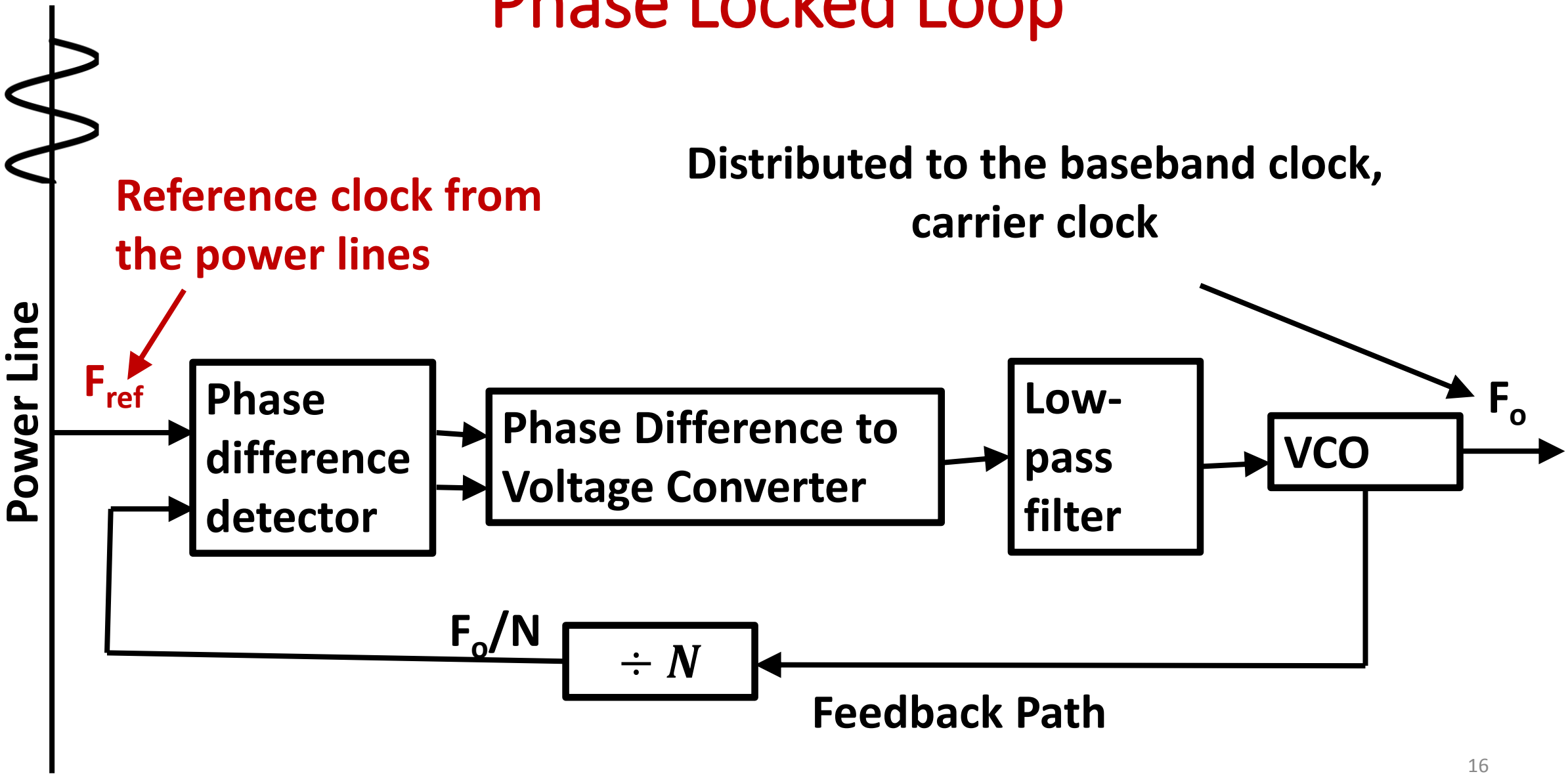
own carrier clocks using a PLL.

transmitted on
the Power Lines

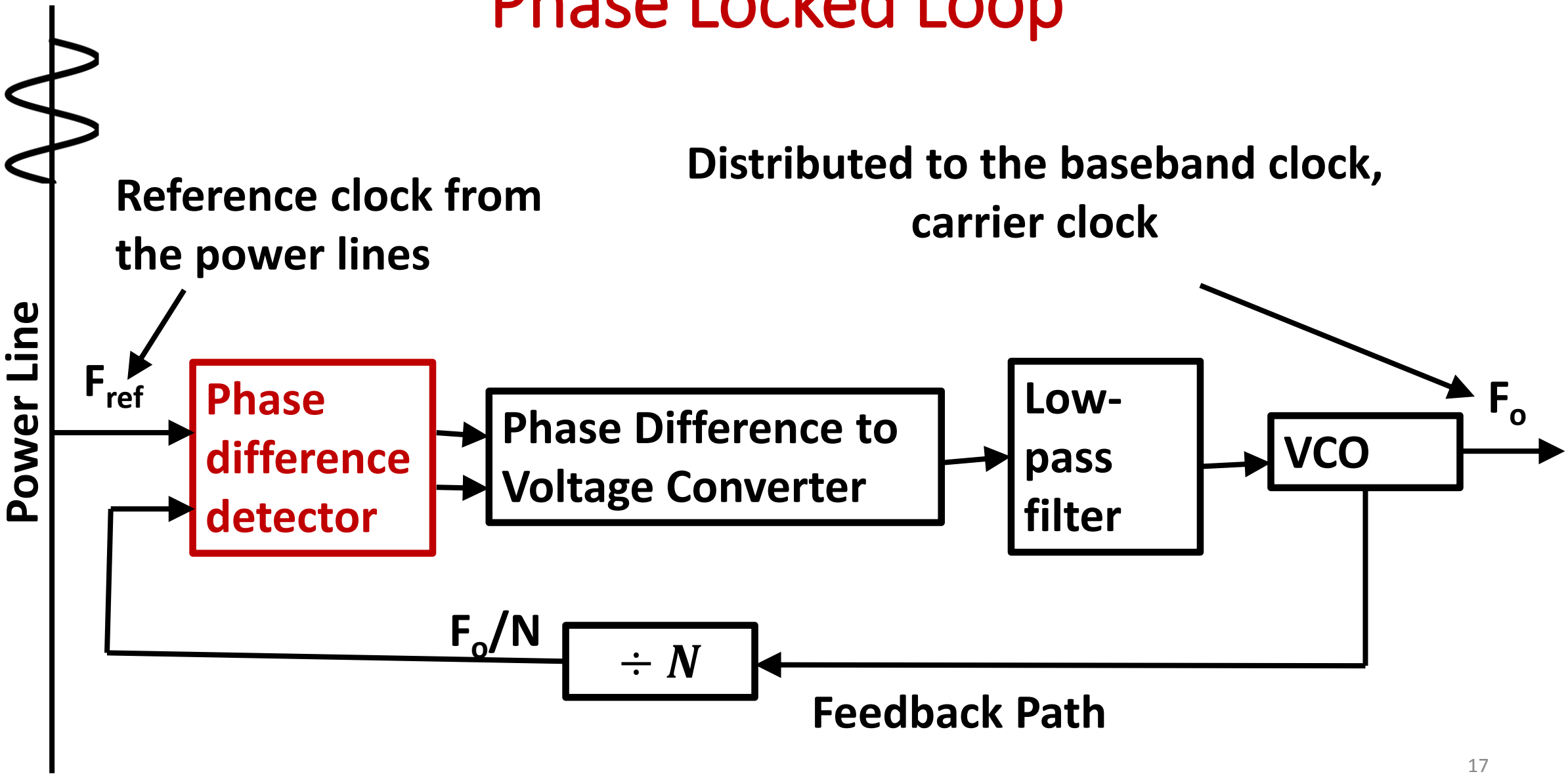
Vidyut



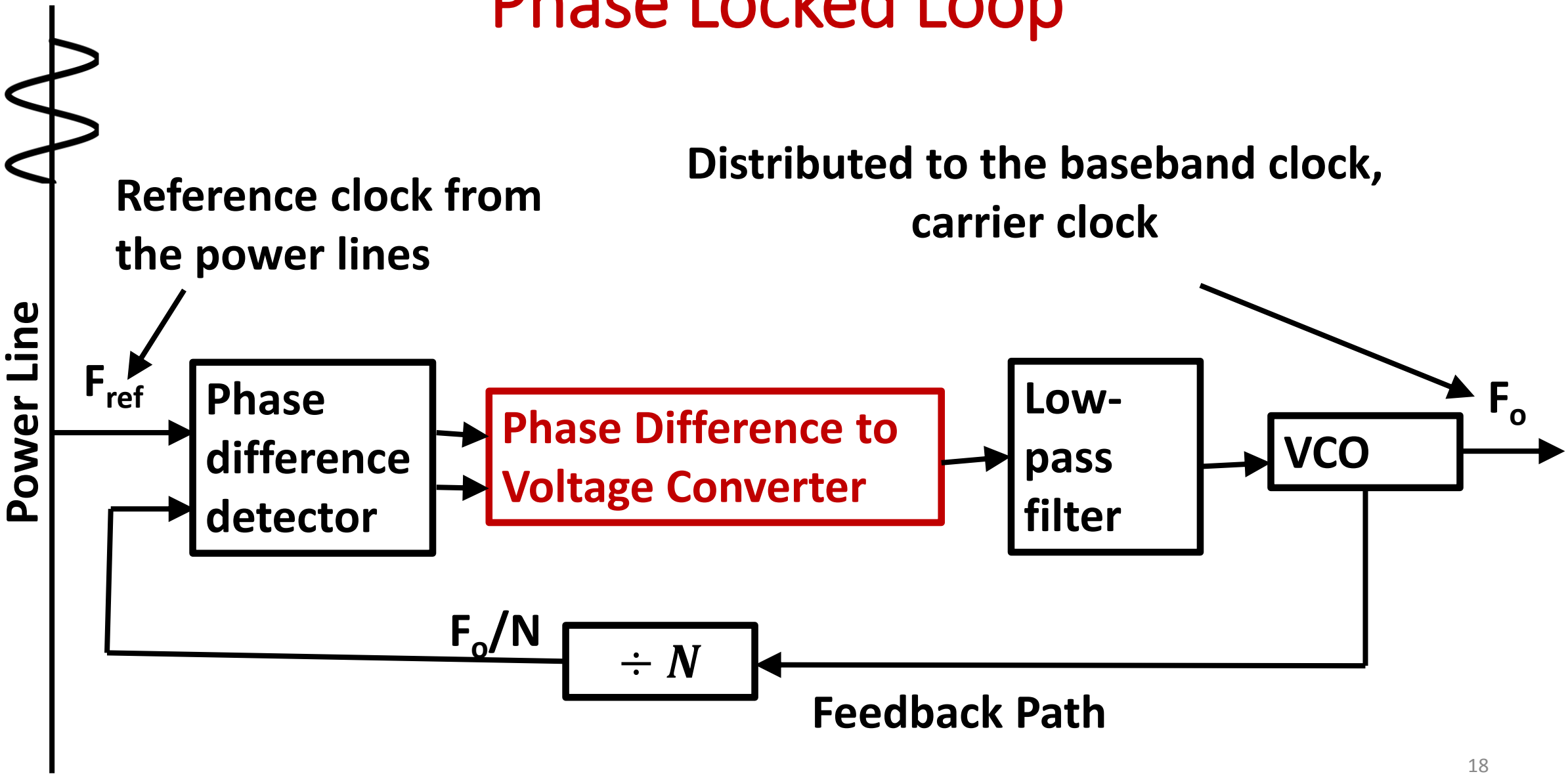
Phase Locked Loop



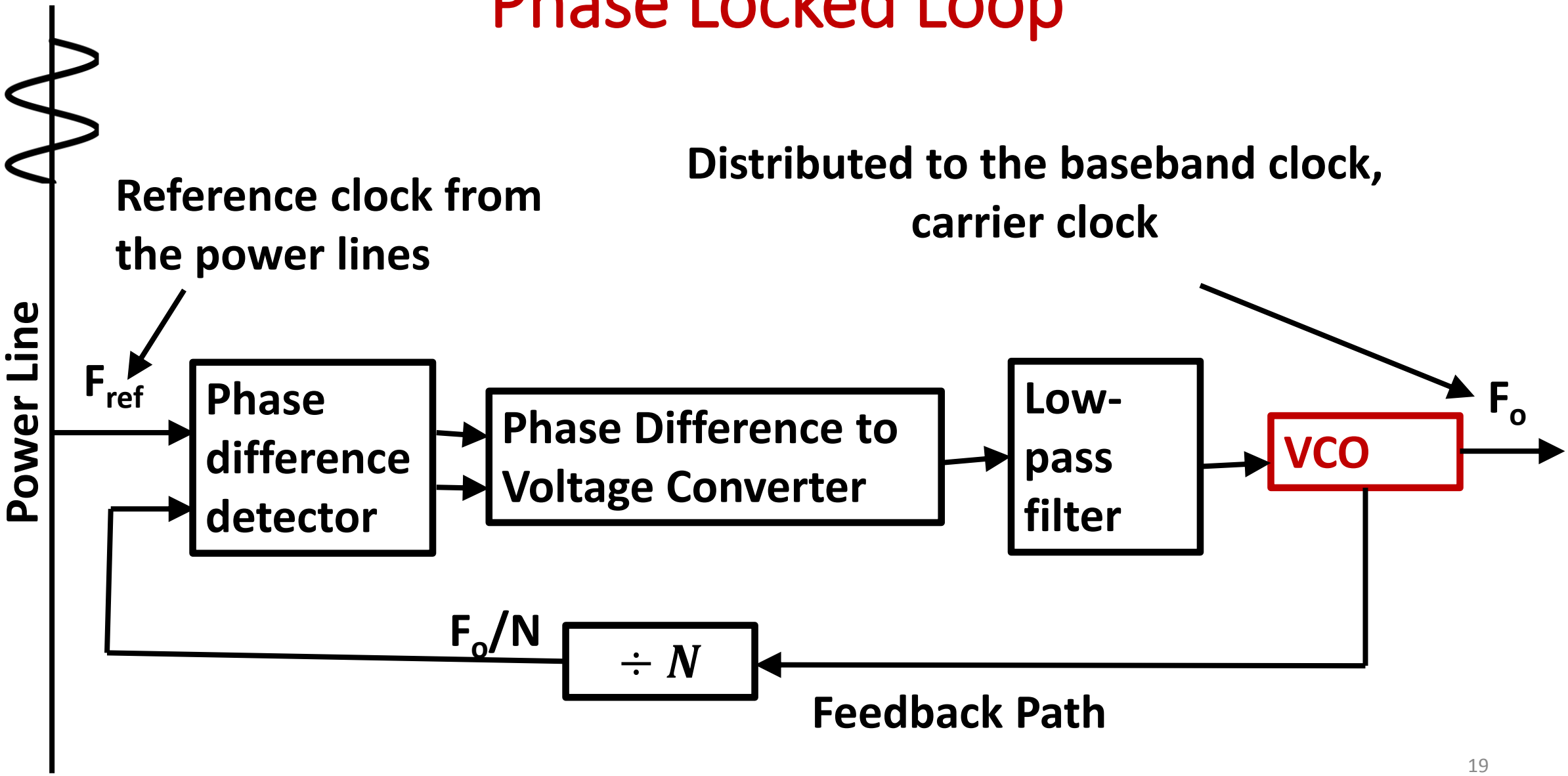
Phase Locked Loop



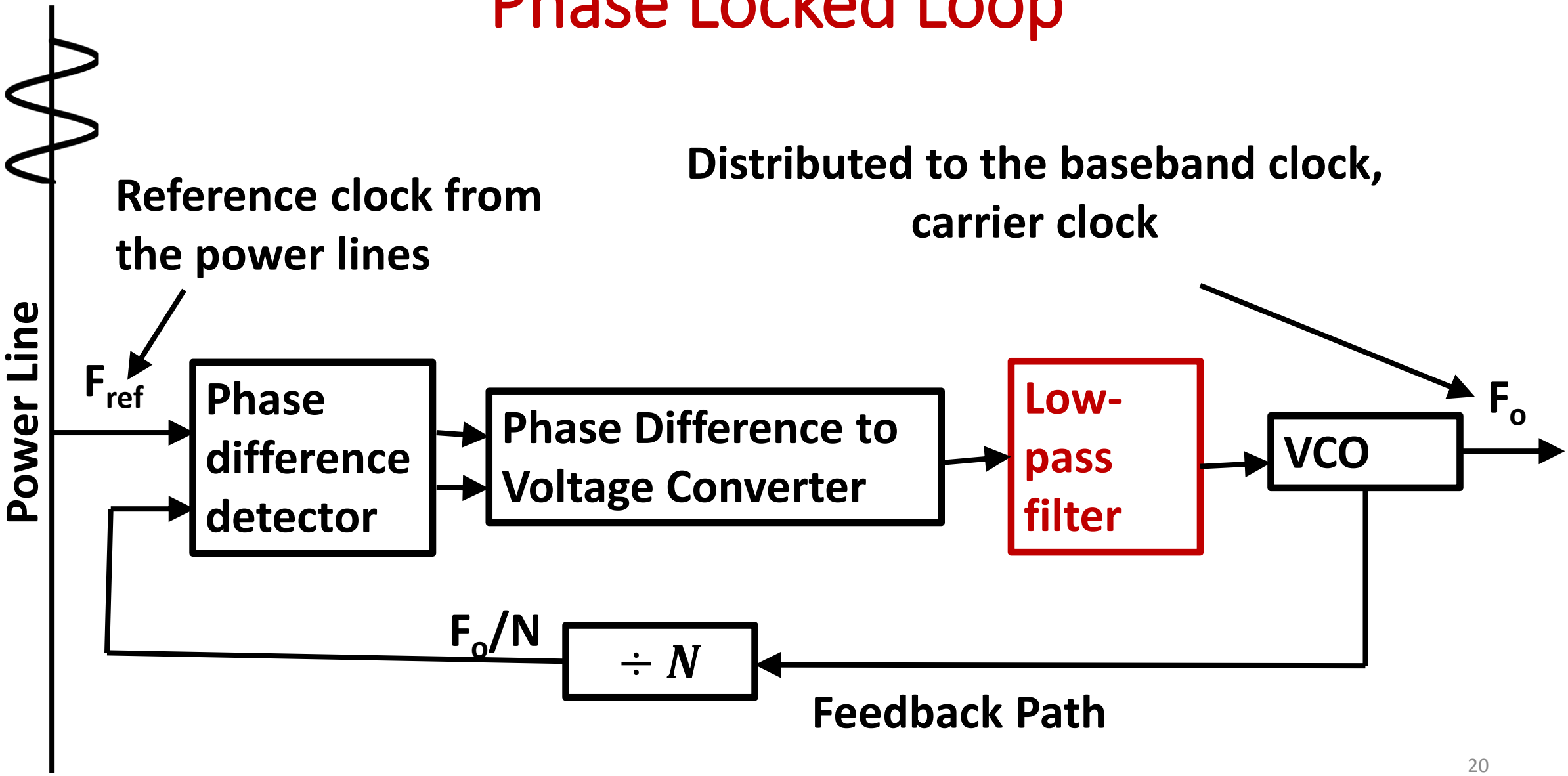
Phase Locked Loop



Phase Locked Loop



Phase Locked Loop

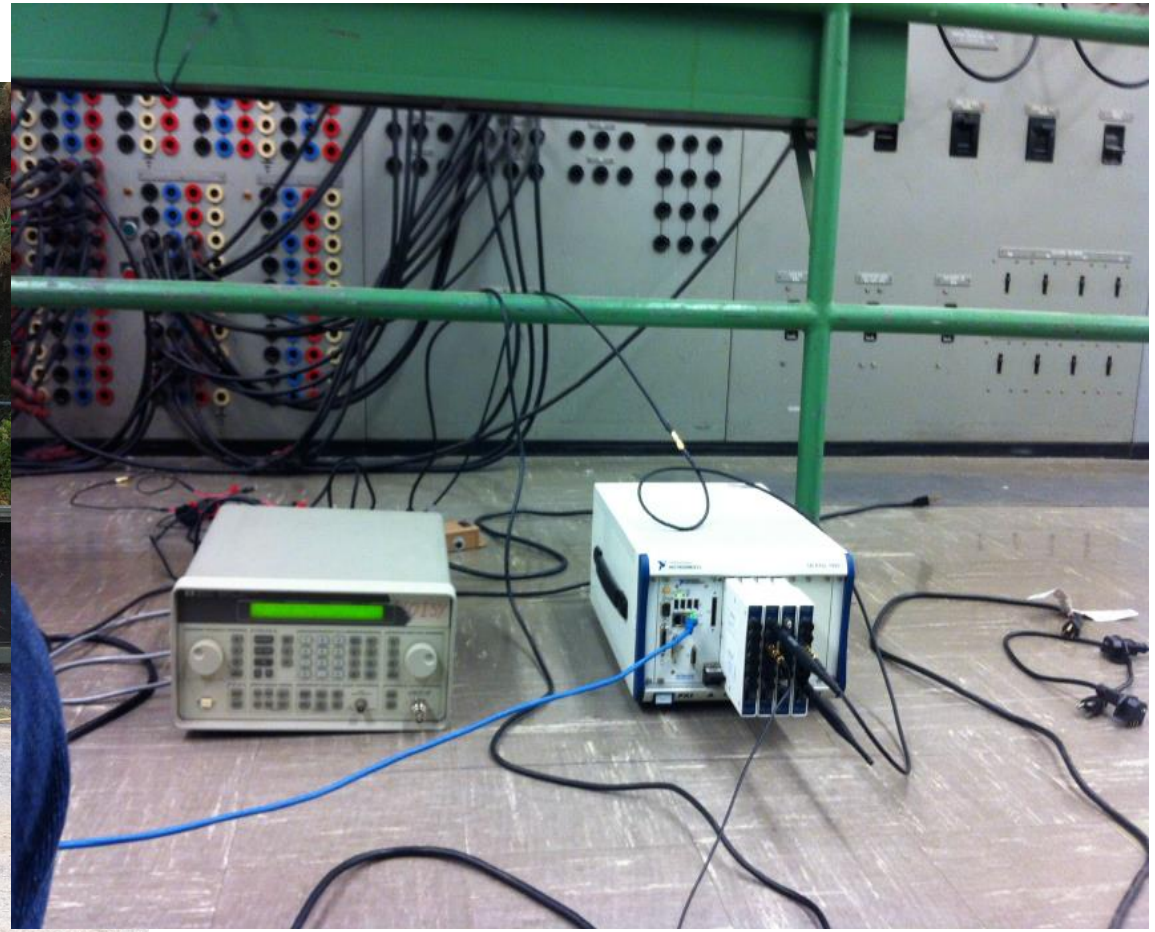


How to select the reference frequency?

Selecting the Reference Frequency

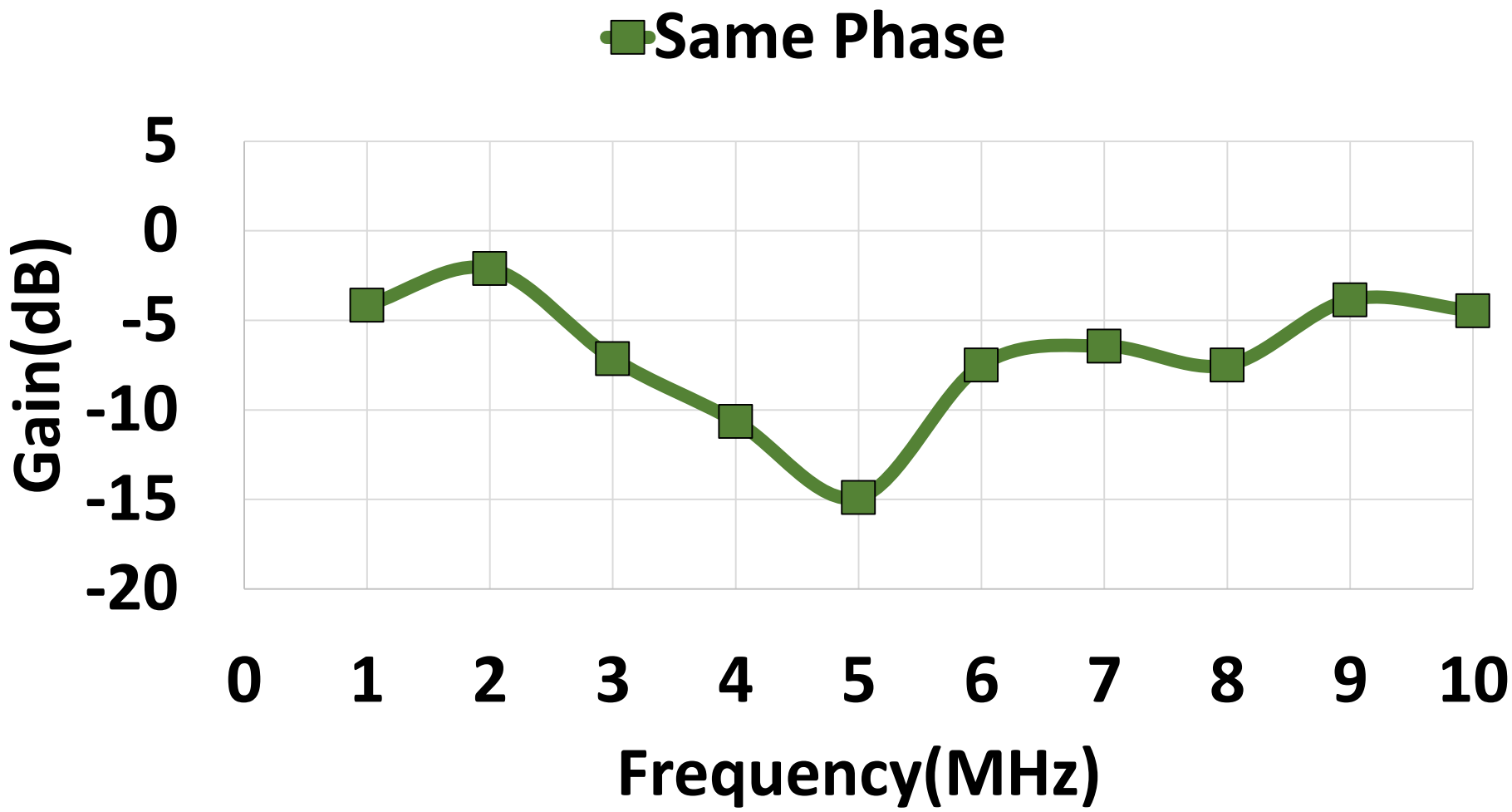
- Determined by the Power Distribution Network
  - Elements like transformers/distribution panels

Measuring Characteristics

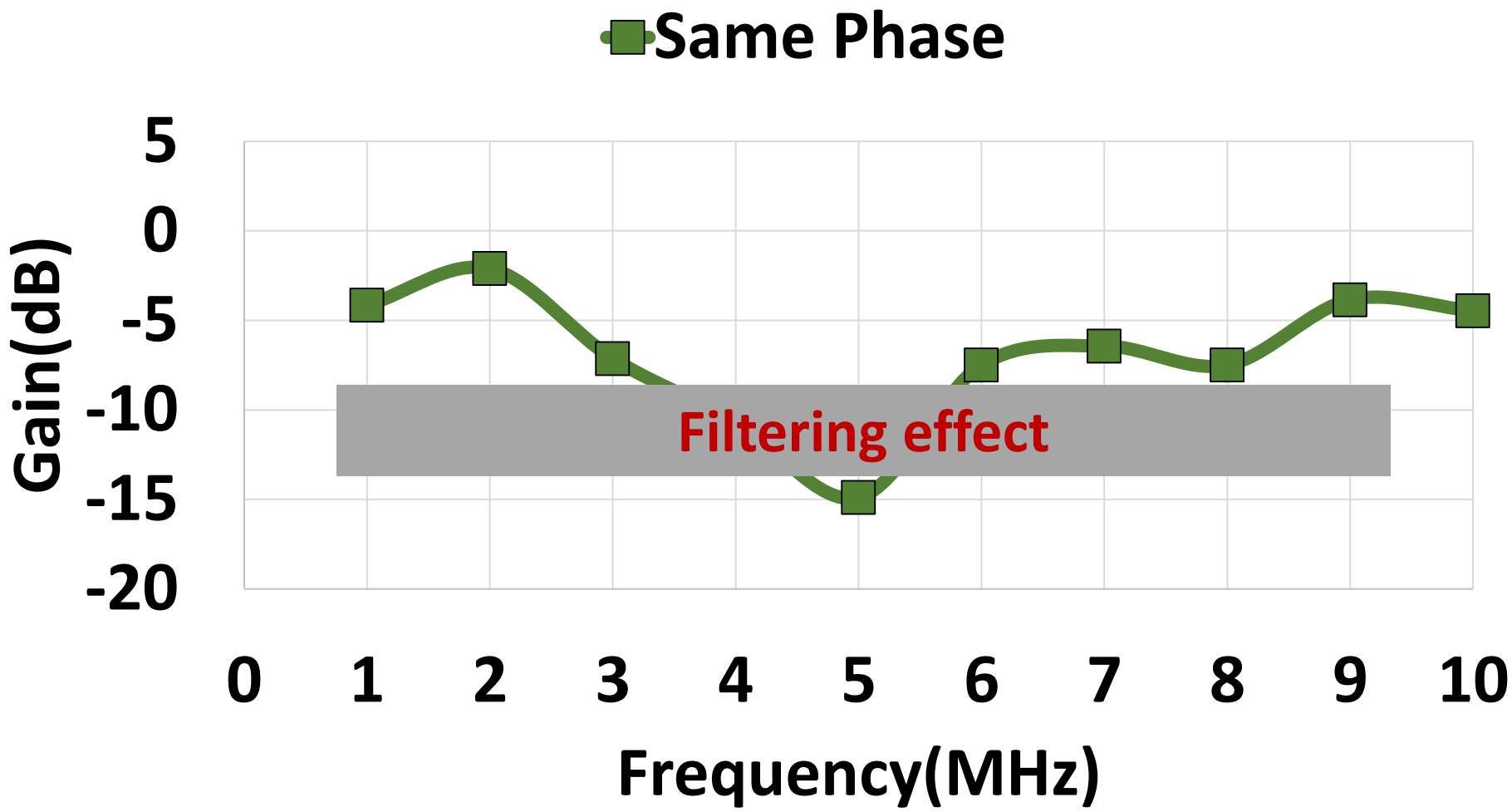


Transformer Response

Transformer Response



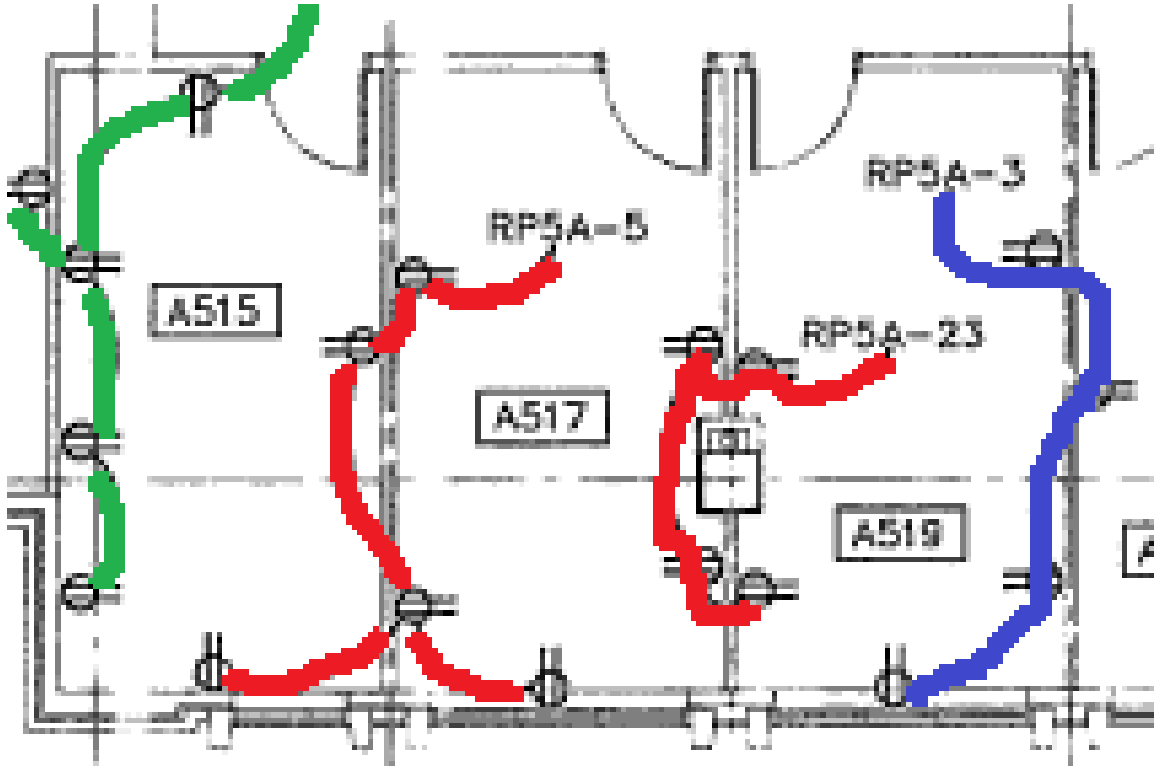
Transformer Response



Three-Phase Power Supply

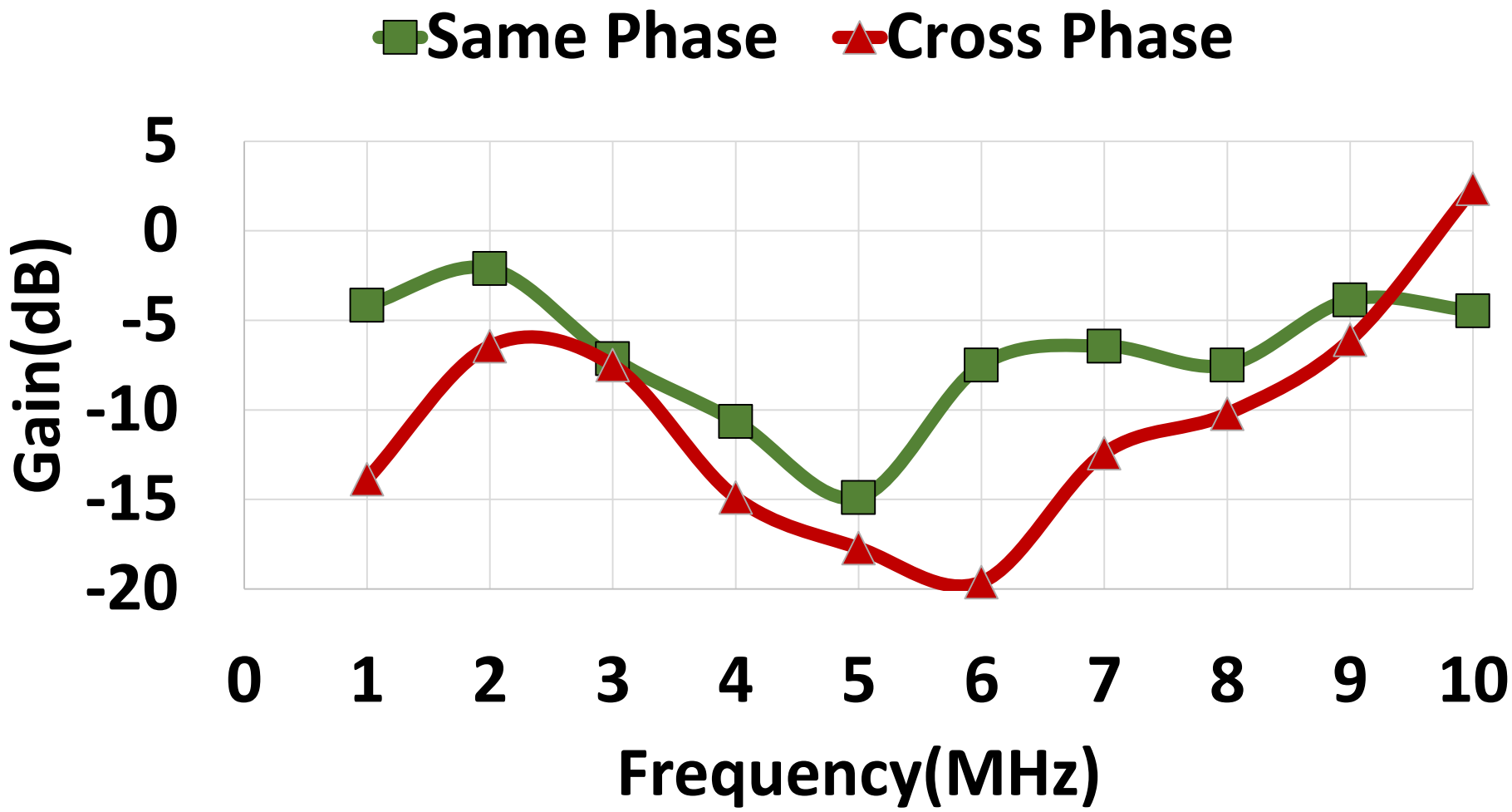
The three phases are *physically* isolated

Do we need a separate reference clock for each phase?

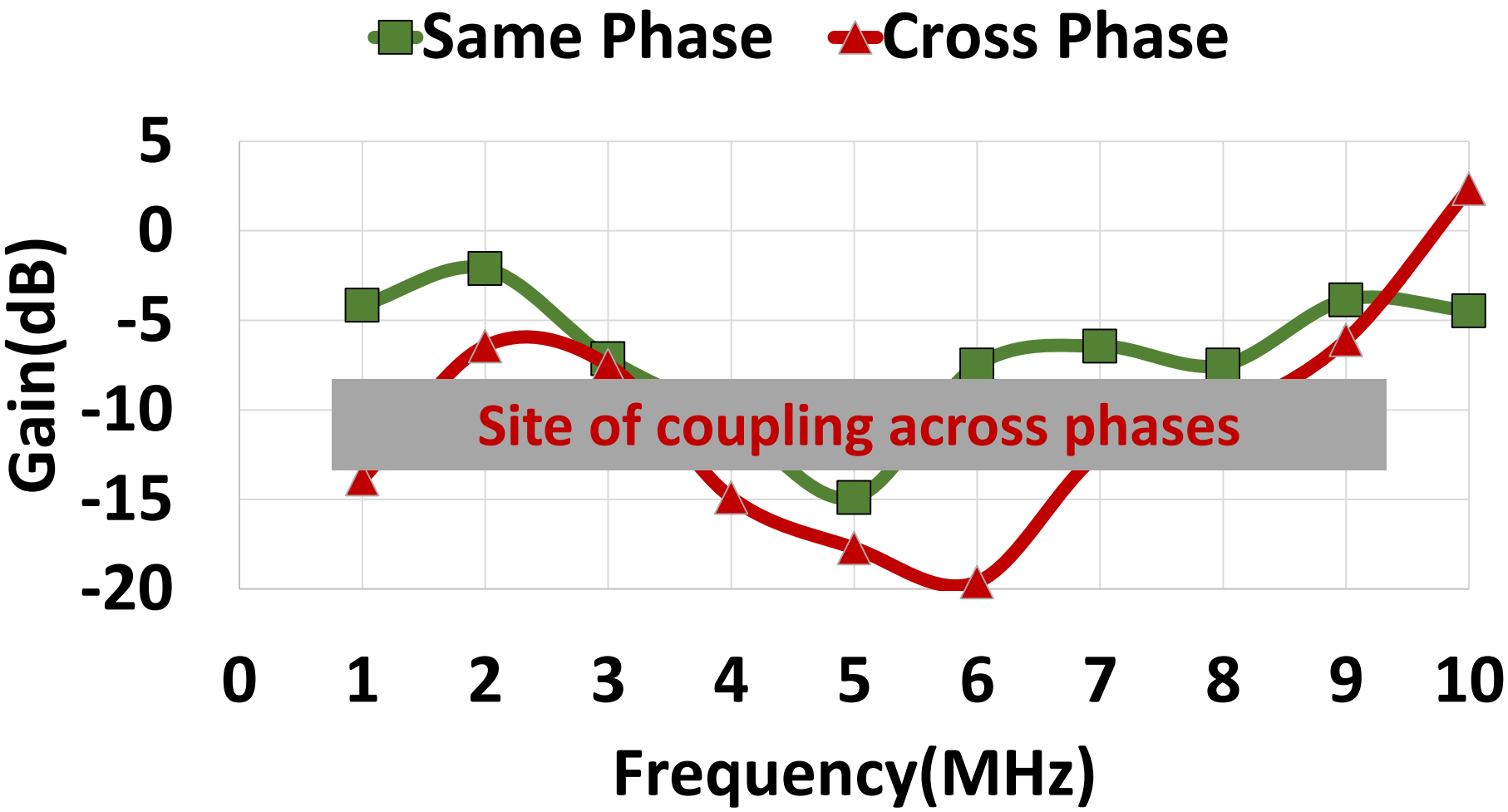


Transformer Response

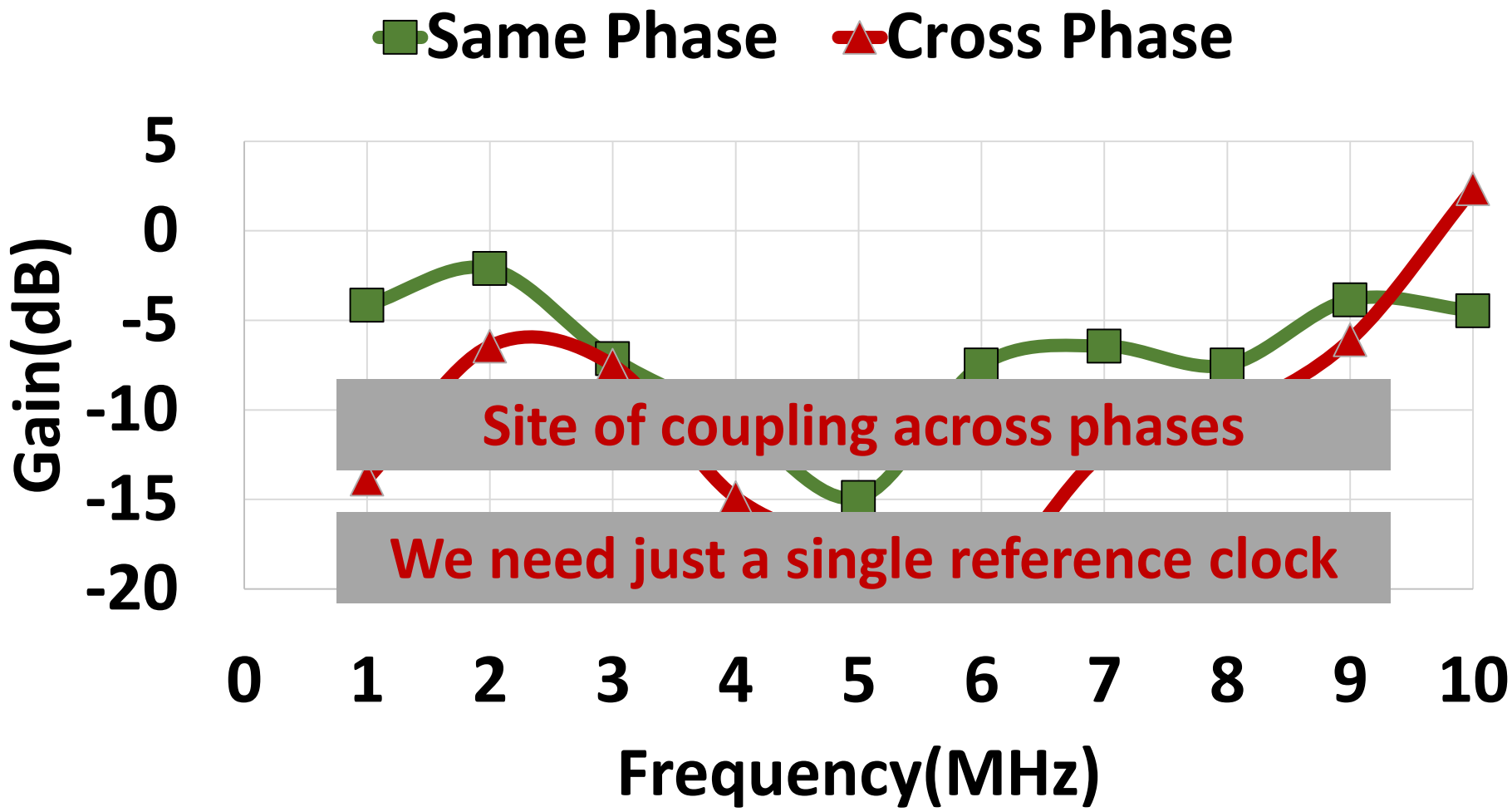
Transformer Response



Transformer Response



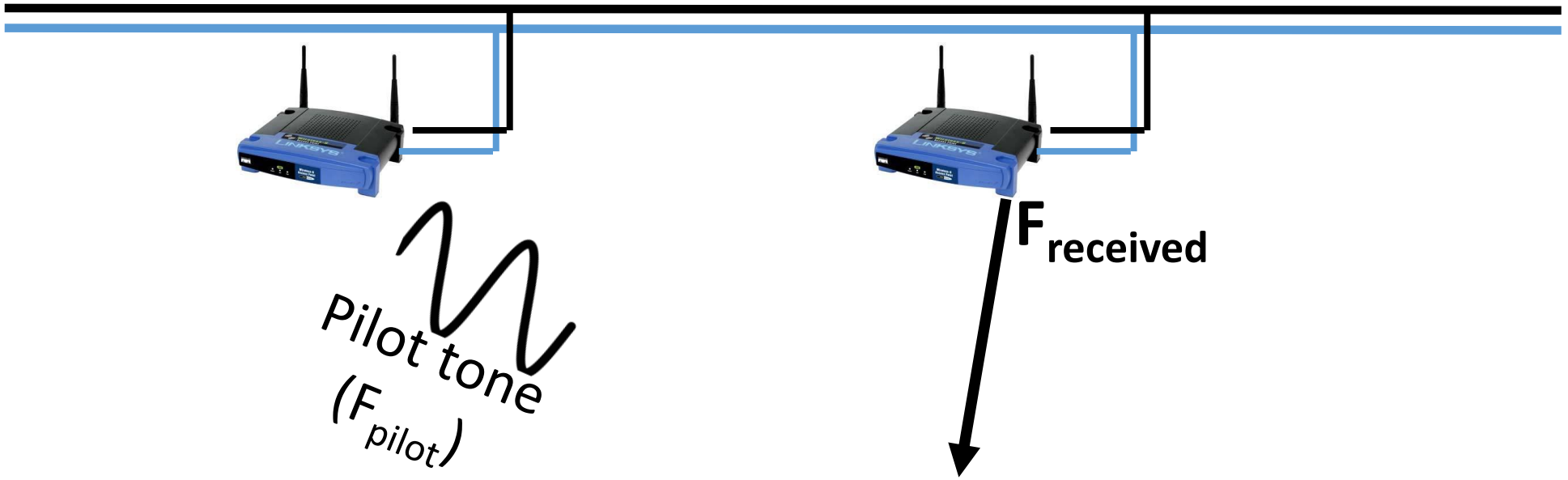
Transformer Response



Evaluation: How effective is Vidyut's phase synchronization?

Evaluating Phase Mismatch

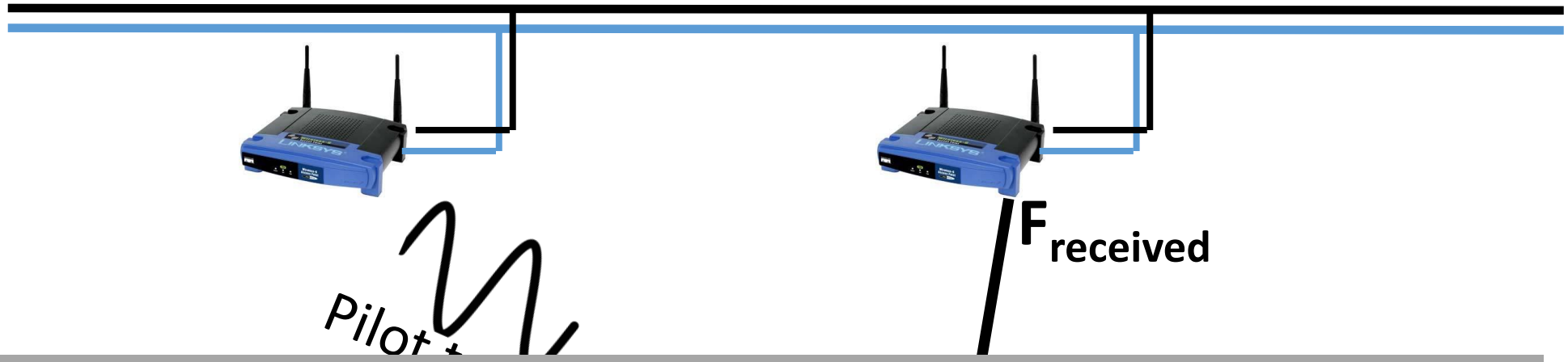
Both APs synchronized using Vidyut



$$\Phi_{mismatch} = (F_{received} - F_{pilot}) \times T + \Phi_{initial}$$

Evaluating Phase Mismatch

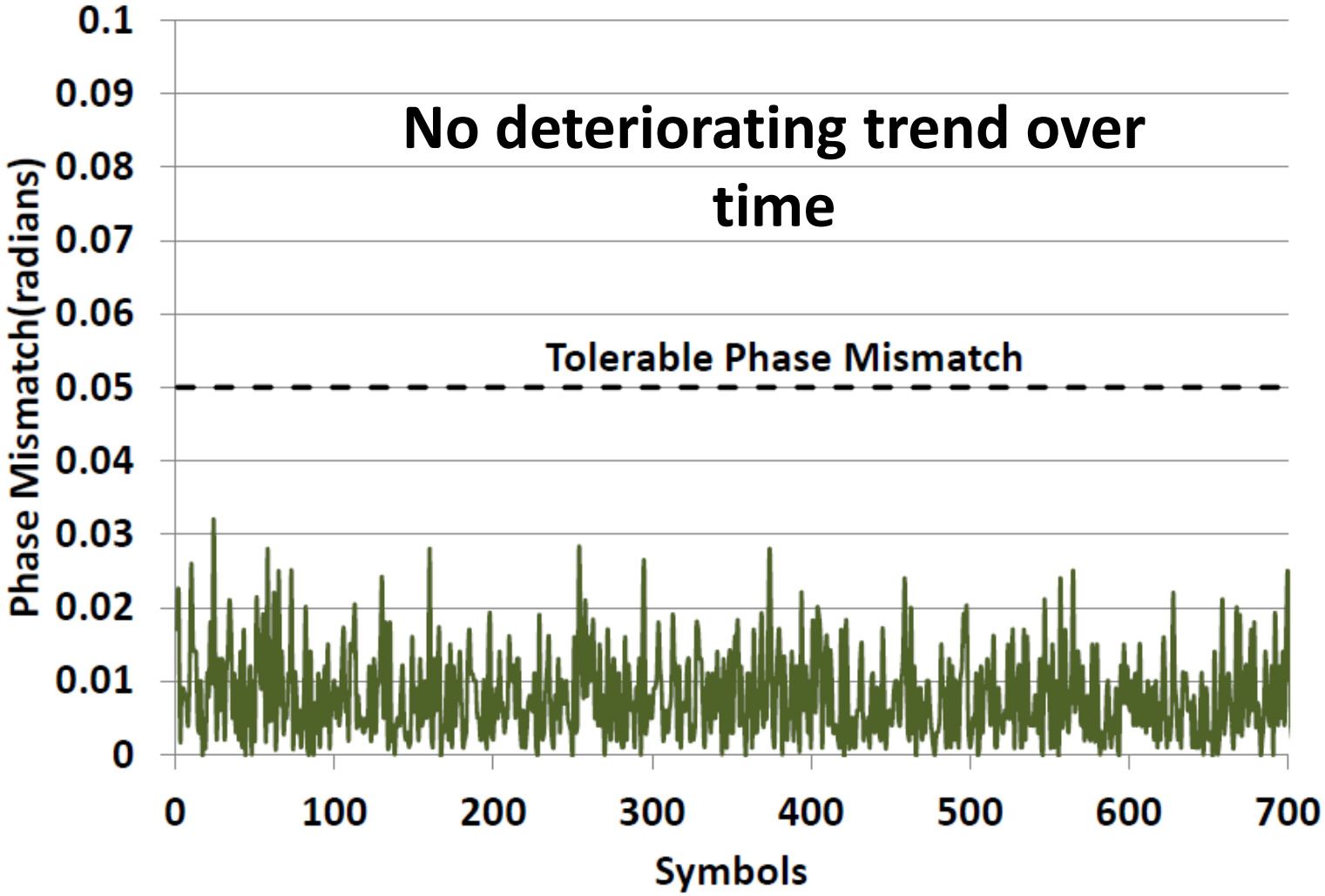
Both APs synchronized using Vidyut



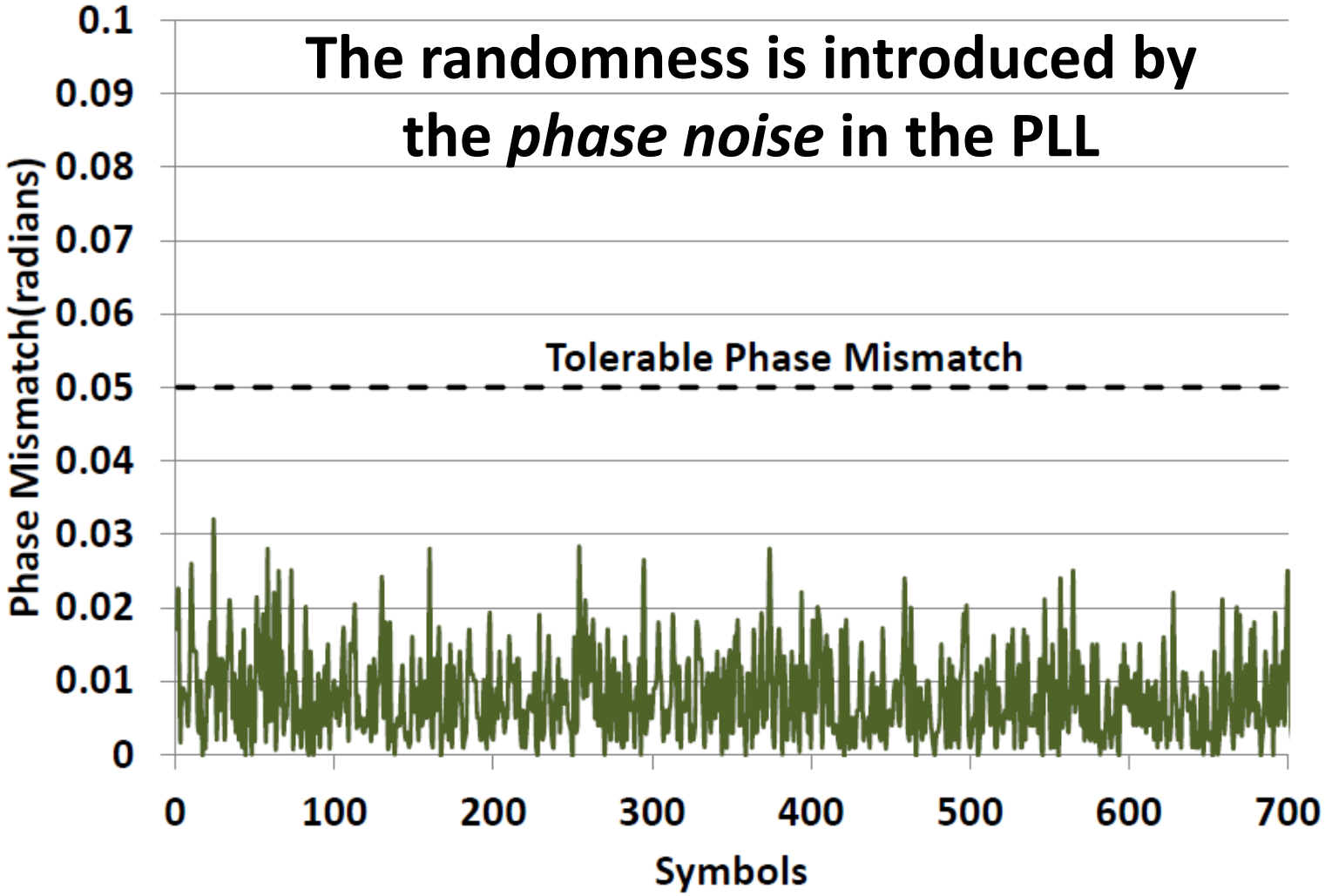
When both nodes are synchronized, $F_{received} = F_{pilot}$ making $\Phi_{mismatch}$ constant over time

$$\Phi_{mismatch} = (F_{received} - F_{pilot}) \times T + \Phi_{initial}$$

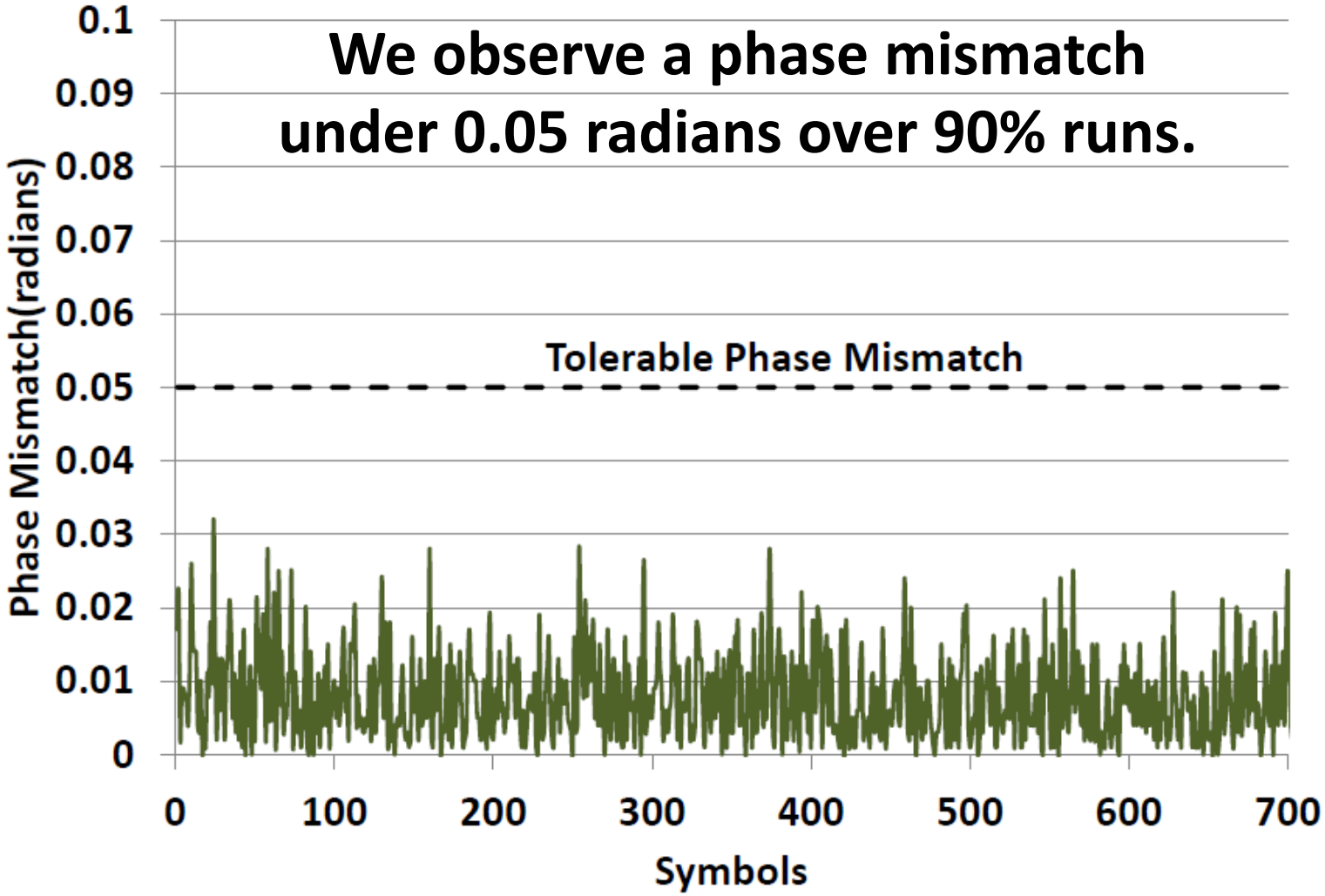
Phase Synchronization Over Time



Phase Synchronization Over Time



Phase Synchronization Over Time

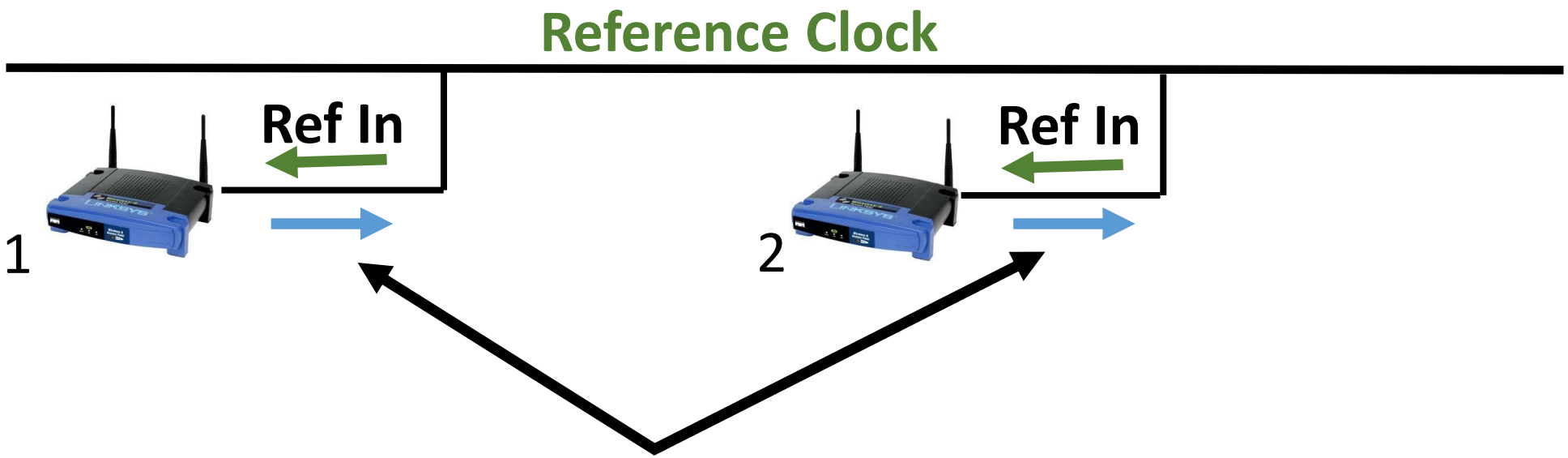


Power Distribution Network

- Power lines are designed to carry power at 50/60 Hz
  - The higher frequency of the reference clock attenuates over distance.

Each AP *regenerates* the reference clock back on to the power lines

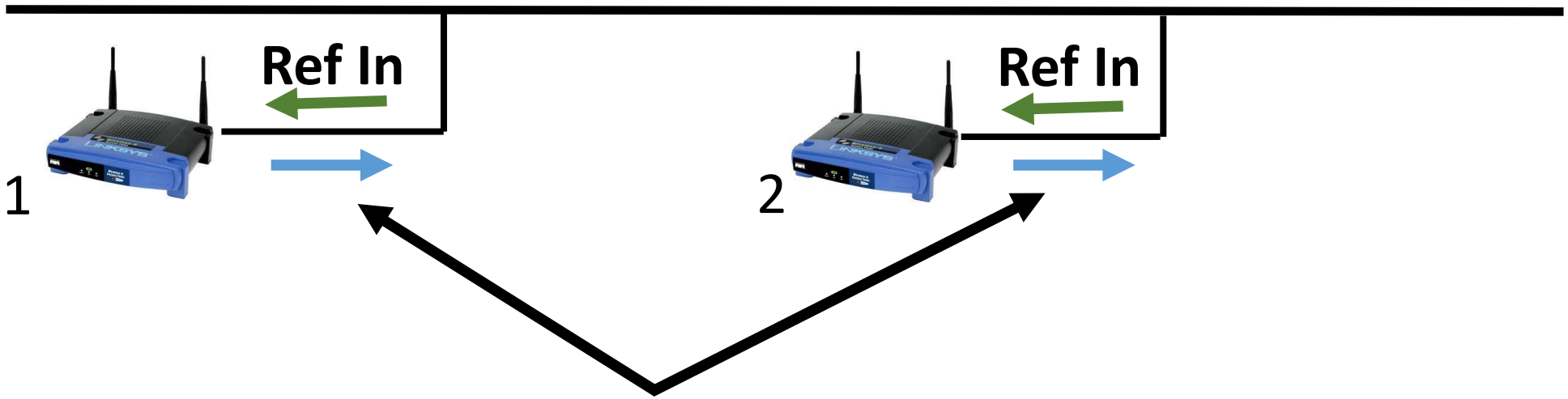
Clock Regeneration



Each AP feeds back a Reference clock phase matched to *Ref In* back on to the power lines.

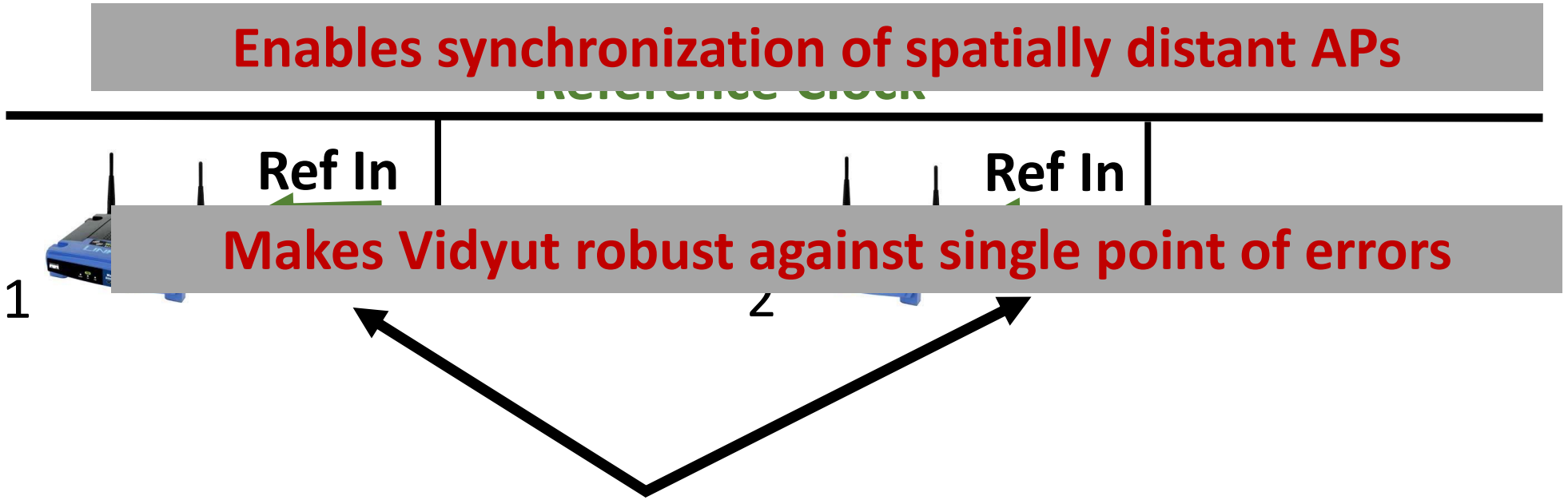
Clock Regeneration

Enables synchronization of spatially distant APs



Each AP feeds back a Reference clock phase matched to *Ref In* back on to the power lines.

Clock Regeneration



Each AP feeds back a Reference clock phase matched to *Ref In* back on to the power lines.

Regeneration Effect on Clock Synchronization

- Each clock regeneration adds a distinctive phase noise characteristics
- The phase mismatch between a pair of nodes does not correlate with the number of clock regenerating sources between them.
- Details in the paper.

Achieving Distributed Time Synchronization

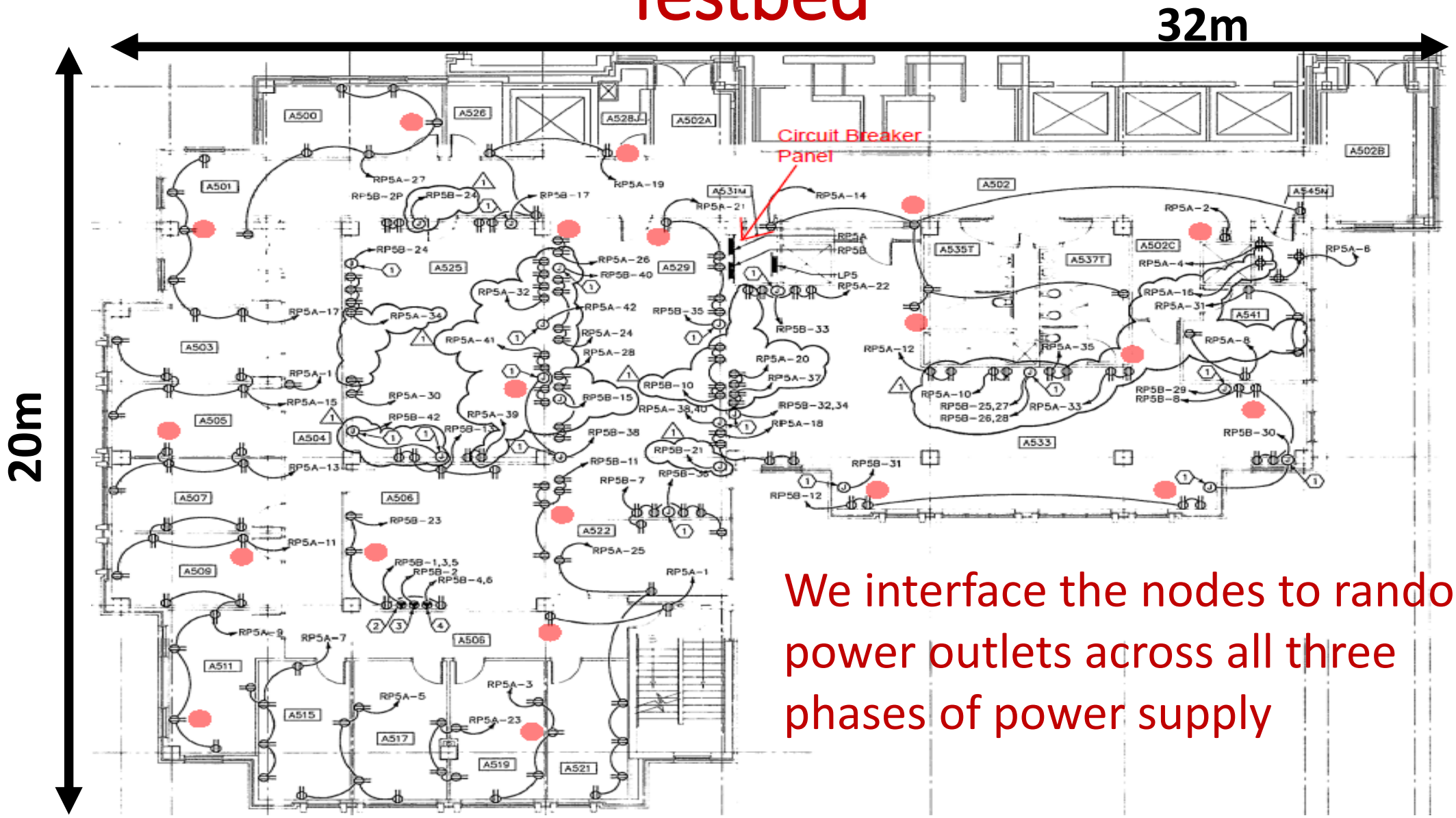
- We adopt the principles proposed in [1].
- Utilize the stable power frequency to achieve distributed time synchronization
- Details in the paper.

[1]. Rowe et.al, Low-power clock synchronization using electromagnetic energy radiating from ac power lines, SENSYS, 2009

Implementation

- Eight NI based SDR nodes
  - NI-5791 RF Front End
  - Accepts Reference Input/ Drives PLL output
  - 10 MHz OFDM in the 2.4 GHz ISM Band
  - PXIe-7965R FPGA ..
- Agilent 8648C : 10 MHz Reference Clock

Testbed



We interface the nodes to random power outlets across all three phases of power supply

Evaluation: Performance gains of Vidyut-enabled Network MIMO.

Setup

Divide the eight nodes into four APs and four clients.

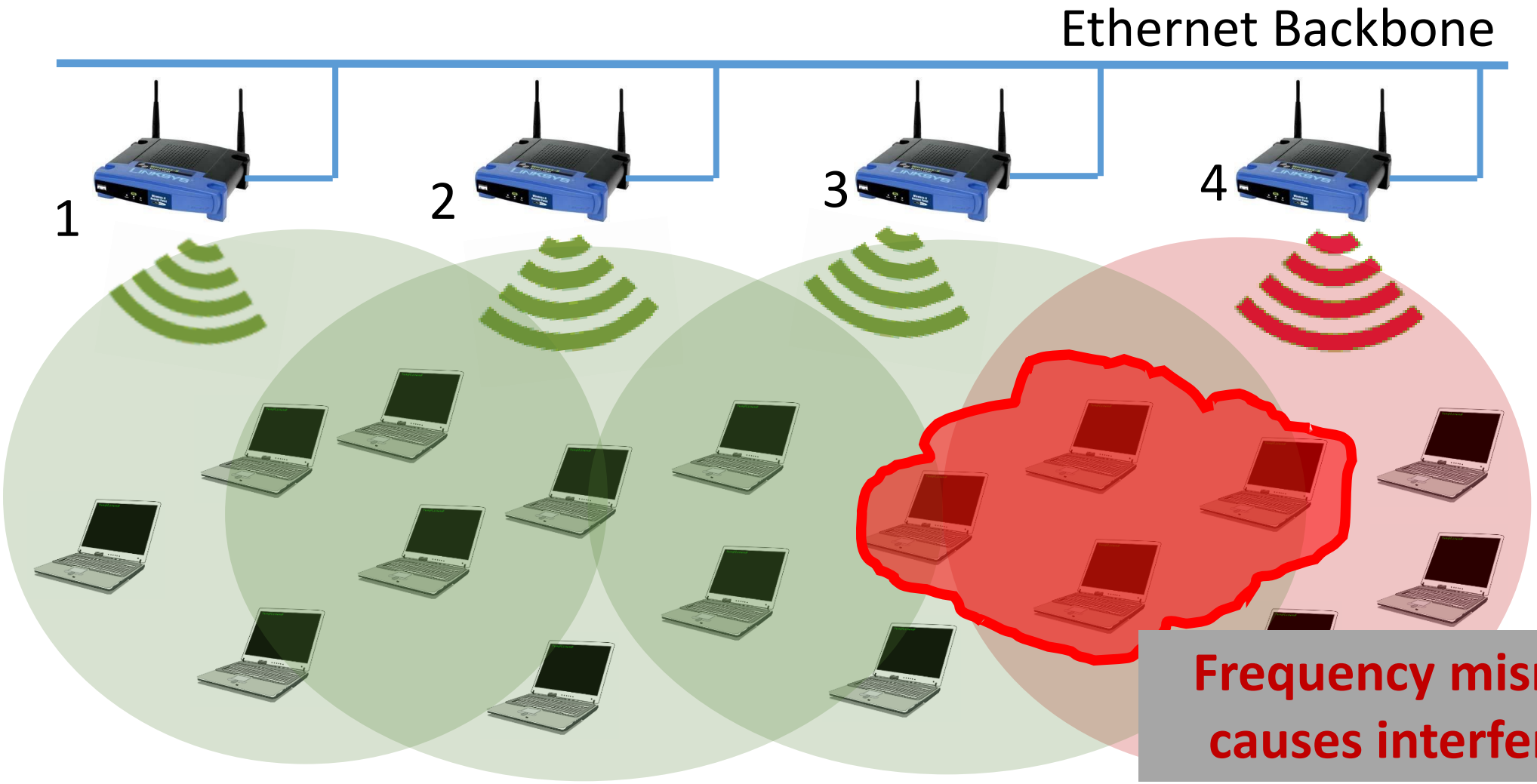
Place the nodes at random locations as before such that the APs are divided into *two* clusters

Each cluster has clients to service

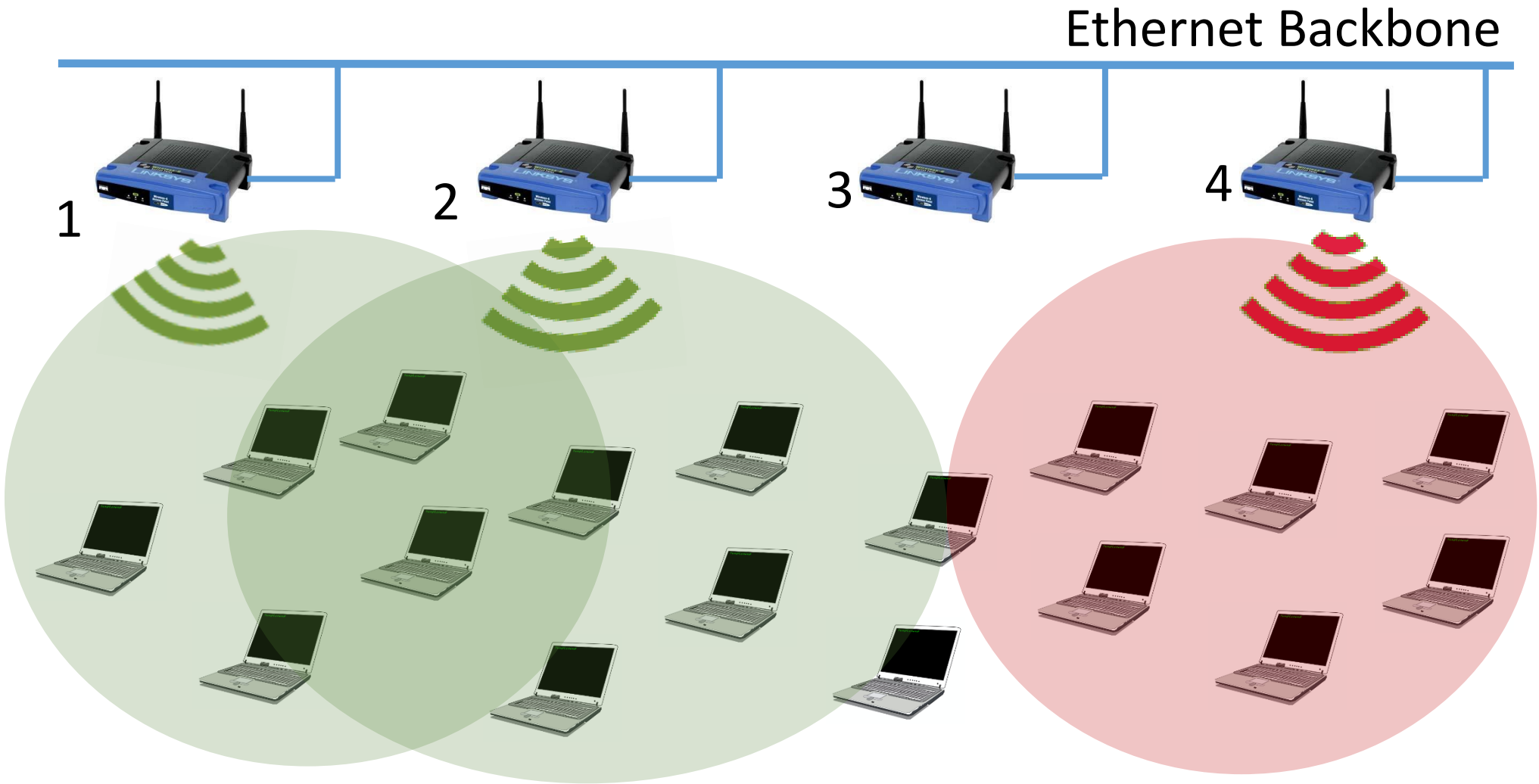
Compared schemes: MegaMIMO, NEMOx[1]

[1]. Zhang et.al, Scalable Network MIMO for wireless networks, Mobicom, 2013

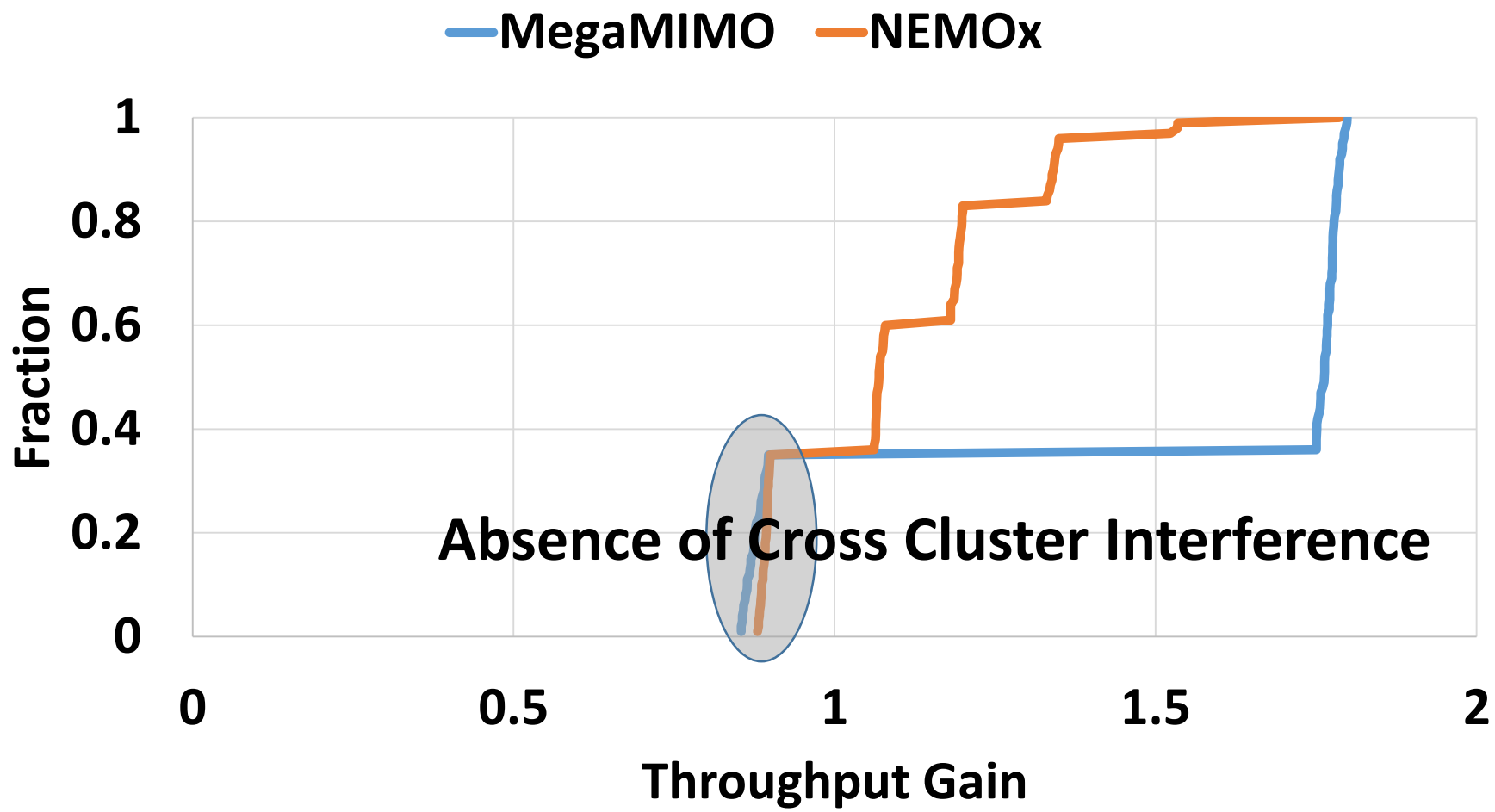
NEMOx


Ethernet Backbone
1
2
3
4
Frequency mismatch causes interference

NEMOx



Throughput Gain



As the Number of Clusters Increases

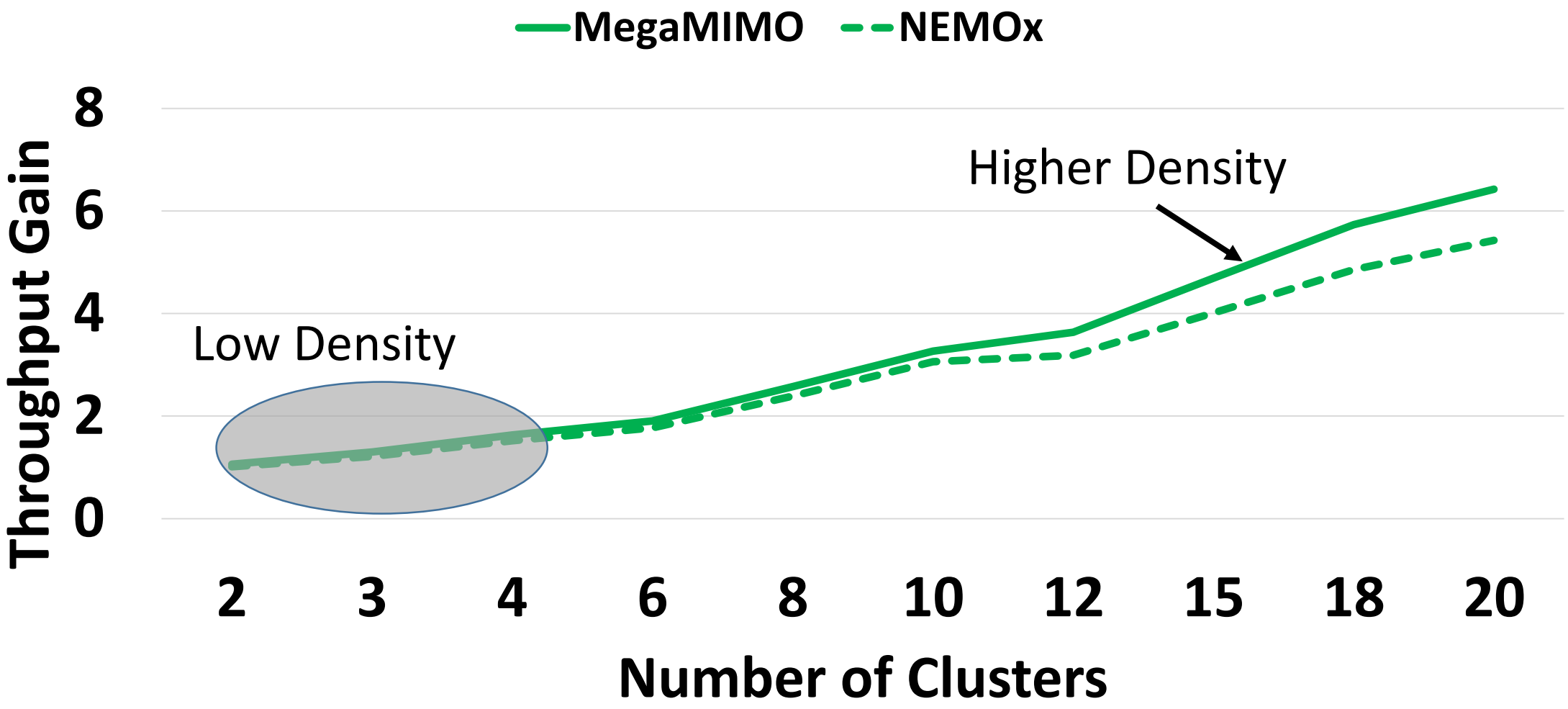
MATLAB based simulation

Account for increase in noise at each client due to phase mismatch between APs as their number increases.

Provisions slackness for variance in time synchronization

MegaMIMO and NEMOx are implemented using a TDMA over CSMA type MAC

As the Number of Clusters Increase



Future Work

- Client selection in the clusters is an important design decision that has been left for future work.
- As the number of nodes participating in Network MIMO increases, the challenge of processing the resulting large volumes of data needs to be addressed.
- Distributed synchronization across multiple collision domains can enable scalable implementation of exciting theoretical and systems work.

Thanks!

Vidyut

Language of Origin: Sanskrit
Definition: Electricity
Alternate Pronunciations: Probably will not help.