Vidyut: Exploiting Power Line Infrastructure For Enterprise Wireless Networks

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ABSTRACT

Global synchronization across time and frequency domains significantly benefits wireless communications. Multi-Cell (Network) MIMO, interference alignment solutions, opportunistic routing techniques in ad-hoc networks, OFDMA etc. all necessitate synchronization in either time or frequency domain or both. This paper presents Vidyut, a system that exploits the easily accessible and ubiquitous power line infrastructure to achieve synchronization in time and frequency domains across nodes distributed beyond a single-collision domain. Vidyut uses the power lines to transmit a reference frequency tone to which each node locks its frequency. Vidyut exploits the steady periodicity of delivered power signal itself to synchronize distributed nodes in time.

We validate the extent of Vidyut's synchronization and evaluate its effectiveness. We verify Vidyut's suitability for wireless applications such as OFDMA and multi-cell MIMO by validating the benefits of global synchronization in an enterprise wireless network. Our experiments show a throughput gain of 8.2x over MegaMIMO, 7x over NemoX and 2.5x over OFDMA systems.

1. INTRODUCTION

Synchronization significantly benefits wireless communication. Exciting new avenues of wireless communications require tight synchronization across distributed nodes to be realizable. For example, Network MIMO, a technology that scales the throughput of the network with the number of the transmitters, requires synchronization in frequency and time domains across all transmitters. Opportunistic ad-hoc routing techniques that exploit either sender (Sourcesync [14]) or receiver side diversity of the wireless medium require acceptable levels of time synchronization across the distributed routing nodes. Source coding techniques such as lattice coding techniques assume synchronization between the transmitters. Frequency and time synchronization are essential for interference alignment solutions. While radio technology for individual nodes keeps continually improving (in terms of antenna technology, data processing capability etc.), in order to realize the previously mentioned wireless solutions the challenge of coordinating distributed nodes remains. One of the main challenges in this regard is achieving synchronization across distributed nodes.

Global *time* synchronization techniques have been explored for sensor networks. However, these techniques achieve a time synchronization in the order of milliseconds, while Wi-Fi-like systems need synchronization in the order of nanoseconds [16]. Recent works have demonstrated frequency synchronization between distributed nodes for Network MIMO applications (MegaMIMO [15],Airsync [2]). However, these techniques are limited by the transmission range of a lead transmitter. MegaMIMO, for example, achieves distributed synchronization across a group of APs by having a lead AP among them transmit a pilot tone over the air. The remaining APs synchronize to the lead AP by referencing this pilot tone. However, the group of APs must be within the range of the lead AP. We refer to this group of APs as a *cluster*.

Vidyut utilizes power-lines to achieve synchronization between nodes distributed beyond a cluster. At its crux, Vidyut distributes a stable reference clock along the power-lines. APs distributed across space access this reference clock to synchronize their carrier clocks. Fig. 1(a) presents an example to highlight the difference of Vidyut from prior frequency synchronization techniques. This example illustrates the *distinct* advantage of Vidyut: Vidyut achieves frequency synchronization *across* clusters. This enables Network MIMO across clusters. Further, this example illustrates that throughput gain of our Vidyut implementation increases with the number of clusters as shown in Section 6.

There are many challenges in realizing Vidyut. First, the power distribution network of an enterprise has multiple electrical elements with distinct functionality. Fig. 2 shows the electrical network in an enterprise building. The reference frequency used in Vidyut has to propagate through all of these elements. Section 2 briefly discusses a typical power distribution network. Section 3 studies the propagation characteristics of these elements in order to choose the frequency of the synchronization signal.

Second, a single reference frequency source on the power-lines for the entire enterprise network has a single point of failure: if the signal source fails so does Vidyut. Section 3 presents a distributed mechanism to provide a reliable synchronization signal on the power-line. Every Vidyut AP regenerates a reference clock and sends it back to the power-lines. This eliminates a single point failure for Vidyut.

The example in Fig. 1(a) implicitly assumed time synchro-

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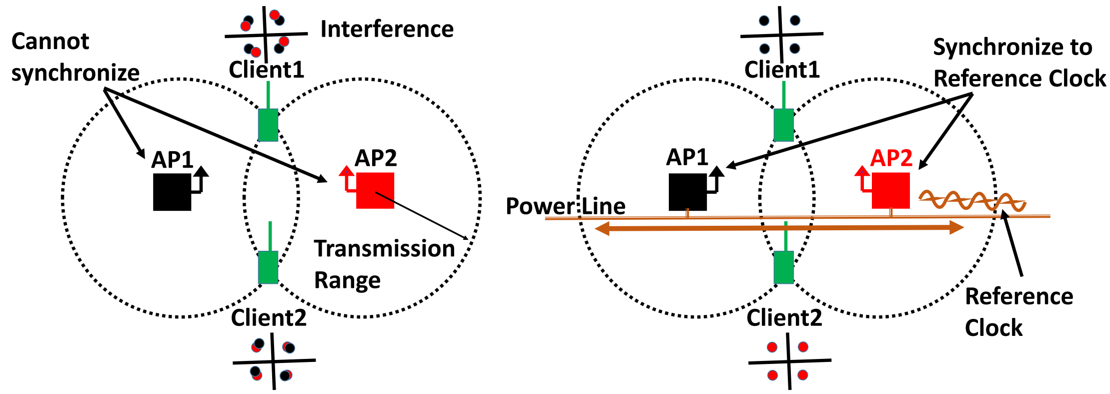


(a) Interference caused due to lack of synchronization

(b) Achieving throughput gain by enabling Network MIMO

Figure 1: Motivating Vidyut: Access points (APs) outside of each other's transmission range cannot be synchronized using MegaMimo, [15], and NemoX, [21]. They form two distinct clusters. This causes interference when the APs simultaneously transmit. They need to take turns to avoid interference. In Vidyut APs are synchronized using power-line. Simultaneous activation of APs enable interference-free network MIMO. Vidyut enables cross-cluster synchronization and provides a linear throughput gain with increasing clusters.

nization across the nodes. Vidyut borrows its time synchronization idea from the work published in [16]. Vidyut utilizes the stability of the time period of the power signal as a reference for time synchronization across distributed nodes. A fixed offset from the zero-crossing of the power signal is used as an event which each Vidyut node reports to the central server. The central server then computes the phase offset between Vidyut nodes. The technique is described in detail in Section 3.

1.1 Results

MegaMIMO reports that a phase mismatch of under 0.05 radians between a pair of transmitters results in negligible SNR degradation over all channel conditions. Vidyut provides frequency synchronization with a **mean phase mismatch of approximately 0.0218 radians** (over the duration of one 802.11g symbol). We observe a phase mismatch of under 0.05 radians in 90% of the experiments. Further, we verify that the frequency synchronization presented by Vidyut is steady over time by observing that the phase mismatch between Vidyut nodes does not deteriorate over 700 symbols (For a symbol duration of 4 μseconds).

Vidyut provides **time synchronization within 450 ns with a mean of approximately 225 ns**. While this variation is too high to support short guard intervals of 802.11n/ac standards (400ns), it is sufficient to support regular guard intervals of 802.11n/ac (800ns).

Our implementation of Vidyut provides a throughput gain of approximately 2x over MegaMIMO and NEMOx in the four node topology illustrated in Fig. 1(a). We simulate throughput gains for networks up to 20 clusters with four nodes per cluster. Vidyut presents a **throughput gain of up to 8.2x over MegaMIMO and 7x over NEMOx** for these networks.

Further, we compare a Vidyut backed OFDMA system with an OFDMA system consisting of unsynchronized transmitters with free running oscillators. We show a throughput gain of up to **2.5x** as the number of OFDMA transmitters increases to 7.

1.2 Contributions

To the best of our knowledge, this is the first solution to provide synchronization across multiple collision domains. We develop a simple, robust and scalable synchronization mechanism, Vidyut, and evaluate its applicability to provide *global* synchronization. We demonstrate the power signal as a cheap, available and stable resource for distributed time synchronization for Wi-Fi-type applications.

2. POWER-LINES AND DISTRIBUTION: A BACKGROUND

We look at the power distribution network and the power-line channel briefly before discussing Vidyut in detail.

2.1 Power Distribution

Power is typically delivered on three phases. Power on each phase from the substation is distributed to various buildings at a voltage of the order of 13KV. Typically, each building has a *large* three-phase transformer (with a power rating of around 500KVA) that steps down this voltage to around 480V or 240V on each phase to make it safe to distribute power within building premises. Further, the buildings have *smaller* three-phase transformers (power rating of around 65 KVA) that step down this voltage to 110V to deliver it to end appliances.

Our department building has eight floors. One *large* three-phase transformer (13KV/480V) with a typical power rating of 500 KVA sits outside the building to transform the power from the substation to a safer voltage to distribute within the building. The power from this transformer feeds two (480V/110V) three-phase transformers with a power rating of 65 KVA each. These two transformers are situated inside the building. Power from these two transformers is distributed throughout the building. One transformer feeds power to the first four floors while the other feeds the remaining four floors. Each phase is distributed on a physically isolated bus. Thus, power is delivered to each floor on three physically isolated buses.

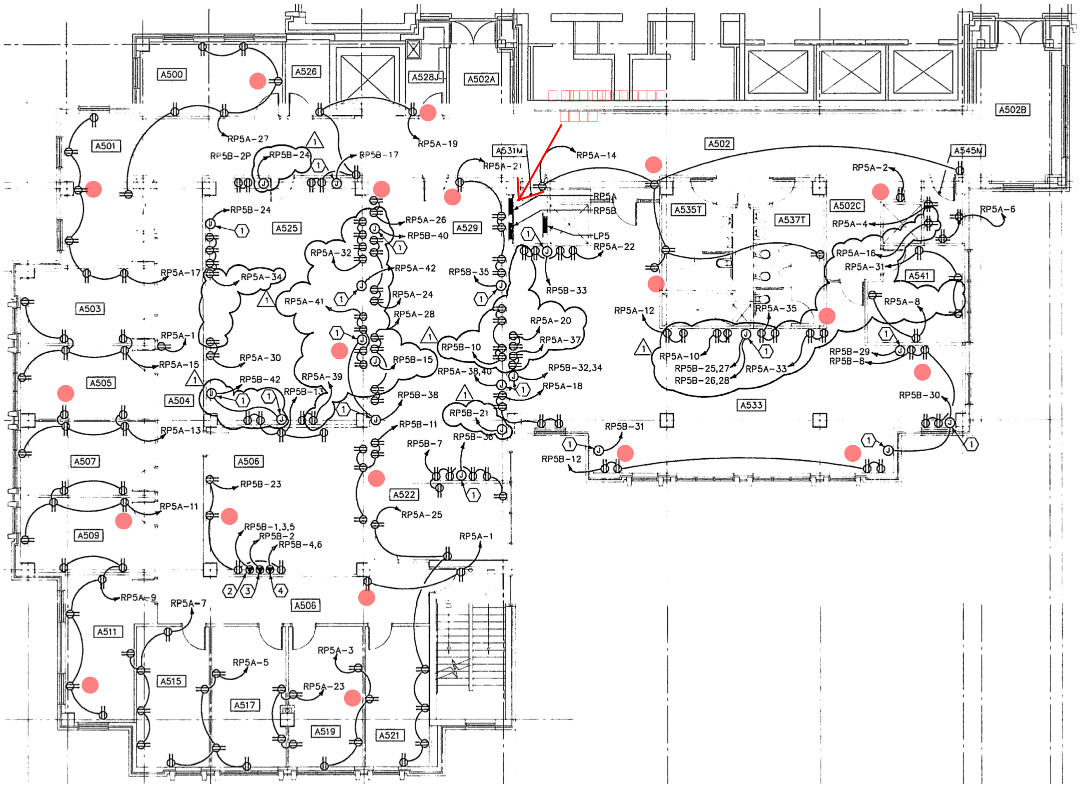


Figure 2: Typical power distribution in a floor of a building. The free curves indicate circuits. Each circuit powers six to ten power outlets. The circuits branch from a circuit breaker panel (indicated in the figure). The branching itself is not explicitly indicated. The red circles adjacent to the power outlets indicate the power outlets accessed by Vidyut nodes. The power outlets cover all three phases and are live.

Fig. 2 illustrates the power distribution network on one of the floors. As indicated in Fig. 2, power is distributed across each floor on different branches (circuits). Each branch typically powers six to ten power outlets. All power outlets connected to the same branch draw power on the same phase. All circuits on the same phase branch from a bus carry power at that phase. Thus, power outlets on the same phase but connected to different branches are connected together electrically at the bus carrying power at that phase. The three buses corresponding to the three distinct phases are housed in a *circuit breaker panel*. Each floor consists of two circuit breaker panels. Each circuit is connected to its bus through a circuit breaker. A circuit breaker is instrumental in isolating faulty circuits from disrupting power distribution on rest of the circuits.

The electrical routing of this building is a reasonable representation of typical electrical connections in a large building. Section 3 studies the implications of these electrical elements on Vidyut's design.

2.2 Power-Lines: The channel

The primary function of power-lines is to deliver power at 60 Hz. The capacitance and inductance presented by the power-lines are known to attenuate high frequency (of the order of MHz and beyond) signals and are thus *parasitic* at these frequencies. Besides the attenuation caused by power cables, the power lines are subject to multiple sources of noise. These include noise due to change in loading conditions, switching power supplies and simple background noise. While extensive literature studying the channel response [19, 20] and noise [13, 22] of power-lines exists, they have been studied from the perspective of achieving reliable power-line communication.

However, the objective of Vidyut is distinct from that of power-line communications (PLCs) in the following regard: Vidyut is only responsible for distributing a stable reference clock (a single tone) across the power-line network of an enterprise. Thus, when designing Vidyut, our primary concern is to find tones of frequencies that pass through the various electric circuit elements with minimal losses and **not** to find a band of frequencies that is most suitable for communicating data between two nodes with high throughput and/or high reliability.

Thus, in summary, the channel response of power-lines, the effect of loading, sources of noise and the effect of different electric elements such as circuit breaker panels, transformers, the physical isolation between circuits on different phases, etc. are investigated with the objective of finding a frequency tone that can be distributed across an enterprise network while achieving the required synchronization to implement desirable applications such as Network MIMO, OFDMA, Interference Alignment etc.

3. Vidyut: DESIGN

Vidyut presents a suite of techniques to achieve synchronization over the span of an enterprise network. Vidyut

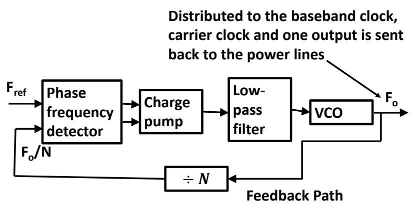


Figure 3: Simplified block diagram of a PLL.

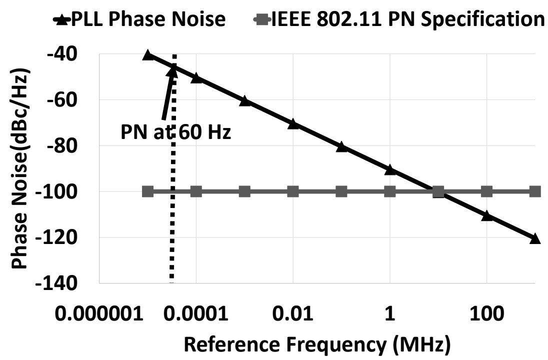


Figure 4: Phase Noise of a typical PLL Frequency Synthesizer: The reference frequency and the frequency divider influence the output phase noise.

utilizes the power line infrastructure to share a reference clock across the enterprise network. This section details the challenges presented by the power lines to the distribution of this reference clock. Further, it presents the impact of these on the design decisions of Vidyut.

3.1 Frequency Synchronization

The opportunity presented by the power line infrastructure is enticing for the following reasons. The infrastructure already exists and is accessible by the majority of the nodes in an enterprise network. Thus, it presents an opportunity to achieve synchronization even between hidden nodes. The proposed solution would require no change in the MAC or higher layers for the purpose of achieving distributed synchronization since the solution is confined in the physical layer. Vidyut avails the power line infrastructure to distribute a reference clock accessible to nodes in an enterprise network. Each node locks its own carrier frequency to this reference clock in phase to achieve frequency synchronization among distributed nodes. While the idea is straightforward, the following questions need to be tackled to use the power-lines to distribute a reference clock: What is the ideal frequency of the reference clock?

3.1.1 Determining the reference clock frequency

Power is delivered at a stable frequency of 60 Hz (or 50 Hz). So then, the question arises: Why not use the power frequency itself as a reference? Which metric is indicative of the suitability of a reference clock for Vidyut? The answer to these questions can be better understood when the parameters affecting the performance of the frequency synthesizing element –the Phase Locked Loop (PLL)– are better understood. Fig.3 illustrates a simplified block diagram of a clock distribution circuit based on a PLL.

A Vidyut node synchronizes its baseband and carrier clocks to the reference frequency using a PLL in the clock distribution core. The PLL in the clock distribution core performs two functions: **(1)**Ensures that each clock output of the distribution core is phase locked to the reference frequency. **(2)** Multiplies the clock output by a preprogrammed factor to generate the desired output clock[1]. For example, the clock distribution core multiplies the reference clock of 10 MHz by 240 to generate a carrier clock output of 2.4GHz (which is then fed to the mixer to up-convert the baseband streams to RF or vice-versa).

Typically, a PLL consists of a **phase/frequency detector (PFD)** that generates a digital (or analog) signal directly proportional to the phase mismatch between the output of the PLL and the reference clock. This signal accumulates over time and feeds a voltage input to a **Voltage Controlled Oscillator (VCO)** to minimize the phase mismatch between its output and the reference clock. In addition, the PLL incorporates a low-pass filter to increase the stability of the PLL by preventing it from responding to sudden changes in the reference clock. This filter is referred to as the **loop filter**. All the components in the PLL have intrinsic noise characteristics. The phase noise of the PLL is one such metric that quantifies the accuracy with which the PLL synchronizes its output to the reference clock. Intuitively, as the multiplicating factor of the output clock increases, the intrinsic noise of the components of the PLL is exaggerated. Thus, when the reference clock is at a frequency of 60 Hz, to generate a carrier frequency of 2.4 GHz, the multiplicative factor is 40 million. This significantly degrades the phase noise of the PLL, well beyond the limits specified by the IEEE 802.11 standards. The 802.11a standard specifies a phase noise of the order of -95 dBc/Hz while the 802.11g standard specifies a phase noise of the order of -100 dBc/Hz [12].

Eq. 1 defines the relationship between the phase noise of AD9511(the PLL used in the clock distribution core of our Vidyut node implementation [1]) at a desired frequency with the frequency of the phase/frequency detector (f_{PFD}) and the multiplicative factor(N) used to attain the desired frequency from f_{PFD}.

$$PhaseNoise(dBc/Hz) = -218 + 10log(f_{PFD}) + 20logN \quad (1)$$

Fig. 4 plots the phase noise of a PLL for a carrier frequency of 2.4 GHz as the reference frequency is swept from 10s of Hz to 1 GHz. As indicated in the figure, for reference frequencies below the order of a MHz, the PLL phase noise characteristic is degraded beyond phase noise specification provided by the IEEE 802.11 standard. Thus, frequencies below 1 MHz **cannot** provide an acceptable reference for Wi-Fi applications.

3.1.2 Characterizing Transformers

At Vidyut's frequencies of interest (beyond 1 MHz), the two types of transformers discussed in Section 2 behave as filtering elements. Further, due to the construction of a transformer, it is also a site for electrical coupling between phases. Here, we characterize these phenomena.

[1]In practice, this effect is produced by dividing the clock output and feeding it back to the phase/frequency detector.

As a filtering element: The transformers have a distinct filtering characteristic.We perform a series of experiments across transformers to measure the pass band characteristics of these transformers.

Transformers in the power distribution network are designed to transform power from one voltage to another at power frequency. At significantly higher operating frequencies, however, the transformer acts more as a filtering element than a power transformer. The copper windings and the ferrite core of the transformer introduce capacitive and inductive loads at high frequencies (of the order of MHz). The windings have an inductive response. The gap between the windings is capacitive in addition to the parasitic capacitance of the ferrite core. This load is *parasitic.*

First, we characterize the *large* 500 KVA, 30KV/95KV transformer. We connect two such transformers in a back-to-back configuration, i.e., connect the primary sides of the two transformers across all three phases. We evaluate the back-to-back configuration because Vidyut's reference signal has to traverse through two such transformers in such a configuration in order to be available to wireless nodes connected to the power outlets in enterprise buildings. We observe that this configuration attenuates signals (in the MHz range) below 8 MHz to the noise floor. From 8 MHz to 10 MHz however, the clock signal can be recovered on the primary side of the second transformer. At 10 MHz it presents a high attenuation of ≈ 23 dB.

Second, we characterize the filter response of 27 KVA, 240V/480V transformer. While this transformer is not of the same power rating as the *smaller* transformer in our department, it is approximately of the same size and thus is a reasonable representation of parasitics introduced by typical smaller transformers found within buildings. We inject a single tone on the primary side and we measure its power on the secondary side. The transformer acts as a notch filter in the frequency range between 1-10 MHz allowing frequencies below 3 MHz and frequencies above 9 MHz. The transformer is left de-energized for this experiment also. The filter response of the transformer is illustrated in the Fig. 6.

In summary, the large transformers (500 KVA) present high attenuation to high frequency signals, while the smaller transformers present notch filter characteristics with tolerable attenuation in the pass band. This suggests that if the smaller transformers draw power from different power sources, and thus through different large transformers, then distribution of Vidyut's reference across these smaller transformers will be unreliable due to the high attenuation of the large transformers.

As a phase coupling element: Owing to the construction of a typical three phase transformer, it is also a site of coupling between phases. To evaluate the coupling between phases across a 500 KVA transformer, we inject a signal on the primary side of a de-energized transformer on a phase, say phase 1, and measure the signal on phase 2 and phase 3 on the primary side of the transformer. Then, we inject a single tone on a phase, say phase 1, on the primary side and measure the signal on phase 2 and phase 3 on the secondary side. The coupling response for the 500 KVA transformer and the 27 KVA transformer are illustrated in Fig. 5 and Fig. 6 respectively. The strong coupling across phases suggests that the transformers can route a reference clock on one phase to the other phases. Thus while a transformer plays a

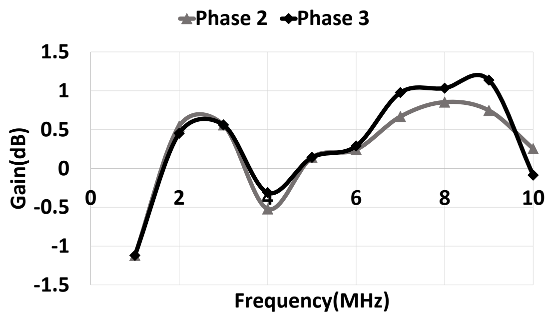


Figure 5: Coupling response of 500KVA transformer.

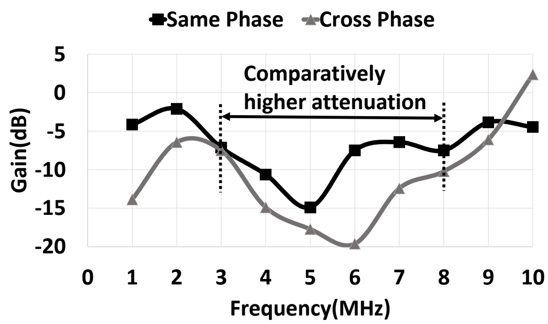


Figure 6: Filter response of 27 KVA transformer.

significant role in determining the frequency of the reference clock distributed around the building, it also presents a site of coupling between physically isolated phases.

Thus, both the transformers are sites of coupling between phases. The evaluation suggests that Vidyut's reference clock can be shared reliably across circuits connected to different smaller transformers as long as these transformers are connected to the same power source. These experiments to isolate the characteristics of the transformer were performed in a de-energized state for safety reasons. However, both the filter characteristics and phase coupling effectiveness are determined by the construction of the transformers alone. Therefore, these observations hold even when the transformers are powered.

3.1.3 Attenuation across power distribution network

Power-lines: The power-lines are designed to carry power at 60 Hz. The cable material can introduce capacitance to the high frequency reference clock and cause attenuation of the reference clock. A lot of work has been done to study the attenuation introduced by power lines to signals in the range of 10s and 100s of MHz [19]. Fig. 7 illustrates the attenuation caused by power cables across frequencies as a function of its length. A signal tone was injected into the power cable and measurements were taken at lengths of 10 feet, 100 feet and 200 feet. Fig. 7 illustrates a gradual increase in attenuation with length. However, the attenuation at 10 MHz is comparatively small.

Circuit breaker panel: The other site of attenuation in the power distribution network is the circuit breaker panel. The circuit breaker panel distributes power from a bus on to different circuits. Thus, the reference signal generated on one circuit is dispersed to all the circuits connected to that

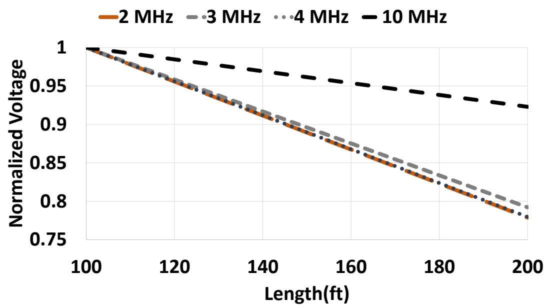


Figure 7: Power cable Attenuation vs Length.

bus at the circuit breaker panel. However, one advantage of transmitting a reference clock in the range of 10s of MHz is that the material between the buses in the circuit breaker panel presents reactive inductance that is *low* enough to allow for coupling across buses. Thus, the circuit breaker panel is another site of cross-phase coupling.

Distributed Clock Regeneration: To overcome the attenuation of power distribution network, every Vidyut node regenerates the reference clock and feeds it back on to the power lines. It is the responsibility of each Vidyut node to ensure that the regenerated clock is phase locked to the reference clock. While it is possible for the regenerated clock to have a phase offset from the original reference clock, as long as the regenerated clock has the same frequency as that of the reference clock, the superposition of these two clocks only affects the duty cycle of the reference clock without affecting its frequency (unless the regenerated clock is out of phase with the reference clock, in which case the two signals destructively interfere). Thus, as long as the frequency of the reference clock remains unchanged, the synchronization between nodes is not affected.

3.1.4 Noise in power-lines

Power-lines experience multiple noise sources. Noise in power-lines can be classified into colored background noise (summation of all low-power noise sources), noise caused by the power lines acting as antennas to broadcast radio signals, periodic impulsive noise caused by switched mode power supplies and asynchronous impulsive noise caused by changing load conditions on the power distribution network. The impulse and background colored noise have a very low power spectral density (PSD) in the MHz frequency band (-110dBV^2/Hz) [22]. The amplitude noise due to majority of the appliances at around 10 MHz is below -30 dBuV/$\sqrt{Hz}$ [13]. Thus, under most circumstances, the noise PSD at 10 MHz is within the acceptable phase noise (-90 to -100dBc/Hz) for a reference clock that is used to generate RF carriers for Wi-Fi applications.

While noise in power lines is a concern for power line communications, its influence on Vidyut is minimal. The reason for this can be understood by looking back at the working of the PLL. The PLL contains a low-pass filter, the loop filter, to minimize the responsiveness of the PLL to impulsive (high frequency) changes in the reference signal and thus increase its stability. Thus the power of broadband noise sources is constrained.

The PLL is a closed-loop network. Assuming the gain of the forward path is G and that of the feedback path is H (1/N:referring Fig. 3) the noise power at the output of the PLL due to the at the reference can be written using Equation 2.

$$noise_{output} = noise_{reference} \frac{G}{1+GH} \tag{2}$$

Outside the loop bandwidth, the contribution of the reference clock noise to the output is ≈ 0 as $G \rightarrow 0$. Within the loop bandwidth, the power of the noise is limited by the bandwidth of the filter.

3.2 Time Synchronization

Vidyut utilizes the power frequency for the purpose of time synchronization. We define an offset, γ from the start (zero crossing of the power cycle) of each period of a power cycle as a time reference for each node.

Each Vidyut node is equipped with a zero crossing detector. Once the nodes have their baseband and carrier clocks phase locked to the reference clock of Vidyut every node connected to the power distribution network measures the time period of the power cycle accurately within a resolution defined by the sampling frequency of the baseband clock. Thus, each Vidyut node can record the offset γ from the start of the power cycle with an accuracy controlled by the time period of the baseband clock.

However, on an absolute scale, there is a time difference between the time each Vidyut node records the γ offset. This difference is the same as the time it takes for the power signal to traverse the distance between the two nodes. Each Vidyut node can report the time instant it records a γ offset to a central server that keeps track of the time at each of the nodes connected to it. Thus, upon receiving the time instant at which each node records the γ offset, the central server can then let each node know its time-offset correction to ensure these nodes transmit simultaneously. This method is illustrated in Fig. 8.

However, if two nodes are close-by, then as illustrated in Fig. 2 the length of the electrical cables between the two nodes is, on most occassions low too. In these cases, the propagation delay of the power signal between the nodes can be assumed to be negligible and each node can use the event recorded at an offset γ as a reference without any relative offset correction between the two nodes. The accuracy of Vidyut's time synchronization method is then limited by the accuracy with which the time period of the power frequency is measured at each node.

Finally, each Vidyut node needs to be given information regarding the phase of the power supply it is connected to. This information is necessary to correct for the constant phase offset between different phases. For instance, if phase A is considered the reference, nodes on phase B and phase C will have to include a phase offset correction of 120° and 240° respectively.

3.3 Power-line Interface

Fig. 9 illustrates a block diagram of Vidyut's interface circuit. Each Vidyut node extracts the reference clock signal from the power lines as well as the power signal at a stepped down voltage. Vidyut's interface circuit consists of an isolation transformer (not indicated in Fig. 9) to protect the Vidyut node from the 110V of the power lines. The stepped down voltage is fed to the zero crossing detector to achieve Vidyut's time synchronization.

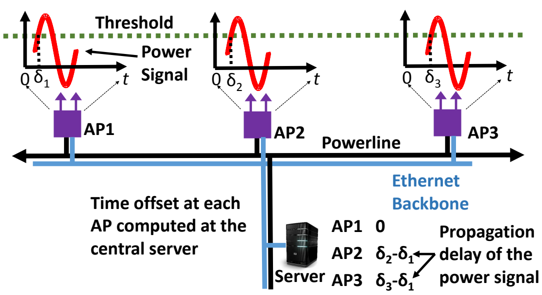


Figure 8: Time synchronization methodology.

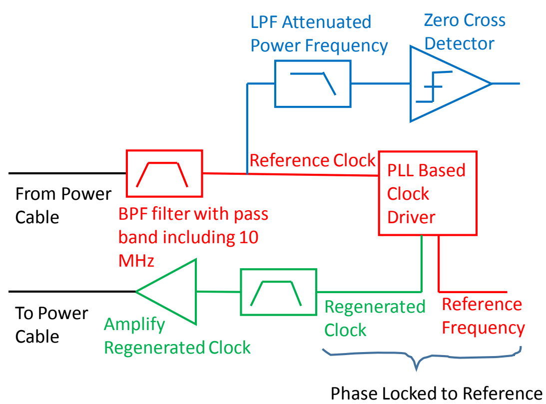


Figure 9: Vidyut's Power interfacing circuit.

A second lead from the power lines is band-pass filtered to obtain a copy of the reference clock signal with band-limited noise. This signal is fed as the reference clock to the PLL of the clock distribution core of Vidyut node. One output of the clock distribution core is used for baseband operations (baseband clock). The second output feeds the mixers in the RF front end that are used to up-convert the baseband signals to RF or vice versa. The third output, referred to as the *regenerated* clock, is sent back on to the power lines. The regenerated clock is phase locked to the reference clock i.e. there is a constant phase offset between the reference and the regenerated clock. A repeater/regenerator module (this is a discrete IC and should not be confused with the Vidyut's regenerated clock output) can be used to ensure the regenerated and reference clock have the same frequency *and* phase. This is however, not mandatory.

4. IMPLEMENTATION

We implement each Vidyut node using NI-5791 radio front-ends. These front ends are each equipped with a PLL based clock distribution core (AD9511) that enables these nodes to synchronize their carrier and baseband clocks to an external reference clock. One output from NI-5791's clock core can be fed back on to the power-lines. While evaluating Vidyut we guarantee the presence of a reference clock when a Vidyut node is connected to the power-lines. We use a 10 MHz reference clock output from a signal generator, Agilent 8648C, as the default reference clock transmitted on to the power lines. While, we provide a default reference clock, it is not necessary for Vidyut to have a default reference clock to achieve distributed synchronization. Mechanisms can be developed to let nodes that do not *see* a reference clock to generate their own reference clock which can then be used by neighboring Vidyut nodes. However, since the focus of this paper is to establish the feasibility of Vidyut from the perspective of signal propagation and integrity, we assume we are given a reference clock. Each Vidyut node outputs its own clock on to the power line medium. We interface the clocks of Vidyut node using the interface circuitry described in Section 3.

5. MICROBENCHMARK EVALUATION

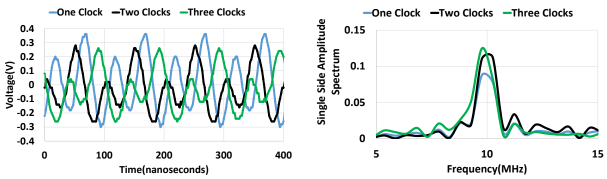
We transmit a reference clock at 10 MHz through the power-lines for the purpose of synchronizing distributed nodes. While this is **not** the only frequency suitable for transmitting the reference clock, we choose 10 MHz following its favorable attenuation characteristics and ability to pass through transformers as detailed in the previous section. Further, the software defined radios used in our experiments accept a default external clock input of 10 MHz and is thus, convenient too.

5.1 Frequency Synchronization:

Frequency mismatch results in increase in noise floor of the receivers. Recent work [15], simulated the effect of phase mismatch between two transmitters on the increase in noise floor at a receiver. It reported that for a phase mismatch under 0.05 radians (over the duration of a symbol), the increase in noise floor is negligible even at high SNR. We evaluate the accuracy of Vidyut's frequency synchronization and the effect of different design decisions of Vidyut on its frequency synchronization performance. We use the following method to estimate the phase mismatch of Vidyut's synchronization.
Method: Two Vidyut nodes are synchronized using the reference clock in the power-lines. The power line medium between the two nodes is changed depending on the objective of the experiment. (Unless specified otherwise, these nodes are connected to a live power network, given in Fig. 2, and are thus subject to noise conditions and load variations typically experienced in a power network.) We assign one of these two nodes, the transmit node, to transmit a pilot tone, F_{pilot}, known to both nodes, over the air. The second node (receive node), placed within the transmission range of the transmit node receives the pilot tone as $F_{received}$. This node then computes the phase offset $\phi(t)$ between the received frequency and the transmitted frequency as a function of time using Eq. 3.

$$\phi(t) = (F_{received} - F_{pilot}) \times t + \phi(t_0) \tag{3}$$

where $\phi(t_0)$ is the initial phase offset. The frequency mismatch is simply the slope of the phase offset as a function of time. Thus, perfect synchronization in frequency results in the phase offset variation being parallel to the time axis. We measure phase mismatch over the duration of 4μ seconds (symbol duration defined in 802.11ac standard).
Effect of distributed clock regeneration: Each Vidyut node regenerates the reference clock and feeds it back on to the power lines. As long as there is a constant phase offset between the reference clock and the regenerated clock and they are not out-of-phase, the frequency of the reference clock does not change. Fig. 10 plots the reference clock traversing the power lines in both the time and frequency domain as the number of clock regenerators increases. The reference clock frequency remains unaffected as the number



(a) Time Domain (b) Frequency Domain

Figure 10: Effect of multiple reference clock sources.

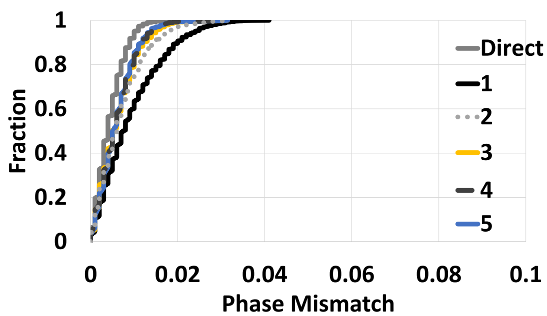


Figure 11: Phase mismatch vs number of intermediate clock regnerations.

of intermediate clock regenerators increases. However, each regeneration site still has a distinct phase noise characteristic. We evaluate the effect of the accumulation of phase noise as the number of regeneration sites increase.

Method: The transmit and receive nodes are synchronized using Vidyut. We add an intermediate Vidyut node between the transmit and receive nodes and measure the phase mismatch between the transmit and receive node. We vary the number of intermediate Vidyut nodes from 0 to 5. For this experiment, all nodes are connected to the *live* power distribution network.

Result: Fig. 11 plots the distribution of the phase mismatch between the transmit and receive nodes as the number of clock regenerators (intermediate nodes) between them is varied. Increasing the number of intermediate Vidyut nodes does not have a direct correlation on the phase mismatch between the transmit and receive nodes. This is because the phase noise of each PLL is random. Hence, the cumulative effect of the phase noise of individual nodes does not accumulate. Further, the phase mismatch distribution is well within the tolerable limits in terms of limiting SNR degradation at receivers. The phase mismatch for majority of the observations is under 0.04 radians.

Power line length: We measure the phase mismatch between the transmit and receive nodes by varying the length of the power-line between these two nodes. For each power cable length, the nodes and the power cable between them are connected to the *live* power distribution network. We repeat the experiment by connnecting the Vidyut nodes to different power outlets (illustrated in Fig. 2). Fig. 12 plots the distribution of the phase mismatch between the nodes for different length of power lines between them. As indicated in the figure, the phase mismatch distribution is largely independent of the length of the power line between the nodes. This is because the attenuation caused by the power lines at this frequency is minimal.

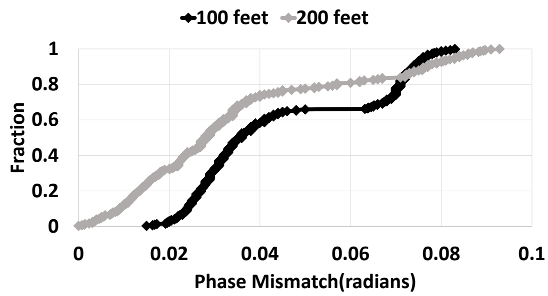


Figure 12: Phase mismatch vs power-line length.

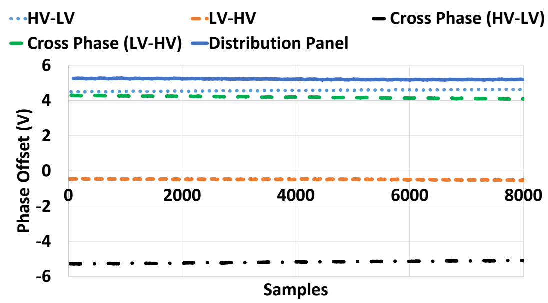


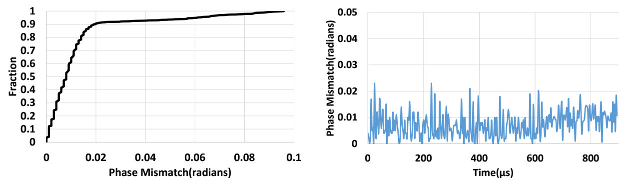
Figure 13: Phase offset between Vidyut nodes on either side of typical elements found in the power grid (transformers/distribution panel). HV (High-Voltage) is the secondary side and LV (Low-Voltage) is the primary side in a step-up transformer.

Effect of Transformers/Circuit Breaker Panel: We evaluate the phase mismatch caused by the frequency response of the transformer by placing the transmit and receive nodes directly across a de-energized transformer. We place the two nodes across the windings of the transformer on same as well as different phases. We perform the experiments on the 27 KVA transformer.

We also evaluate the effect of the circuit breaker panel on the phase mismatch across these two nodes by placing these nodes on different circuits along the same phase on a de-energized distribution panel. We ground all the unloaded circuits to mimic the effect of low-impedance presented by the circuit breaker panel. A qualitative estimate of the phase offset at the receive node for each configuration connected between the transmit and receive nodes is presented in Fig. 13. As illustrated in the figure, the phase offset over time is parallel to the time axis thus suggesting frequency synchronization between the two nodes.

Synchronizing battery powered nodes: We measure the effectiveness of Vidyut to synchronize mobile clients in the following experiment.

Method: The transmit and receive nodes are connected to a *live* power network and synchronized using Vidyut. The location of the transmit and receive nodes is fixed. A third node, not connected to the power network (mobile), is placed within the transmission range of these two nodes. The transmit node transmits a pilot tone over the air at a frequency known to all the nodes, say pilot frequency. The mobile node listens to this pilot tone and computes the frequency offset between the transmit node and itself . Once computed, this node then transmits the pilot tone after accounting for



(a) Phase Mismatch Distribution (b) Phase Mismatch over time

Figure 14: Effectiveness of Vidyut in synchronizing mobile nodes.

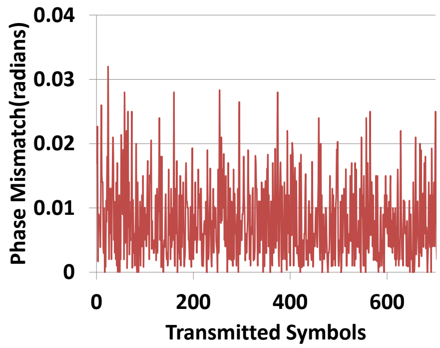


Figure 15: Accumulated phase mismatch as the number of symbols ($4\mu s$) transmitted increases. The phase mismatch between two Vidyut nodes does not deteriorate as the number of symbols transmitted increases. As indicated, the accumulated phase mismatch over time is random since the phase noise distribution of each PLL is random.

this frequency offset. The receive node, synchronized to the transmit node by Vidyut, computes the phase mismatch between the mobile node and itself by listening to the pilot frequency transmitted by the mobile node.
Result: Fig. 14(a) plots the distribution of this phase mismatch. As before, the phase mismatch is calculated over the duration of one symbol (4μseconds). Fig. 14(b) plots the phase mismatch at the receive node over a time duration of 800μseconds. A flat phase mismatch over time indicates that the mobile node synchronizes itself to Vidyut's reference clock. Further, it indicates that the frequency offset between the free-running oscillator of the mobile node and the transmit node is relatively steady with time. This is useful in extending Vidyut for OFDMA type applications.

Phase Mismatch vs Time: We evaluate the phase mismatch between two Vidyut nodes as the number of symbols increases. We connect the transmit and receive nodes to a *live* power network and synchronize them using Vidyut. We fix the location of the transmit and receive nodes. We then track the accumulated phase mismatch between the transmit and receive nodes at the receive node with time. Fig. 15 plots the phase mismatch as a function of time. The phase mismatch is computed over the duration of the symbols transmitted. As indicated, the phase mismatch is relatively steady over time. This is because Vidyut nodes continuously relock to the common reference clock traversing the power lines. Thus, the phase mismatch does not accumulate over time.

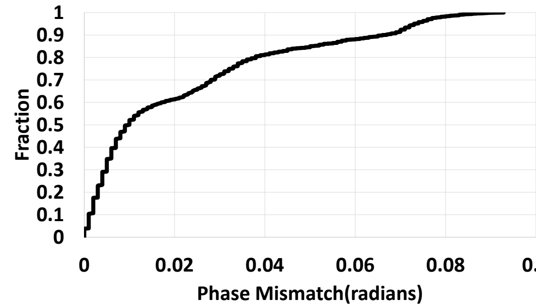


Figure 16: CDF of phase mismatch between two nodes synchronized using Vidyut distributed randomly over the topology in Fig. 2.

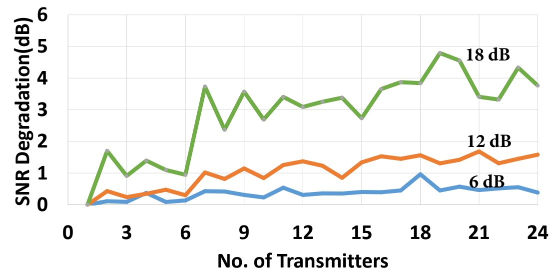


Figure 17: SNR degradation due to phase mismatch across the transmitters as the number of transmitters is increased under different channel conditions.

Impact of Phase Mismatch: Fig. 16 plots the phase mismatch distribution between two nodes synchronized by Vidyut. For each experiment, the nodes are connected to live power outlets randomly, across different phases and across the span of a floor in our department given in Fig. 2. The red circles in Fig. 2 indicate the power outlets to which the Vidyut nodes were connected. The experiment was carried out at different times of the day and thus the phase mismatch in Fig. 16 accounts for the various noise sources experienced in power lines, different load conditions and the effect of the different electrical elements in the power distribution network.As indicated in Fig. 11, the distribution of the phase mismatch between two nodes synchronized by Vidyut is independent of the number of Vidyut nodes sharing the power lines.

We estimate the increase in the noise floor at each receiver for the given phase mismatch distribution (Fig. 16) as the number of transmitters is increased. We plot the mean increase in the noise floor at each receiver as the number of transmitters synchronized by Vidyut is varied. Once we fix the number of transmitters, we vary the channel along three levels of SNR (6,12 and 18 dB). For each setting, we repeat the experiment a hundred times to establish the mean. The increase in noise floor at a receiver for different channel conditions is illustrated in Fig. 17. When the nodes perform Network MIMO using Vidyut in uniform channel conditions of 6dB SNR, the SNR degradation is negligible as the number of transmitters is increased. However, when the channel conditions are uniformly better, the average increase in SNR at each receiver as the number of transmitters is increased to 24 is $\approx$ 4dB.

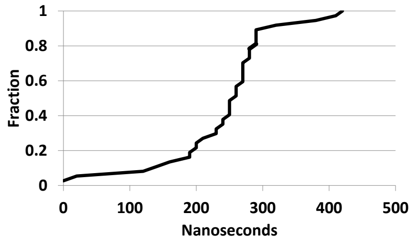


Figure 18: Variance in the power cycle zero crossing.

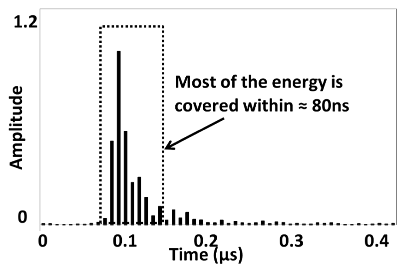


Figure 19: Capturing multipath in an indoor environment.

5.2 Time Synchronization:

As discussed in the previous section, Vidyut utilizes the stable time period of power frequency as a reference for time across distributed nodes. Each node constructs a time averaged time period of the power cycle to filter out the impact of impulsive noise sources. We measure the variance in the zero crossing of the power cycle across random power outlets illustrated in Fig. 2.The cumulative distributed function (cdf) of this variance is illustrated in Fig. 18.

The distribution of the variance in the time period of the power cycle is almost Gaussian indicating the variation in the time period is due to random noise sources. The difference in time period between adjaced periods can be as high as $\approx$ 450 nanoseconds. The average variation in time period is $\approx$ 225 nanoseconds. Further, the measurement of the propagation delay of the power signal between two nodes can introduce errors. To correct for such errors, we provision an additional 100 nanoseconds.

The 802.11n makes a provision for two guard intervals: 400 ns(short) and 800 ns(typical). The intrinsic noise in the power lines makes it hard for Vidyut nodes to operate with the short guard interval since the variation in the time reference itself exceeds the guard interval and leaves no further tolerance for multipath effects. We measure the multipath effects in a typical indoor enviroment in our lab. Our lab space includes multiple cubicles with metallic edges, metallic chairs and tables which all act as reflectors. The multipath profile of this environment is illustrated in Fig. 19. As indicated, most of the energy from multipath sources is covered at the receiver within 80 ns. Thus, even with an average variation of 225 ns, the Vidyut's time synchronization methodology should suffice as a method of time synchronization majority of the times as the difference in signal paths at the receiver will be well within 800 ns.

5.3 Power:

The Agilent 8648C outputs a 10 MHz reference clock at an

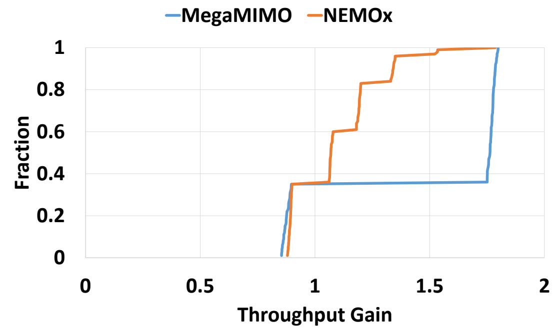


Figure 20: Throughput gain over MegaMIMO and NEMOx.

amplitude above $0.5V_{rms}$. This reference clock has been used to synchronize Vidyut nodes upto 200 feet away. Each NI-5791 based Vidyut node outputs a 2V peak-to-peak square clock output in phase to the reference clock traversing the power lines. With this power we had no trouble synchronizing Vidyut nodes as far as two hundred feet away to enable Enterprise LAN based applications.

6. SYSTEM EVALUATION

The previous section quantifies the accuracy of Vidyut's synchronization in time and frequency domains and analyzes the contribution of different elements in the power lines and Vidyut's own clock circuitry to the synchronization. We now implement two Vidyut backed systems. First, we build an eight node Network MIMO type system. We distribute the eight node locations randomly across the area of a floor in our department illustrated in Fig. 2. For this setting, we analyze the throughput performance of Vidyut and compare it with MegaMIMO and NEMOx. Second, we build an eight node OFDMA type system and analyze Vidyut's distributed synchronization's effect on reliability of communication. For both experiments, the nodes are connected to power outlets of live networks and the experiments were performed during different times of the day. Thus the results presented include the effect of different loading conditions and noise sources experienced in power lines.

Network MIMO: First, we define competing clusters as a set of those clusters (defined in Section 1) that has atleast one client associated to every cluster in the set. We place Vidyut nodes at random locations illustrated in Fig. 2. For all locations, the nodes are synchronized using Vidyut. We place the nodes such that for every distribution of the nodes, we can group all the transmitting nodes into no more than two clusters. Also, a cluster is guaranteed at least one receiver for every node distribution. Fig. 20 plots the distribution of the throughput gain of Vidyut over MegaMIMO and NEMOx. Vidyut achieves a throughput gain of $\approx$ 1.8 times over MegaMIMO during approximately 65 % of the experiments. These are the instances where the nodes are placed in such a way that they form competing clusters. For almost, 60% of the experiments, the throughput gain of Vidyut over NEMOx is quite minimal. The reason for this is that the node density of our testbed is sparse.

We seek to determine the potential benefit of having synchronization beyond two clusters. Since the number of nodes required for bigger networks is prohibitively high, we run a MATLAB based simulation to evaluate the performance

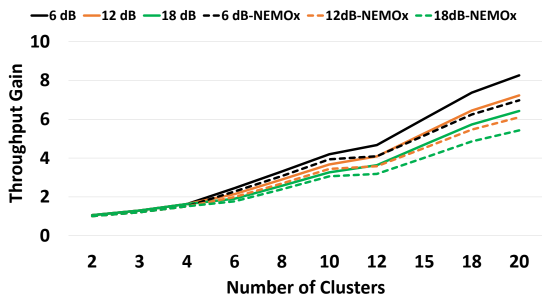


Figure 21: Throughput gain for a Vidyut system compared to MegaMIMO and NEMOx as the number of clusters increases. The thick lines plot the throughput gain of Vidyut over MegaMIMO and the dotted lines over NEMOx.

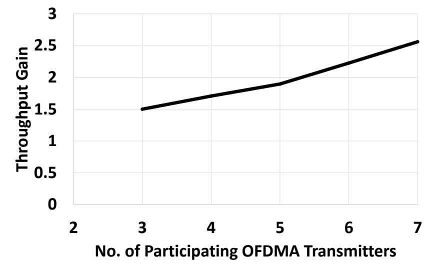


Figure 22: Vidyut backed OFDMA systems show a throughput gain over unsynchronized free-running oscillators.

gains of Vidyut for networks with higher number of clusters. We assume every AP always has data to send to its clients. We compare the performance of Vidyut backed system with MegaMIMO and NEMOx backed systems. We group a set of clients with a cluster if every client is within the transmission range of atleast one AP of that cluster. We implement a TDMA over CSMA type MAC for MegaMIMO and NEMOx systems, by letting all non competing clusters simultaneously transmit in each time slot. While implementing NEMOx, in case of competing clusters, we identify subsets of the competing clusters with distinct interference-free clients and let these APs transmit simultaneously. For the case of Vidyut, since all the APs are synchronized in time and frequency and since the data is sent from a single central server, all the APs can simultaneously send data without causing interference at unintended clients. The clusters and the clients are randomly placed. The number of clients is increased with the number of the clusters as well to ensure there is always a sink for the data demand. The experiment is repeated for 100 runs before increasing the number of clusters. For each run, we perform the experiment over three channel conditions. We assume uniform channel conditions over the span of the network. We let MegaMIMO and NEMOx transmit packets using the short guard interval. For Vidyut, we assume a long guard interval. Further, we account for the increase in noise power due to the phase mismatch of Vidyut.

Fig. 21 demonstrates the throughput benefit of Vidyut over MegaMIMO and NEMOx for larger networks as the number of clusters is increased. As indicated, the gain is negligible for two clusters since the network is sparse and thus the two clusters can simultaneously transmit without interfering with each other in the case of MegaMIMO and NEMOx negating the benefits of Vidyut. However, as the number of clusters and clients increases, the network becomes more dense. Subsequently, the throughput gain of Vidyut system becomes more significant. Vidyut system with 20 clusters presents an average throughput gain of $\approx$ 8.1x over MegaMIMO system and $\approx$ 5.9x over NEMOx system. The simulation incorporates the imperfections in timing and frequency synchronization of a Vidyut system discussed in the previous section. The reduction in gain from an ideal implementation of such a system is indicated.

OFDMA: In our OFDMA implementation, each transmitter transmits on alternate subcarriers, i.e. if $Transmitter_1$ transmits on subcarrier α, then $Transmitter_2$ transmits on subcarrier $\alpha + 1$ and so on. We vary the number of OFDMA transmitters from three to seven. We perform the experiment in two states. First, we synchronize all the participating OFDMA transmitters using Vidyut. Second, we repeat the experiment with unsynchronized transmitters. When the transmitters are unsynchronized, inter carrier interference occurs thereby reducing the throughput of the OFDMA system. Fig. 22 illustrates the throughput gain of a Vidyut backed OFDMA system over an unsynchronized OFDMA system. Vidyut achieves a throughput gain of upto 2.5 times as the number of concurrent OFDMA transmitters is increased from three to seven.

7. RELATED WORK

Time Synchronization: Sourcesync [14] utilizes a synchronization header from a lead transmitter to synchronize transmissions between distributed concurrent transmitters in time domain. Sourcesync achieves time synchronization within 20ns. Sourcesync limits synchronization to nodes within a single collision domain. The work presented in [16] utilizes the electromagnetic radiations from the power frequency to synchronize distributed sensor nodes to enable coarse time synchronization in wireless sensor networks. The synchronization achieved is of the order of milliseconds which is not suitable for Wi-Fi-type applications.

Frequency Synchronization: MegaMIMO [15] and Airsync [2] achieve time and frequency synchronization conducive for MU MIMO systems. Both these techniques rely on a lead transmitter to transmit a synchronization header in the air. Thus, these implementations are applicable only to nodes within a single collision domain. NEMOx, [21], proposes a MAC that advocates opportunistic transmissions from APs within a competing cluster to interference-free clients.

Power-line Communication: The power-line medium is an emerging alternative to cellular and wireless media for Smart Grid, [6], as well as in-home broadband applications [5] [11]. Smart Grid PLC implementations operate in the 10-500 KHz band of the spectrum in The United States with a data rate in the order of 100s of Kbps [5] while in-home broadband PLC applications operate in the 2-86 MHz, [17]. While the communication range of this frequency range is much shorter than the KHz band used for Smart Grid applications, it achieves data rates of the order of a few 100s of Mbps. The works in [3], [18] explore extending the communication range of PLC using amplify-and-forward technique.

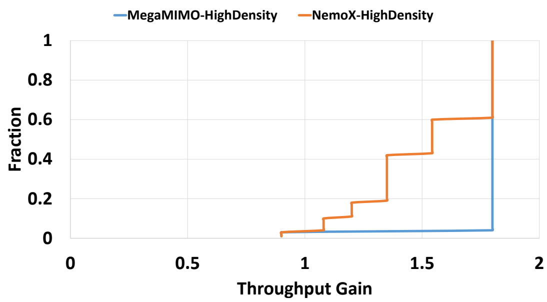


Figure 23: Throughput gains of Vidyut in a two cluster dense network.

While Vidyut requires each node to regenerate the reference clock, Vidyut's objective is distinct from that of power-line communications in the following regard: Vidyut is only responsible for distributing a stable reference clock (a single tone) across the power-line network of an enterprise.

Power-line assisted wireless communication: SNUPI [4] utilizes the power-lines as an antenna to increase the transmission range for wireless sensor nodes. Vidyut directly injects the reference clock on to the power-lines. The work in [8] proposes PLC transmission schemes to assist sharing channel information between wireless relay nodes as well as with synchronization. Vidyut does not require Vidyut nodes to decode PLC packets and achieves synchronization using the physical property of PLLs. Recent works, [9] [10] [7], use PLC together with different wireless communication techniques to enhance performance of wireless networks. In all these solutions, the power-lines are used to transmit data while Vidyut only transmits a reference clock.

8. DISCUSSION

We have demonstrated the feasibility of using power lines as a resource for achieving distributed synchronization across clusters. We demonstrated the throughput benefits of such synchronization from small to large networks. However, as pointed out in the previous section, when the network density is sparse, NEMOx in most cases will do as well, if not better than Vidyut (accounting for inaccuracies in the phase mismatch). Thus, one might be led to believe that Vidyut has benefits for only large networks with large number of clusters. While, we have not dealt with the problem of CSIT, it is a challenge in implementing a Network MIMO network. However, we point out that cross-cluster synchronization is critical even in small networks. The key, however, is for the network to have high density. Fig. 23 illustrates the throughput gain of Vidyut in one such two cluster network. Thus, cross-cluster synchronization has significant benefits even for small networks.

Effect of Vidyut on existing PLC: The current state-of-the-art PLC standards employ OFDM with bit-loading schemes [17]. These standards specify a bandwidth of operation ranging from 2 MHz to 86 MHz using 3,455 subcarriers. The single-tone reference used for Vidyut will cause existing PLCs to skip one of its subcarriers. Therefore, the effect on PLCs will be insignificant.

One can consider a hybrid global synchronization technique that includes the long distance benefit of Vidyut with higher accuracy of other systems such as MegaMIMO. However, this is left as work for future research.

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