Vidyut: Exploiting Power Line Infrastructure for Enterprise Wireless Networks

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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

Ethernet Backbone

1 2 3 4

Dense Client Distribution
Enterprise WLAN

Ethernet Backbone

Dense Client Distribution
The APs share medium (time/frequency/code) to mitigate interference.
Multiple APs coordinate to emulate a single virtual AP with many antennas – Network MIMO
All four APs can serve their clients simultaneously without needing to share the medium.
The coordinating APs need to be synchronized in frequency and time
Network MIMO Implementation\(^1\)

Network MIMO Implementation

Frequency mismatch causes interference
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?
Each AP uses the reference clock on the power lines to synchronize their own carrier clocks using a PLL.
Each AP uses the reference clock on the power lines to synchronize their own carrier clocks using a PLL. All APs are synchronized transmitted on the Power Lines.
No Frequency mismatch = No interference
Phase Locked Loop

Reference clock from the power lines

Distributed to the baseband clock, carrier clock

Power Line

Phase difference detector

Phase Difference to Voltage Converter

Low-pass filter

VCO

Feedback Path

$F_{\text{ref}}$

$F_o / N$

$F_o / N \div N$

$F_o$
Phase Locked Loop

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\[ F_{\text{ref}} \]

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Feedback Path

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$\div N$
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Power Line

\( F_{\text{ref}} \)

Phase difference detector

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Low-pass filter

\( VCO \)

Feedback Path

\( \frac{F_o}{N} \)

\( \div N \)

\( F_o \)
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

Gain (dB) vs Frequency (MHz)

- Same Phase

Gain (dB):
-20 -15 -10 -5 0 5 10 15 20

Frequency (MHz):
0 1 2 3 4 5 6 7 8 9 10
Transformer Response

Gain (dB) vs. Frequency (MHz)

- Same Phase

Filtering effect
Three-Phase Power Supply

The three phases are *physically* isolated.

Do we need a separate reference clock for each phase?
Transformer Response
Transformer Response

- Same Phase
- Cross Phase

Gain (dB) vs Frequency (MHz)

- Gain in dB ranges from -20 to 5 dB.
- Frequency (MHz) ranges from 0 to 10 MHz.

The graph shows the transformer response with different phase configurations, indicating variations in gain at various frequencies.
Transformer Response

- **Same Phase**
- **Cross Phase**

Site of coupling across phases
Transformer Response

- Same Phase
- Cross Phase

Site of coupling across phases

We need just a single reference clock
Evaluation: How effective is Vidyut’s phase synchronization?
Evaluating Phase Mismatch

Both APs synchronized using Vidyut

\[ \Phi_{\text{mismatch}} = (F_{\text{received}} - F_{\text{pilot}}) \times T + \Phi_{\text{initial}} \]
Evaluating Phase Mismatch

Both APs synchronized using Vidyut

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

$$\Phi_{\text{mismatch}} = (F_{\text{received}} - F_{\text{pilot}}) \times 1 + \Phi_{\text{initial}}$$
Phase Synchronization Over Time

No deteriorating trend over time

Tolerable Phase Mismatch
Phase Synchronization Over Time

The randomness is introduced by the phase noise in the PLL

Tolerable Phase Mismatch
Phase Synchronization Over Time

We observe a phase mismatch under 0.05 radians over 90% runs.
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
Each AP feeds back a Reference clock phase matched to \textit{Ref In} back on to the power lines.
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 \textit{Ref In} back on to the power lines.

Enables synchronization of spatially distant APs

Makes Vidyut robust against single point of errors
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
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\textsuperscript{1}

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

Ethernet Backbone

Frequency mismatch causes interference
NEMOx
Throughput Gain

Absence of Cross Cluster Interference
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

Throughput Gain

Number of Clusters

MegaMIMO
NEMOX

Higher Density

Low Density

2  3  4  6  8  10  12  15  18  20

0  2  4  6  8

2  3  4  6  8
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.