Exploring Power Network Signatures for Information Forensics

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http://www.ece.umd.edu/~minwu/research.html

Include joint research with Adi Hajj-Ahmad, Ravi Garg, Hui Su, Avinash Varna, Chau-Wai Wong; Kari Klaus, and Douglas Oard.

Forensic Questions on “Time” and “Place”

- When was the video actually shot? And where?
- Was the sound track captured at the same time as the picture? Or super-imposed afterward?
- Explore fingerprint influenced by power grid onto sensor recordings

Ubiquitous Forensic Fingerprints from Power Grid

- Electric Network Frequency (ENF): 50 or 60 Hz nominal
  - Change slightly due to demand-supply
  - Main trends consistent in same grid

Traces in the Environment: Exploring Power Network Signatures for Information Forensics

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**Ubiquitous Forensic Fingerprints from Power Grid**

- **Electric Network Frequency (ENF):** 50 or 60 Hz nominal
  - Change slightly due to demand-supply
  - Main trends consistent in same grid
- **ENF** can be “seen” or “heard” in sensor recordings
  - Power grid influences electronic sensing (E/M interference, vibration etc)
  - Help determine recording time/location, detect tampering, etc.

ENF matching result demonstrating similar variations in the ENF signal extracted from video and from power signal recorded in India

**Light Sensing Circuitry**

- Convert light intensity falling on the diode into current
- Use an amplifier with a high gain ($10^6$) to convert weak current to measurable voltage levels
- Digitize and record circuit output voltage (e.g. to a PC sound card)
  - Reference ENF signal recorded in parallel
  - Step down using a transformer and voltage divider

**ENF Research Roadmap At-A-Glance**

- **Estimate ENF Signal** (instantaneous freq.):
  - Robust, high resolution;
  - Exploit harmonics
- **Visual Modality:**
  - Handle aliasing – exploit rolling shutters;
  - Handle motion;
- **Modeling & Analysis:**
  - Statistically modeling of ENF signals;
  - Anti-Forensics.
- **Novel Applications:**
  - Location & integrity;
  - Stream alignment;
  - Digital humanity – on historical recordings, ...

**Instantaneous Frequency Estimation**

- **Time-domain** zero crossing method in early prior art
- **Spectrogram approach** (Short-Time Fourier Transform)
  - Maximum energy from signal around respective freq. range
  - Weighted energy by spectral strength to find freq. centroid over a given range:
    - => Robust to outliers, simple to compute, work well in practice
- **High-resolution subspace approach:** MUSIC, ESPRIT
  - Theoretical foundations in statistical signal processing
  - More sophisticated frequency tracking with stochastic models

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Min Wu (UMD): ENF for Media Information Forensics
**ENF Experiment on Photodiodes**

A total of 50-minute recording
- A fluorescent lamp placed near the sensing circuitry
- Sensor recording started at a 15-sec. delay from reference signal

**ENF Results: from Photodiodes**

- Frequency fluctuations almost identical
- Photodiode ENF signal has twice the fluctuations of reference ENF
- Weighted energy method gives highest correlation peak

**Aliasing Effect in Spectral View**

- Example: A video camera at 29.97 fps used for indoor recording in a 50 Hz ENF geographical area
- Multiple copies of ENF signal appear at different frequencies
- Bandwidth of each replica is different, high bandwidth replica helps ENF extraction
- Some replicas of ENF signal are mirrored version of original ENF signal in spectrum
Verifying Time of Recording: India

- Video recording started at same time as reference ENF signal
  - Static video; measure change in average frame intensity
  - Observe: power frequency not tightly controlled

Verifying Time of Recording: China

- Video recording started at 50-sec delay with reference signal
- Correlation of 9.79Hz band is higher than 10.09Hz band
  - Came from higher harmonic with bigger spread
  => Can enhance ENF estimate by combining several harmonics

Verifying Time of Recording: USA

- Video recording was started of a delay of 35 seconds with power mains signal
- ENF signal appears close to DC (at 0.12 Hz)
  - ENF signal close to content frequencies
  - Challenging to extract for surveillance video

ENF Extraction: the Effect of Motion

- Video recording started at same time as reference ENF signal
  - 1st 5 minutes: camera is panning => avg frame intensity changes
  - Afterward: surveillance type of scenario

Camera panning

Highest corr. at k=0
**ENF Extraction: Outdoor Night Scene**

- CMOS Sensors ~ exploit rolling shutter
  - Start with static video; then adapt to handle motion
  - Simple case: estimate visual scene by average of all frames
- **Experiment:** Night outdoor video of a lighted parking lot

![Video Screenshot](image1)

<table>
<thead>
<tr>
<th>Time (seconds)</th>
<th>Frequency (Hz)</th>
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<tbody>
<tr>
<td>0</td>
<td>59.99</td>
</tr>
<tr>
<td>20</td>
<td>60</td>
</tr>
<tr>
<td>40</td>
<td>60.01</td>
</tr>
<tr>
<td>60</td>
<td>60.02</td>
</tr>
</tbody>
</table>

Reference ENF from power

ENF estimated from video

**Tampering Detection**

- Adding a clip into original video leads to **discontinuity** in ENF
  - Clip insertion can also be detected by comparing the video ENF signal with the power ENF at corresponding time

![ENF signal from Video](image2)

From Time Stamps to Location

- **High correlation** of ENFs in audio & video captured at same time
  - => can extend to synch multiple media streams

![ENF signal from Video](image3)

- **Anti-Forensic Study:** possible to remove narrow-band ENF; but much harder to tamper/transplant a valid ENF w/o being caught

![Audio and Video ENF](image4)

**“Forensic Binding” of Audio and Visual Tracks**

- **From Time Stamps to Location**
  - Match with ENF references over times + grids
    - Verify or exhaustively search for the matching location on grid level

- What if no concurrent references available?
  - Explore overall characteristics of ENF in a grid
  - Also reduce computation of exhaustive search

Source: US Grid image is from InTech online
Explore Machine Learning to Infer Location

- Inter-Grid location-of-recording estimation from sensing signals containing ENF traces
  - Identified useful features for recognizing from power and audio

Proposed Features

- Apply operations on equal-sized ENF signal segments (8mins) to extract quantitative feature values.

I. Mean, Variance, Range of ENF segment.

II. Statistical properties from applying a Wavelet transform
  - Use variances of final Approximation, and Detail signals as feature values.

Proposed Features (cont’d)

III. Features related to statistical modeling of ENF signals.
  - We showed that a US ENF signal can be modeled as AR(2) process.
  - Use AR parameters and variance of innovation \( \nu[n] \) as features.
  \[
  s[n] = a_1 s[n-1] + a_2 s[n-2] + \nu[n]
  \]

<table>
<thead>
<tr>
<th>Index</th>
<th>Feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mean of ENF segment</td>
</tr>
<tr>
<td>2</td>
<td>log(range) of ENF segment</td>
</tr>
<tr>
<td>3</td>
<td>log(variance) of approx. after wavelet analysis</td>
</tr>
<tr>
<td>4-7</td>
<td>log(var.) of 4 detail signals after wavelet analysis</td>
</tr>
<tr>
<td>8-9</td>
<td>AR(2) modeling parameters</td>
</tr>
<tr>
<td>10</td>
<td>log(var) of innovation signal after AR(2) modeling</td>
</tr>
</tbody>
</table>

Classification Accuracy on 11 grids:
- Power signal: 90%
- Audio signal: 83%

Sample Feature Values
**From Time Stamps to Location**

- Match with ENF references over times + grids
  - Verify or exhaustively search for the matching location on grid level

**Can ENF Pinpoint to Locations Within a Grid?**

- Main trend of ENF is known to be the same in a grid
- “Microscopic” traces
  - Aggregated effect of local events and propagations from elsewhere

**Can we determine where within a grid?**

- E.g. DC or NYC in US East?
- Look at subtle traces in ENF
- Relate ENF correlation with distance

**Determine Location Using ENF (cont’d)**

- Signal details of ENF can help locate signal origin in a grid
- Results of concurrent data from five U.S. east locations
- On-going: more data & validation; from noisy media signals

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![US Grid image](inTech-online)

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**Example:**

- 3 east-coast locations on U.S. Eastern interconnection grid
- Conduct simultaneous power recordings, two per location
- Use 2-sec frames with 1-sec overlap
- Use ESPRIT for instantaneous ENF frequency estimation

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![Graphs](examples.jpg)

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![Graphs](examples.jpg)
Beyond Adversarial Settings:
- Exploring ENF in Historic Recordings
- Synchronize multiple A/V streams

**ENF in Historical Recordings**
- Two ENFs may appear in digitized tape recordings
  1. original ENF; and
  2. ENF at time of digitization
- => Provide digital preservation guidelines to better utilize invisible traces
- Distortions and artifacts
  - Drifting; low SNR; etc.
- Ongoing: create a historical ENF database
  - Timestamp recordings of historic importance

**Speed Restoration: ENF as Intrinsic Freq. Reference**
- NASA Apollo 11 Mission recording

<table>
<thead>
<tr>
<th>Before Restoration</th>
<th>After Restoration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectrogram</td>
<td>Spectrogram</td>
</tr>
</tbody>
</table>

**ENF for Video Synchronization**
- Few tools to stitch video but many for images – Why?
- Using ENF to align multi video: simple & efficient
  - Less constraints on viewing angle, camera calibration, etc

- Estimate ENF signals from videos (either sound or visual track)
- Calculate correlation coefficient as a function of lag
- Find lag with peak correlation
Video Synch. Using Intrinsic ENF in Audio

- Demo-1: Videos in the gym before synchronization
- Demo-2: Videos at different locations of Kim Lab Building before synchronization

Video after synchronization

<table>
<thead>
<tr>
<th>Video Clip</th>
<th>5 min</th>
<th>10 min</th>
<th>15 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Av. abs. error</td>
<td>0.21 sec</td>
<td>0.16 sec</td>
<td>0.14 sec</td>
</tr>
</tbody>
</table>

2 synched stopwatches (as ground truth)

More on ENF Aliasing: CMOS Rolling Shutter

- CMOS imaging sensors: Low cost; low power
- Rolling shutter in CMOS sensor: sequential row readout
  - Different rows exposed at different time
  - Often considered bad: distortions on fast moving scenes (see wiki)

Can we exploit row sampling to overcome ENF aliasing?

Align Visual Streams using ENF Row Signals

- Video signal: combination of visual component and ENF component.

1. Estimate visual component
2. Subtract visual component
3. Take row averages as source signal
4. Frequency estimation from source signal
**Motions and Brightness Changes**

- **Address motions in video:**
  1. Find and use only static regions.
  2. Estimate motion vector & carry out motion compensation.

- **Compensate for brightness changes:**
  - Brightness changes occur due to camera’s automatic gain control.
  - Model brightness change as a linear transform
  - Carry out linear compensation.

**ENF Research & References**

**Estimate ENF Signal** (instantaneous freq.):
- Robust, high resolution;
- Exploit harmonics
- SPL’13, APSIPA ’12, ACM MM’11, TIFS’13

**Visual Modality:**
- Handle aliasing – exploit rolling shutters;
- Handle motion
- TIFS’13, ICIP’14, ACM MM’14 Immersive Media

**Modeling & Analysis:**
- Statistically modeling of ENF signals;
- Anti-Forensics.
- WIFS’12, CCS’12, twoTIFS’13

**Novel Applications:**
- Location & integrity;
- Stream alignment;
- Digital humanity (historic audio)
- ICASSP’12-13, WIFS’13 / TIFS’15, iConf’14, ACM MM’14 Immersive

**THANKS to many who paved ways ...**

- Use static regions when possible
- Compensate for object & camera motion
- Compensate for brightness changes
- Estimate ENF

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**Demos: ENF from Visual Track**

- **Align ENF signals estimated from video for sync.**
  - Use 2 cameras equipped with rolling shutter.
  - Hallway video with motion & auto brightness change.
Include joint work with colleagues, graduate & REU students

Kari Klaus, Doug Oard; Wei-Hong Chuang, Ravi Garg, Adi Hajj-Ahmad, Hai Su, Avinash Varna, Chau-Wai Wong; Michael Luo (MERIT REU), Maggie Xiong (Cyber Security REU)

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