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Low-Power Clock Synchronization using Electromagnetic Energy Radiating from AC Power Lines
(Apply Directly Where it Hertz)

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Why Time Synchronization?

- **Event Ordering**
- **Low Duty Cycle Networking**
- **Time Division Multiple Access (TDMA)**
  - Energy-efficient
  - High-throughput

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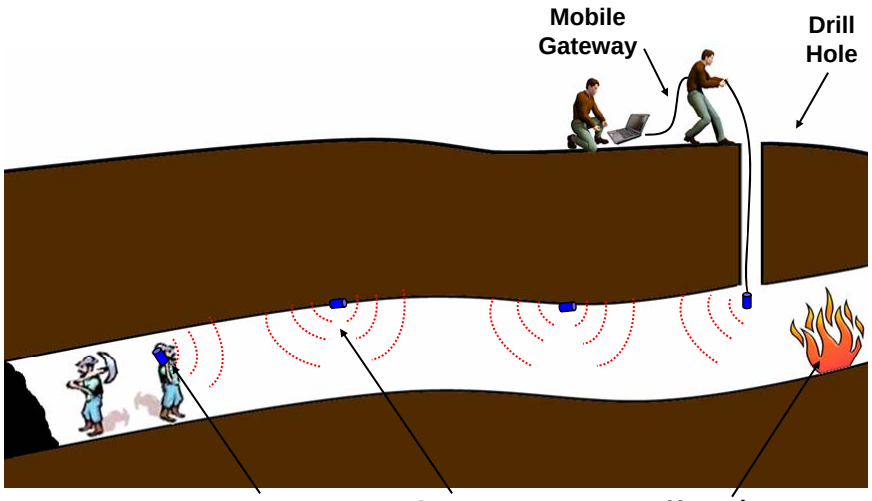
Looking back at 2006



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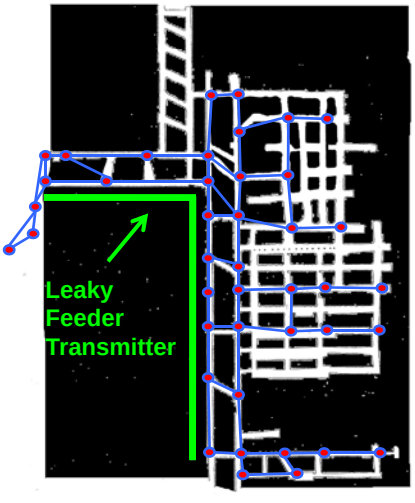
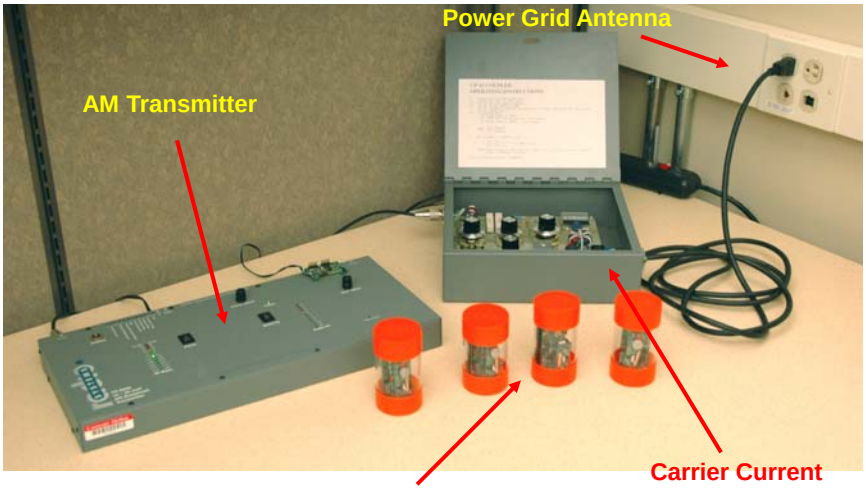
NIOSH Research Coal Mine

near Pittsburgh



NIOSH: National Institute for Occupational Safety and Health

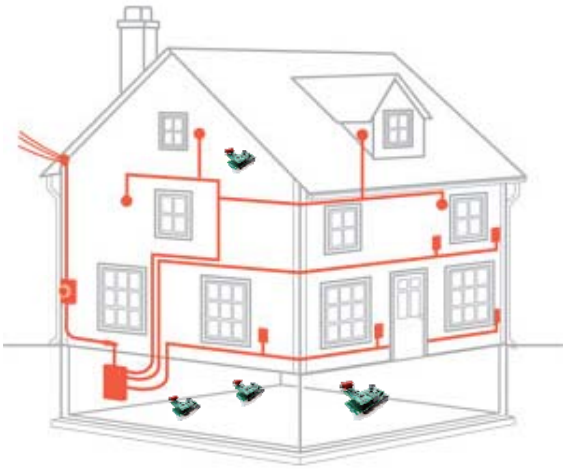
Very Complex. Expensive.

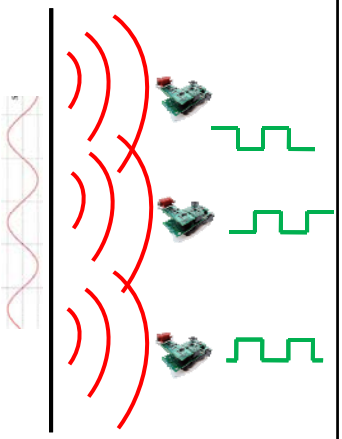


Other Synchronization Approaches

- **Sensor Network Time Synchronization**
  - Flooding Time Sync Protocol, FireFly-inspired Time Sync, Reference Broadcast
  - What about energy?
  - Imagine extremely low duty-cycles…
- **Global Broadcasts**
  - WWVB atomic clock, GPS, Radio Data Service (RDS)
  - Does not work well indoors
- **Simultaneous Observations**
  - Quasar Pulses, Quantum Entangled Particles
  - Not practical (yet)

Wirelessly Receive Power-Line Magnetic Field

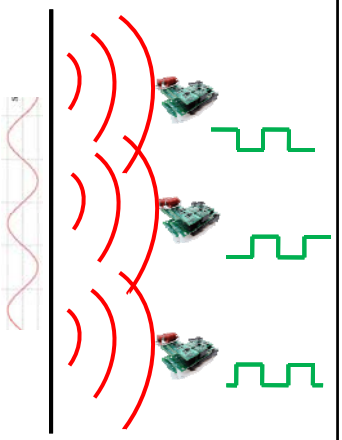




Mains Powerline

"Syntonization" vs Synchronization

- The 60 Hz frequency from the electrical line acts as a common global clock source
- The phases will differ depending on the angle of the receiver with respect to the magnetic field
- Signal due to imbalances in grounding loops



Mains Powerline

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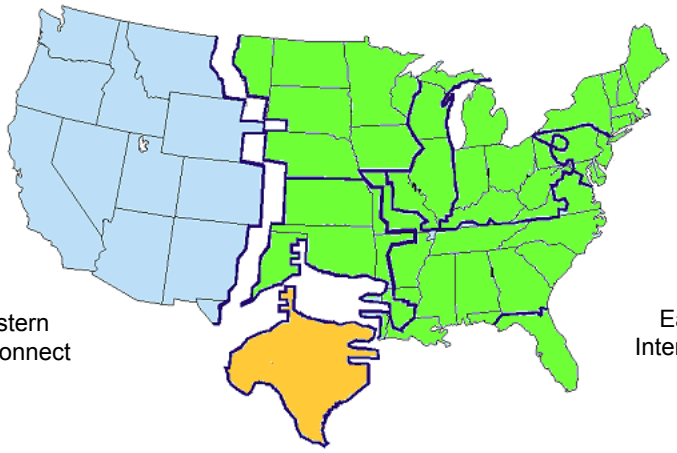
Powerline 60 Hz

- **Field Strength**
  - Home
    - 17 milli-gauss (as much as 10 gauss)
  - Industrial
    - As much as 100 gauss
  - Power Line
    - 3 milli-gauss at 60 meters
  - Earth
    - .02 milli-gauss

- **Stability**
  - 10^{-5} stability (typical oscillator is 10^{-5})
  - 10^{-8} differential delay stability between two points
  - Many old alarm clocks and appliances used the sine wave from direct contact to lines as a cheap clock

Clock Sources



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Why use a *Syntonistor*?

- Once phase offsets have been established, the device remains synchronized for long periods of time without exchanging messages
- Errors can be detected by monitoring for rapid changes in the 60Hz signal

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Challenges

- Low-power receiver → *Inductance / Resonance*
- Robustness to noise → *PLL Filtering*
- Common time reference
- Absolute phase adjustment

} *WSN Protocol*

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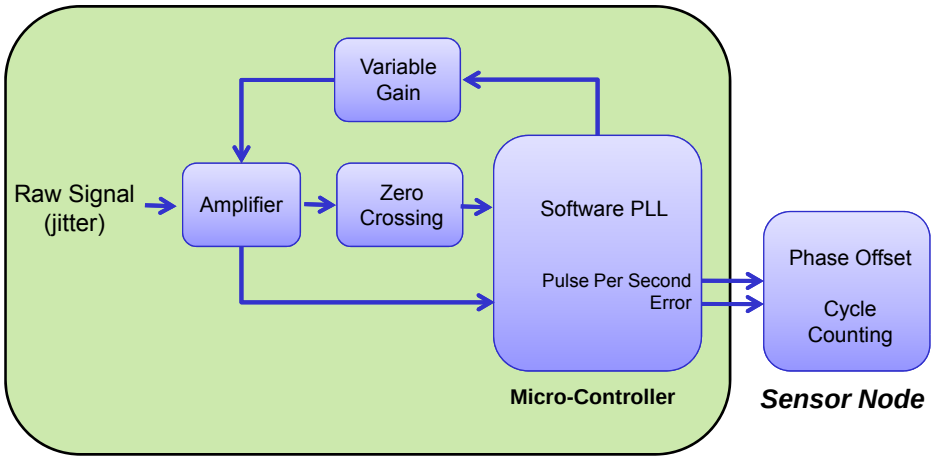
Block Diagram



Syntonistor

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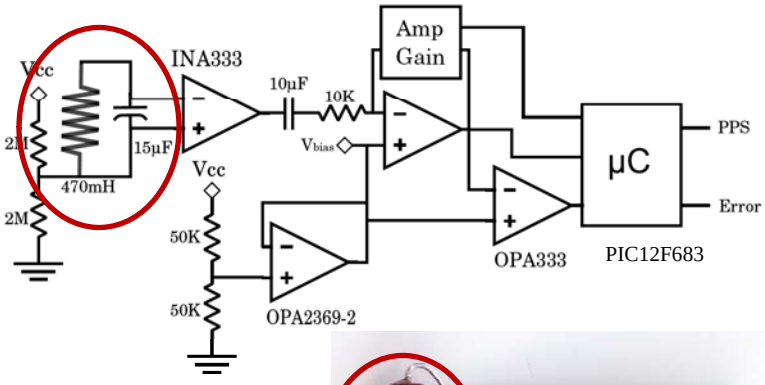
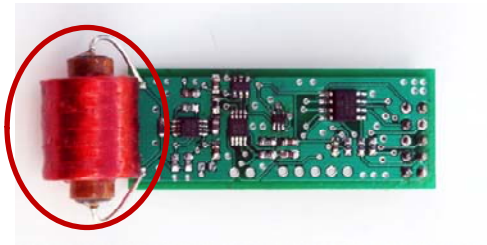
Syntonistor Hardware



Tank Circuit Tuned to 60Hz



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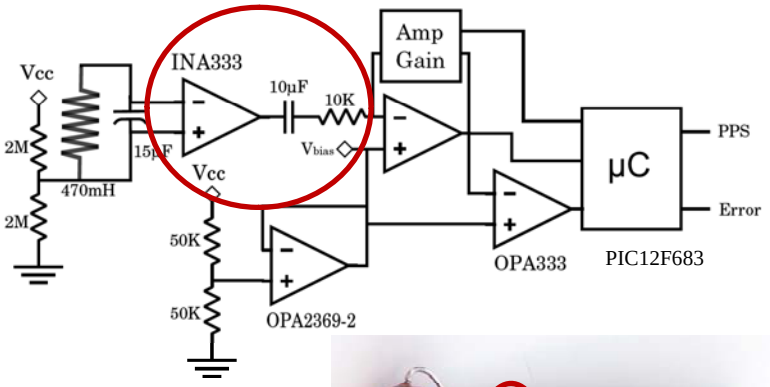
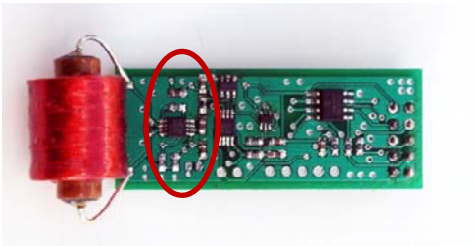
Syntonistor Hardware



1st Amplifier /
High-Pass Filter



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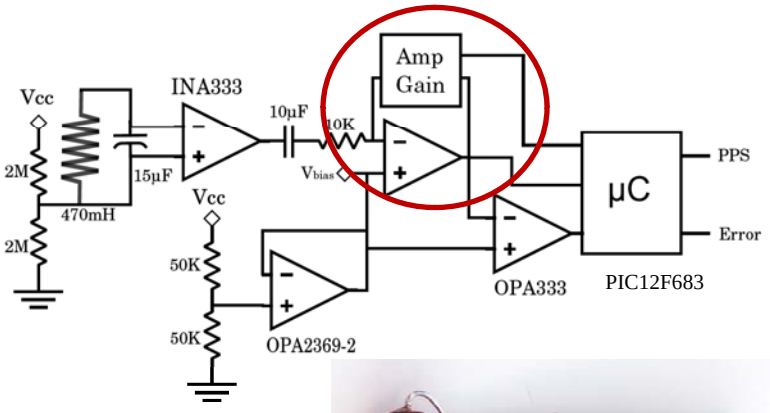
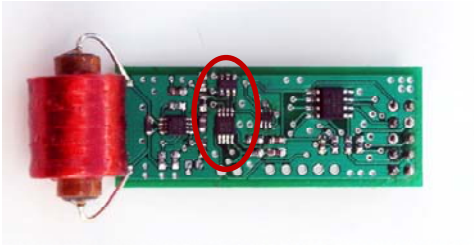
Syntonistor Hardware



2nd Amplifier /
Auto-Gain



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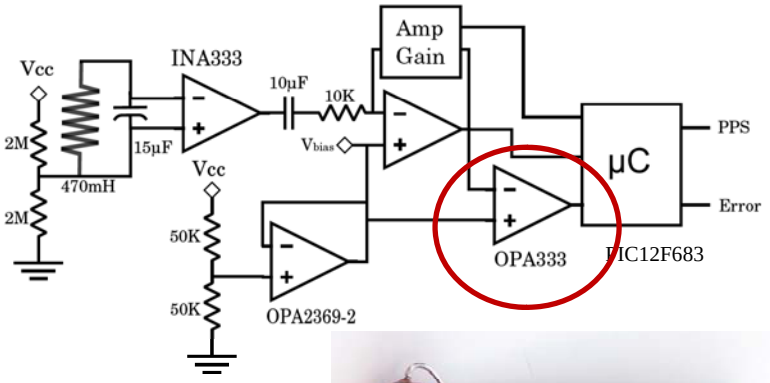
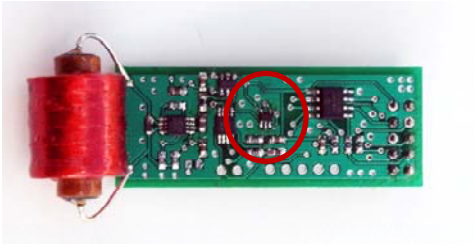
Syntonistor Hardware



Zero-Crossing Detector



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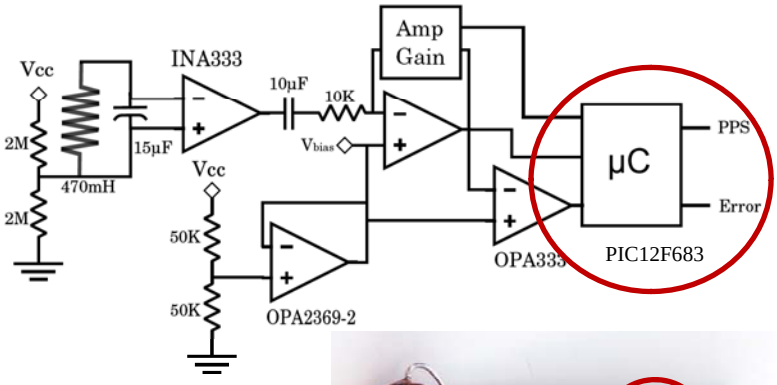
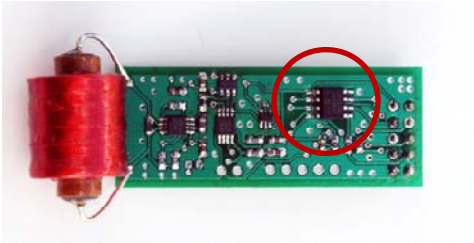
Syntonistor Hardware



Micro-controller



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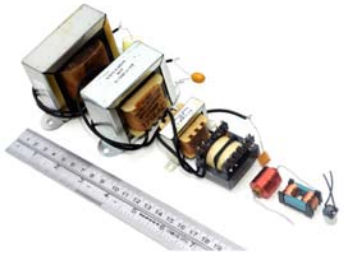
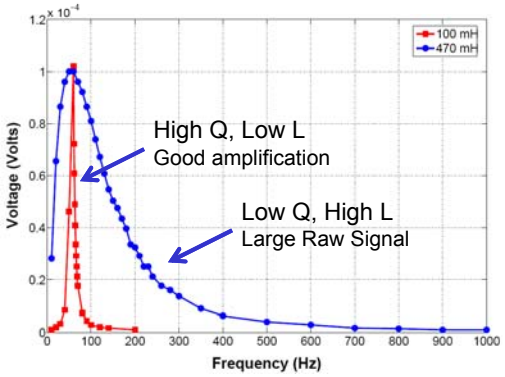
Tank Circuit (low Q)?





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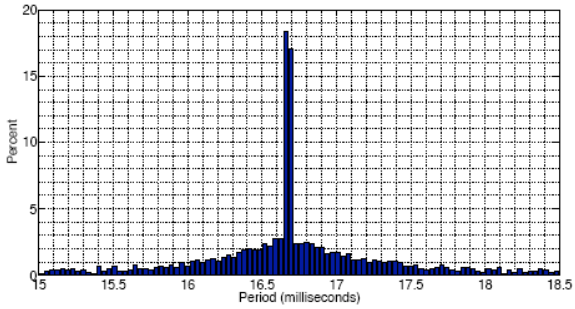
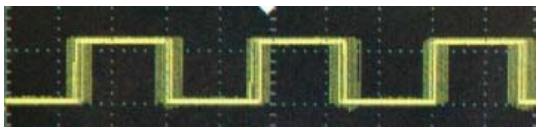
The raw signal





O-scope with delay 10 second persistence

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Phase-Locked Loop (PLL)

- Adjust *period* of output signal based on *phase difference* compared to input signal
- Classic controls problem
- We used a Proportional-Integral-Derivative (PID) controller
  - Low gains with reasonable I-term since we do not require extremely fast convergence

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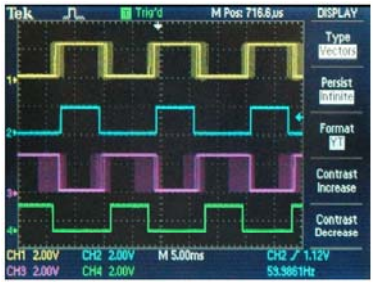
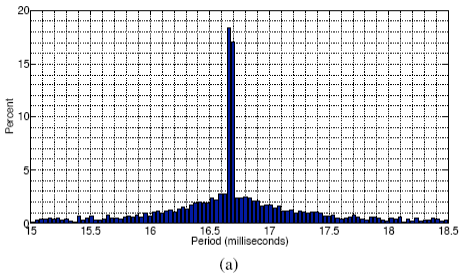
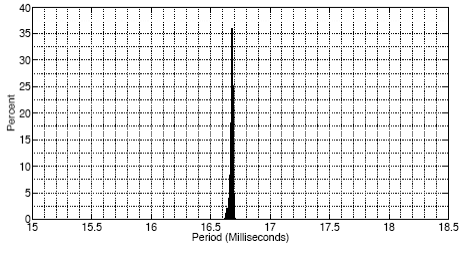
Cleaning up the jitter





(a)



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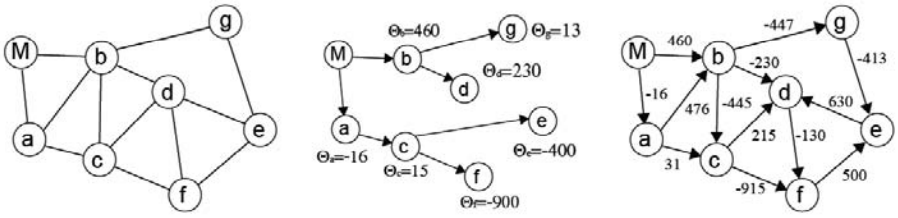
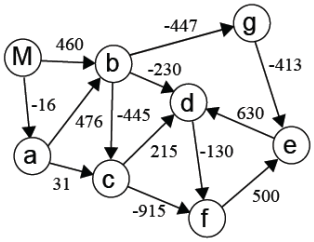
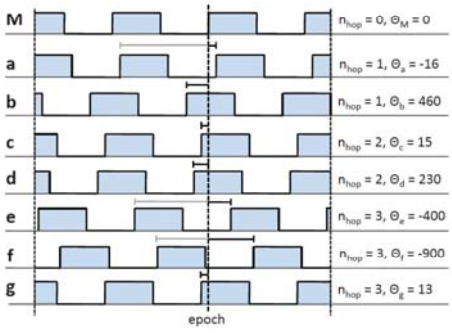
Protocol (1 of 2)



1. **Build Spanning Tree**
2. **Flooding Time Synchronization**
   - **Determine phase offset from initial epoch**
3. **Phase Offset Adjustment**

Protocol (2 of 2)



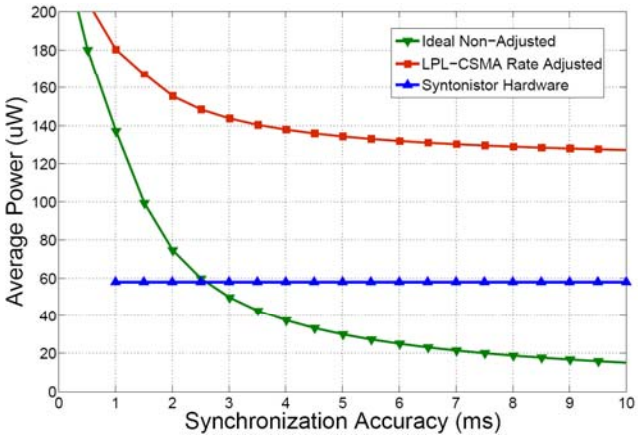


- **Simple**
- **MAC protocol independent**

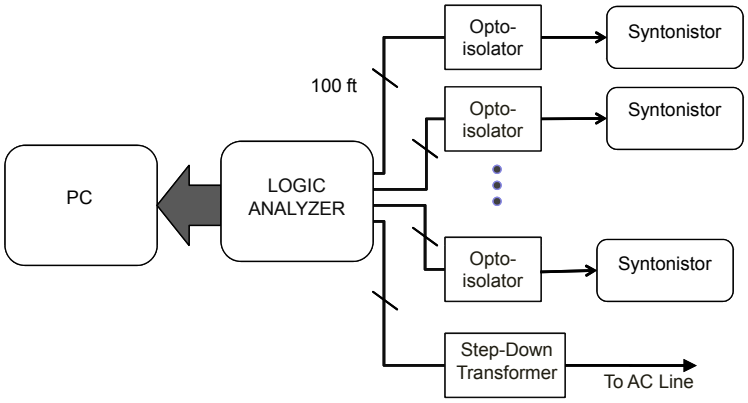
Synchronization Energy (1 of 2)

- **Ideal non-adjusted approach**
  - Send a packet when local clock drift exceeds required synchronization
    - Assume perfect re-sync and ideal MAC protocol
- **LPL-CSMA (B-mac) rate adjusted**
  - Add a MAC protocol to Ideal approach, but now we apply clock rate adjustment based on multiple packets
- **Syntonistor**
  - Consumes 58μW

Synchronization Energy (2 of 2)

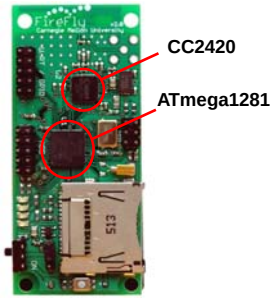


Experimental Setup



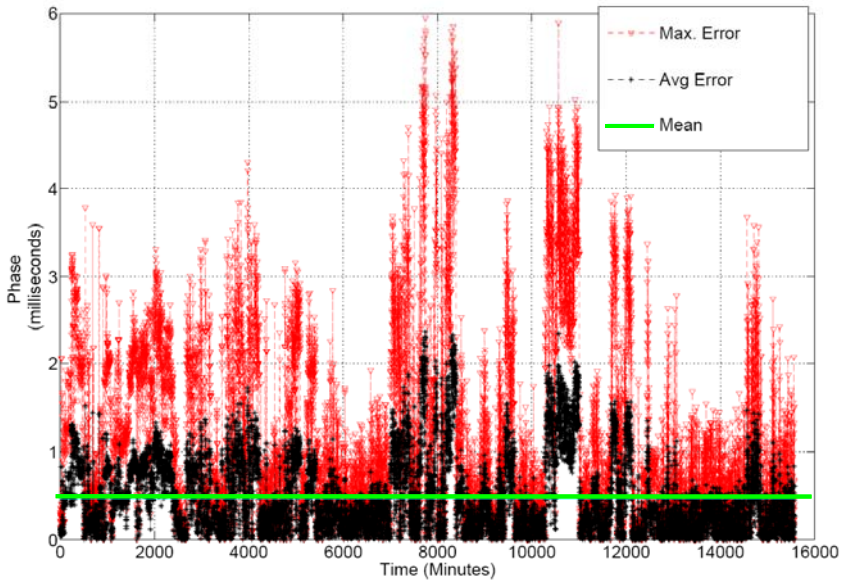
FireFly running Nano-RK

- **C GNU tool-chain**
- **Classical Preemptive Operating System Multitasking Abstractions**
- **Real-Time Priority-Based Scheduling**
  - Rate-Monotonic Scheduling
- **Built-in Fault Handling**
- **Resource Reservations**
  - CPU, Network, Transducer Resource Control
  - Forms Virtual Energy Budget



http://www.nano-rk.org

8 nodes, 10000 ft^2, 11 days



Interference

- **Indoors**
  - High Frequency sources are bad (computers, TVs, etc.)
  - Some devices are good (lights, etc.)
  - Transformers radiate a clean signal for multiple meters
    - AC adapters are like transmitters
- **Outdoors**
  - Strong signal 50 meters from buildings
  - Near power lines (buried or above ground) works very well
  - Surprising where one finds power lines

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Limitations

- **No Mobility**
  - Due to low frequency
- **Only operates near power**
  - Not good for the ocean, space or remote areas
- **Requires extra hardware (cost)**
  - This can be optimized

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Conclusion

- **Developed a hardware device that locks onto the magnetic field from power lines**
  - Consumes 58μW
  - Ambient magnetic filed energy is already there
- **Using a high-level protocol, network-wide synchronization is possible**
  - Typically less than 1*ms* accuracy
- **Remains synchronized without exchanging any packets**
- **Locally detects errors without sending packets**

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Thank You.

Questions?

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