Electric Network Frequency Optical Sensing Devices

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Presenter's bio

Constantine Kotropoulos received the Diploma degree with honors in Electrical Engineering in 1988 and the PhD degree in Electrical & Computer Engineering in 1993, both from the Aristotle University of Thessaloniki.
He is currently a Full Professor in the Department of Informatics at the Aristotle University of Thessaloniki. He was a visiting research scholar in the Department of Electrical and Computer Engineering at the University of Delaware, USA during the academic year 2008-2009 and he conducted research in the Signal Processing Laboratory at Tampere University of Technology, Finland during the summer of 1993. He has co-authored 66 journal papers, 214 conference papers, and contributed 9 chapters to edited books in his areas of expertise.
He is co-editor of the book "Nonlinear Model-Based Image/Video Processing and Analysis" (J. Wiley and Sons, 2001). His current research interests include forensics; audio, speech, and language processing; signal processing; pattern recognition; multimedia information retrieval; biometric authentication techniques; and human-centered multimodal computer interaction.
Prof. Kotropoulos was a scholar of the State Scholarship Foundation of Greece and the Bodossaki Foundation. He is a senior member of the IEEE and a member of EURASIP, IAPR, and the Technical Chamber of Greece. He was a Senior Area Editor of the IEEE Signal Processing Letters and he has been a member of the Editorial Board of the journals: Advances in Multimedia, International Scholar Research Notices, Computer Methods in Biomechanics & Biomedical Engineering: Imaging & Visualization, Artificial Intelligence Review, MDPI Imaging, MDPI Signals, and MDPI Methods and Protocols.
Prof. Kotropoulos served as Track Chair for Signal Processing in the 6th Int. Symposium on Communications, Control, and Signal Processing, Athens, 2014; Program Co-Chair of the 4th Int. Workshop on Biometrics and Forensics, Limassol, Cyprus, 2016; Technical Program Chair of the XXV European Signal Processing Conf., Kos, Greece, 2017; Technical Program Chair of the 5th IEEE Global Conf. Signal and Information Processing, Montreal, Canada, 2017; General Chair of the 2022 IEEE 14th Image, Video and Multidimensional Signal Processing Workshop, Nafplio, Greece; Technical Program Chair of the 2023 IEEE International Conf. on Acoustics, Speech, and Signal Processing, Rhodes, Greece.

Outline

- The Electric Network Frequency (ENF) criterion is a powerful tool in forensic sciences introduced by Catalin Grigoras[1].
- The ENF acts as a fingerprint in multimedia forensics applications. It exists in 50 Hz/60 Hz in Europe/U.S. power grids.
- The ENF criterion has some unique properties.
  1. ENF signal occurs in random way.
  2. The ENF pattern is identical in the same network.
  3. Apart from the fundamental frequency, the ENF also exists in its higher harmonics.

[1] C. Grigoras. "Digital audio recording analysis: The electric network frequency (ENF) criterion," *Int. J. of Speech Language & the Law*, 12(1):63–76, 2005.

The main contributions of the paper:

- Two optical devices are used to measure the ENF signal in indoor environments illuminated by two different light sources.
- The first optical sensing device is based on a photodiode. It is developed for capturing ENF variations in indoor lighting environments. The second one is a GoPro Hero 8 camera.
- Another device that captures the ENF directly from power mains is implemented. This device serves as a ground truth ENF collector.
- Extensive experimental evidence demonstrates that under certain conditions, the photodiode sensing device delivers a reliable reference (i.e., ground truth) ENF signal.
- This could benefit practitioners and find use in real-life applications where it is quite difficult to acquire ground truth ENF through a Frequency Disturbance Recorder (FDR).

- The ENF can be estimated in videos captured under the illumination of fluorescent bulbs in indoor environments[2]. ENF variations caused by power grid networks affect the illumination intensity and each frame captures a time-snapshot of ENF.
- ENF video estimation approaches can be divided into two categories based on the recording sensor type.
  1. The first category consists of videos captured by charge-coupled device (CCD) sensors, which employ a global shutter mechanism.
  2. The second category consists of videos captured by complementary metal oxide semiconductor (CMOS) sensors. Such sensors employ a rolling shutter mechanism, which acquires a row at a time in each video frame[3].

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[2] R. Garg, A. L. Varna, A. Hajj-Ahmad, and M. Wu, ""Seeing" ENF: Power-signature-based timestamp for digital multimedia via optical sensing and signal processing," *IEEE Trans. Inf. Forensics and Security*, 8(9):1417–1432, 2013.

[3] H. Su, A. Hajj-Ahmad, R. Garg, and M. Wu. "Exploiting rolling shutter for ENF signal extraction from video," In *Proc. IEEE Int. Conf. Image Process.*, pages 5367–5371, 2014.

- The light intensity is fluctuating at twice the nominal frequency of ENF, i.e., 100 Hz in Europe, and 120 Hz in the U.S.
- The lower temporal sampling rate of cameras capturing video recordings compared to frequency components in light flickering results to a significant aliasing of ENF signals. These frequencies can be derived by applying the sampling theorem[4]. The aliased frequency f_E emanated from fluorescent illumination is

$$f_E = |f_I - \gamma f_s| \leq \frac{f_s}{2} \qquad (1)$$

where f_s denotes the sampling frequency of camera, f_I is the frequency of light source illumination, and γ denotes an integer.

[4] A. V. Oppenheim and R. W. Schafer, *Discrete-Time Signal Processing*, Prentice Hall, Upper Saddle River, NJ, USA, 3/edition, 2009.

- The ENF estimation from video recordings was carried out by applying:
    1. The Simple Linear Iterative Clustering (SLIC)-based approach[5].
    2. Bandpass filtering around the aliased light flickering captured by the camera for various filter orders as was set in each experiment.
    3. The Estimation of Signal Parameters via Rotational Invariant Techniques (ESPRIT) is used unless otherwise stated.
- The ground truth ENF was estimated using the spectrum combining approach[6].

[5] G. Karantaidis and C. Kotropoulos, *An automated approach for electric network frequency estimation in static and non-static digital video recordings," Journal of Imaging, vol. 7, no. 10, 2021*

[6] A. Hajj-Ahmad, R. Garg, and M. Wu, *"Spectrum combining for ENF signal estimation," IEEE Signal Process. Letters, vol. 20, no. 9, pp. 885–888, 2013*

- The first circuit was based on the photodiode BPW21 to collect light intensity fluctuations. This photodiode was chosen due to its excellent light and spectral sensitivity in the visible range.
- Two operational amplifiers with a positive and a negative feedback loop were used to amplify the photocurrent generated by a photodiode and produce a linear correlation between the light intensity and the current generated[7].
- The operational amplifiers OP07D were used as current-to-voltage converters to capture the fluctuations and pass them to the laptop sound card. The voltage from the power mains was dropped to 18 Volts AC with the use of a center-tapped transformer.
- Also, a full bridge rectifier along with a voltage regulator pair (LM7805/7905) was used to convert the AC voltage to DC to power the operational amplifiers.
- The next step was to wire appropriately the two amplification stages of the operational amplifiers.

[7] W. Hernandez, "Input-output transfer function analysis of a photometer circuit based on an operational amplifier," Sensors, vol. 8, no. 1, pp. 35–50, 2008.

- A second circuit was implemented to extract the ENF from the power mains. A transformer was used in order to lower the power mains AC voltage from 220 Volts to 18 Volts. A voltage divider further decreased the voltage to about 3 Volts peak-to-peak in accordance with the laptop sound card voltage tolerance[8].
- A high pass filter was used to eliminate the DC component with a cut off frequency at 32 Hz.
- An anti-aliasing filter stage was deployed to control the cut-off frequency that was set at the Nyquist frequency.
- The ENF extracted from power mains served as reference ENF. In practice, the reference ENF is recorded by an FDR (see Fig. 1).

[8] A. Triantafyllopoulos, A. Foliadis, G. Roustas, I. Krillis, F. Athanasiou, and M. Papaioannou, "Exploring power signatures for location forensics of media recordings," IEEE Signal Processing Cup 2016, Tech. Rep., 2016.

Optical Sensing Devices

Design and Implementation

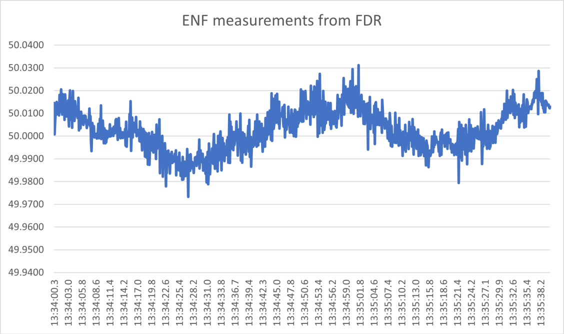

Figure 1: Snapshot of measurements collected by FDR #3505 on April 7, 2023.

- To record simultaneously the ENF mains signal and the light intensity signal at a proper voltage level, we employed:
    1. A 3.5 mm stereo jack cable to feed the ENF mains signal to the left channel of the sound card.
    2. The light intensity signal from the photodiode to the right channel of the sound card.
- The developed devices are depicted in Fig. 2. The diagram of the devices is shown in Fig. 3.

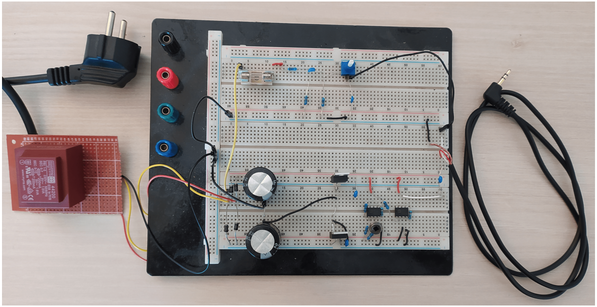

Figure 2: On the left, the transformer of the circuit is depicted. On the top, the breadboard that contains the circuit to extract the ground truth ENF from the power mains is shown. On the bottom, the photodiode circuit along with the full bridge rectifier and voltage regulation stages can be seen. On the right, the 3.5 mm audio jack is depicted.

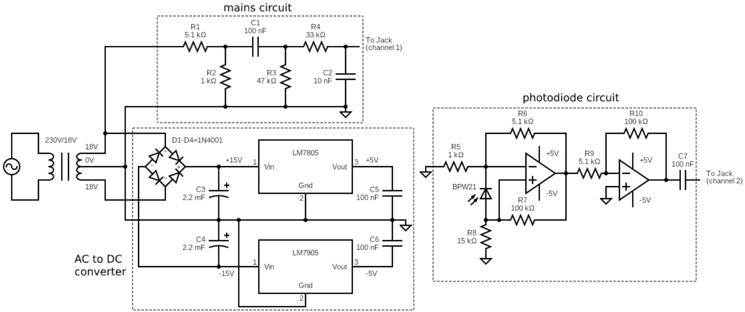

Figure 3: Detailed circuit diagram of the developed device. On the left, a 230/18V center-tapped transformer is shown. The top part consists of a voltage divider and two filtering stages for the acquisition of the power mains voltage. The central part of the diagram depicts a full bridge rectifier followed by a voltage regulator pair in order to convert the AC signal to +5/-5V DC rails, which are fed into the operational amplifiers. On the right, the photodiode along with its two-stage amplification circuit can be seen.

- Two sets of experiments were conducted to evaluate the performance of the designed devices.
- In the first set of experiments, a GOPRO Hero 8 camera was employed to record a white wall inside a living room. Three different factors were taken into consideration:
  1. Two different light sources, namely, a halogen lamp and an incandescent bulb.
  2. Different distances between the camera and the wall.
  3. Various video recording durations.

- In the second set of experiments, the same camera was used to collect video recordings under realistic conditions including:
  1. A non-static video of a scene with various textures and reflection coefficients illuminated by a halogen lamp, where a moving jacket is introduced to the scene.
  2. A dimly lit hallway illuminated by a halogen bulb displaying human activity of varying obstruction.
  3. A person moving in and out of a very complex scene illuminated by a halogen lamp in medium lighting condition.
  4. The same scene as the previous one, when the lighting conditions are dimmer due to a low-power incandescent bulb.

Figure 4: (a) Top left: Non-static video of a scene with various textures and reflection coefficients illuminated by a halogen lamp, where a moving jacket is introduced to the scene. (b) Top right: A dimly lit hallway illuminated by a halogen bulb displaying human activity of varying obstruction. (c) Bottom left: A video of a person moving in and out of a very complex scene illuminated by a halogen lamp in medium lighting conditions. (d) Bottom-right: The same scene as in bottom-left when the lighting conditions are even dimmer, due to a low power incandescent bulb.

Table 1: Maximum Correlation Coefficient (MCC) Between the ENF Extracted at the Output of the Photodiode device and the Power Mains

# Recording	Halogen	Incandescent
1	0.9906	0.9946
2	**0.9988**	**0.9989**
3	0.9904	0.9975
4	0.9941	0.9982
5	0.996	0.9979
6	0.9934	0.9918
7	0.9935	0.9935

- Seven recordings of 8-minute duration each were captured.
- MCC measurements between the ENF estimated from the photodiode-based device and the power mains are reported.
- For all recordings, the MCC exceeded 0.99 regardless of the light source illuminating the scene.
- The ENF measured at the output of the photodiode-based device can be employed as a ground truth ENF.

Experimental Results

White-Wall Experiments

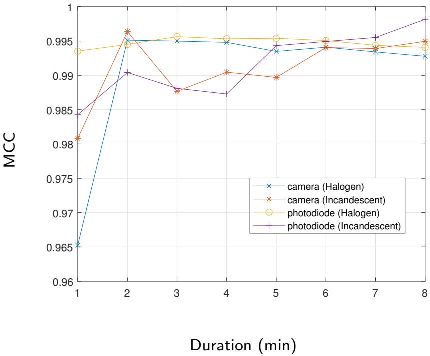

Figure 5: MCC between the ENF estimated from both optical sensors' recordings and the ENF measured at power mains for various durations when two different light sources illuminate the scene.

- The ENF estimated at the output of the photodiode-based device was compared to the ENF measured at power mains.
- The ENF was also extracted from the recording captured by the camera, which was placed 2 m far away from the white wall.
- The top MCC value of 0.9964 was observed between the ENF extracted from a 2-minute video when an incandescent bulb illuminated the scene.
- Regarding the photodiode-based device, the top MCC value of 0.9982 was observed between the ENF extracted from an 8-minute recording when an incandescent bulb illuminated the scene.

Experimental Results

White-Wall Experiments

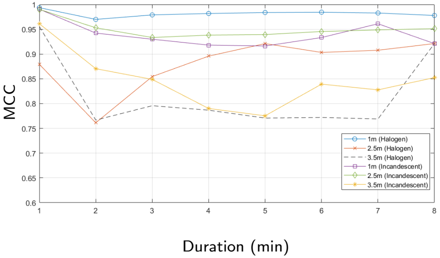

Figure 6: MCC between the ENF estimated from a camera recording and the ENF measured at power mains, when two different light sources illuminate a white wall for varying video duration and distance between the camera and the white wall.

- An experiment was conducted considering all three factors, i.e., distance, duration, and light source;
- The camera was mounted at three different distances from the white wall background, i.e., 1 m, 2.5 m, and 3.5 m.
- Although the initial total duration of the recording was 8 min, we estimated the ENF for video durations $g = 1, 2, \ldots, 8$ min.
- When the camera was mounted at a distance of 1 m, setups including either a halogen lamp or an incandescent bulb yielded high MCC values even for a short video duration of 1 min.

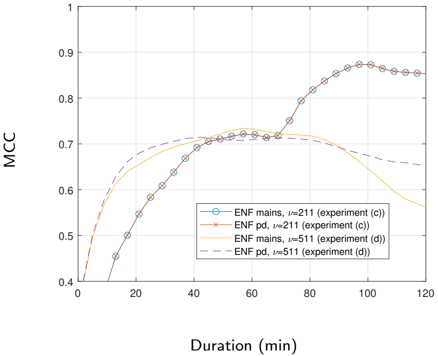

Figure 7: MCC of the ENF estimated from the videos in (c) and (d) against the ground truths (mains and photodiode) for the indicated bandpass filter orders versus duration.

- Two experiments involving videos (c) and (d) are the most challenging, containing a great number of objects, different surfaces, and shadows.
- In the former, the scene was illuminated by a halogen lamp. Applying SLIC and a bandpass filter of order ν=211 before ESPRIT was used for ENF estimation, an MCC of 0.8736 was obtained.
- In the latter, we expected to acquire a lower MCC due to the lower overall light intensity fluctuation in proportion to the obstruction the moving person causes to the scene.
- The procedure is as above, with the difference that a bandpass filter of an order of ν=511 was used. An MCC of 0.7336 was obtained when the ENF extracted from the video was compared to the ENF from power mains;
- An MCC of 0.7143 was measured when compared to the ENF from the photodiode.

Concluding Remarks

- Two optical devices are used to measure the ENF signal in indoor environments illuminated by two different light sources (i.e., halogen lamps and incandescent bulbs).
- The first optical sensor is based on a photodiode and captures light intensity variations enabling ENF extraction in real-life scenarios. The second one is a GoPro Hero 8 CMOS camera.
- Another device that records the ENF signal directly from power mains is also developed.
- ENF estimated from either the power mains or the photodiode-device output follows the same trend, confirming that the photodiode-device can provide a reliable reference ENF signal (i.e., ground truth) replacing FDRs.
- Collecting a valid ground truth is possible without needing a device plugged into power mains. This fact allows battery-powered devices to be used as a means to extract ENF.

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Thank you!

Any Questions?