Stochastic Models for Solar Power

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Outline

- Motivations
- Challenges
- Modeling the Solar Irradiance
- Modeling the Harvested Power
- Results
- Conclusions

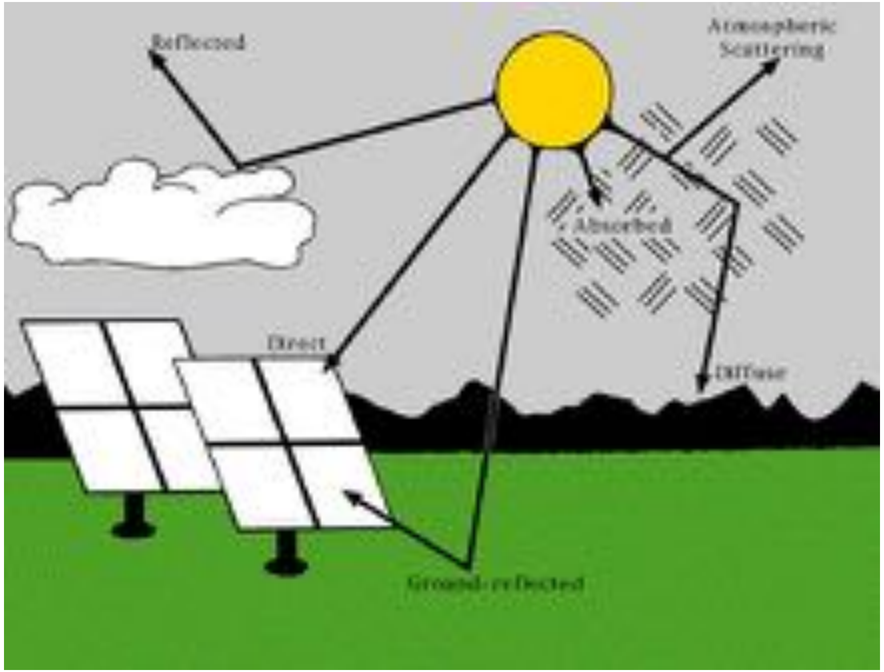
Motivations

- ➢ energy cost
- ➢ a means of reducing environmental footprint
- ➢ really essential for IT such as data centres, base stations,sensors etc.

-> increase in the relative share of ICT products and services in the total worldwide electricity consumption from about 3.9% in 2007 to 4.6% in 2012

Van Heddeghem, W., Lambert, S., Lannoo, B., Colle, D., Pickavet, M., Demeester, P.: Trends in worldwide ICT electricity consumption from 2007 to 2012. Computer Communications 50, 64–76 (September 2014)

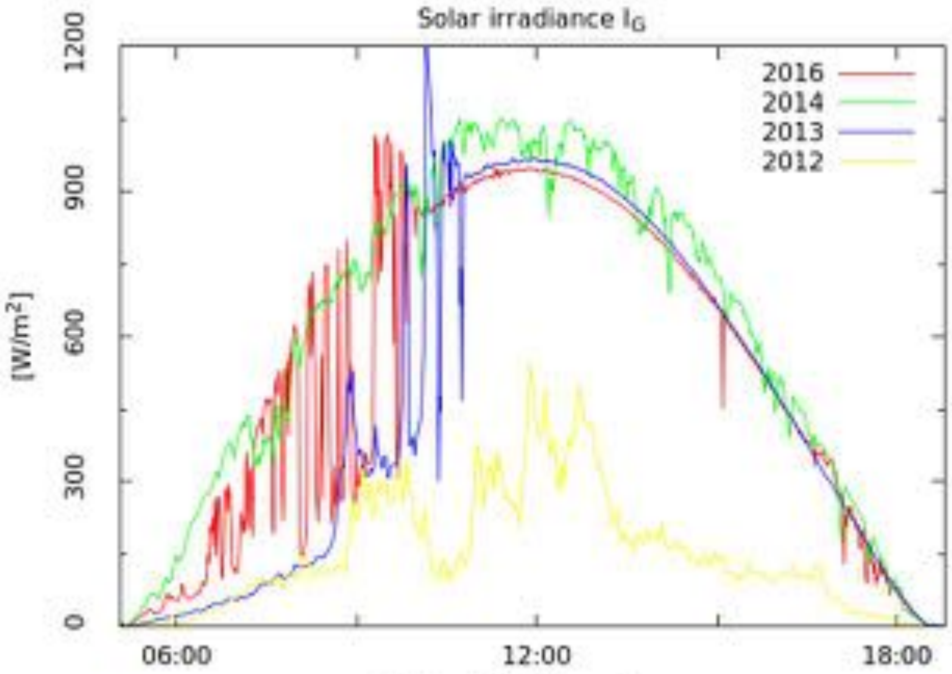
Solar Irradiance



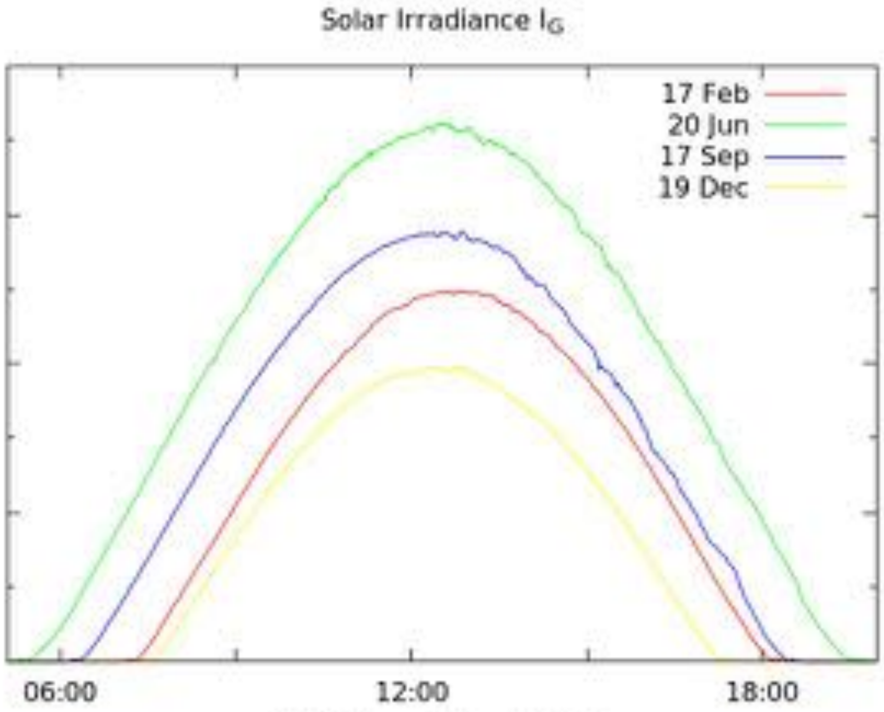
- Direct Normal
- Diffuse Sky
- Ground-Reflected

Global irradiance I_G = Direct Normal + Diffuse Sky

Challenges



(a) May 1st, different years



(b) Different days in 2012

Modeling the Solar Irradiance

Question: How can we capture the perturbations seen in the solar irradiance with respect to clear sky solar irradiance I_{cs}?

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Idea!!!

The global irradiance I_G is a product of a ***multiplicative noise***, denoted **α,** by the clear sky solar irradiance I_{cs}

$$I_G = \alpha I_{cs}$$

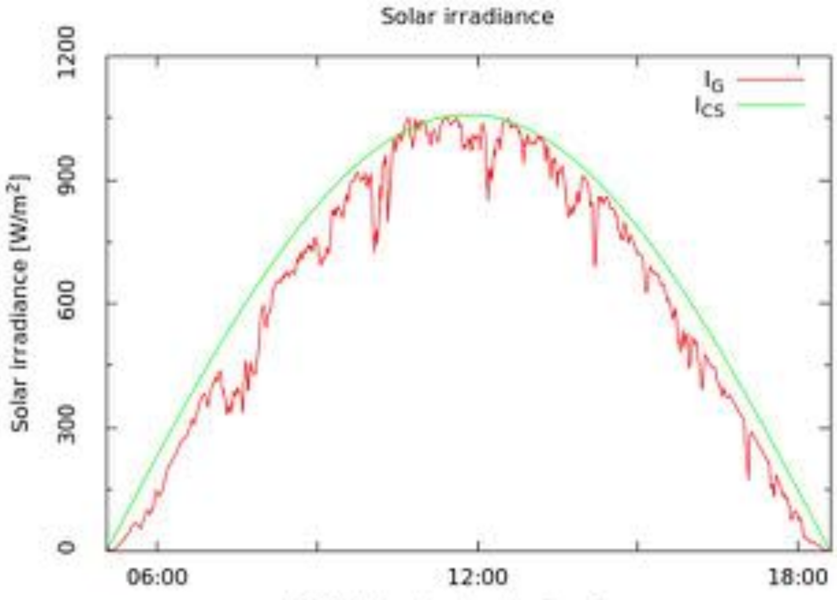
Model separately α and I_{cs}

Modeling the Solar Irradiance

➢ Modeling the clear sky irradiance I_{cs}

$$Ics(time) = MaxClearSky \cdot \sin\left(\frac{time - sunrise}{sunset - sunrise} \cdot \pi\right)$$

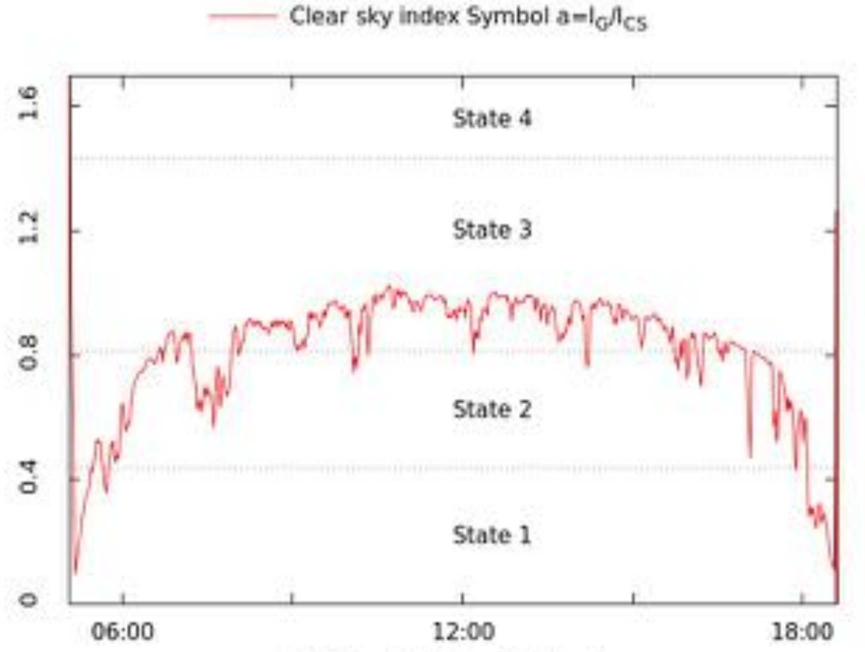
“sunrise”, “sunset” and “MaxClearSky” -> astronomical data
Available for any date and many selected locations from
https://ptaff.ca/soleil/



(a) Global and clear sky irradiance

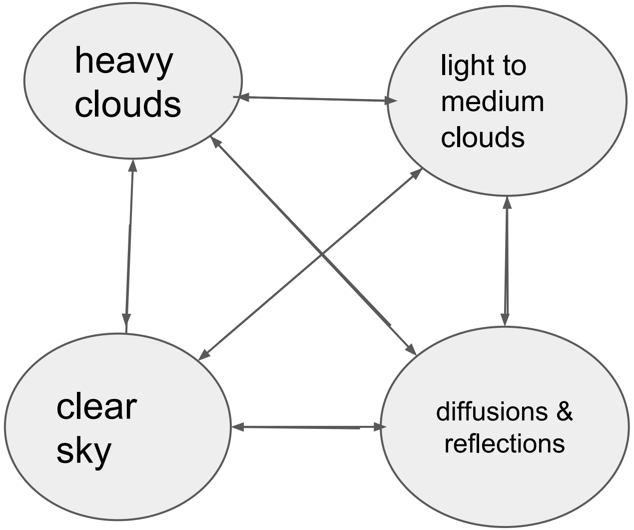
Modeling the clear sky index

- Clear sky index Symbol:
  - **$\alpha = I_G / I_{cs}$**
  - I_G : global irradiance & I_{cs} : clear sky irradiance



(b) Clear Sky Index Symbol a

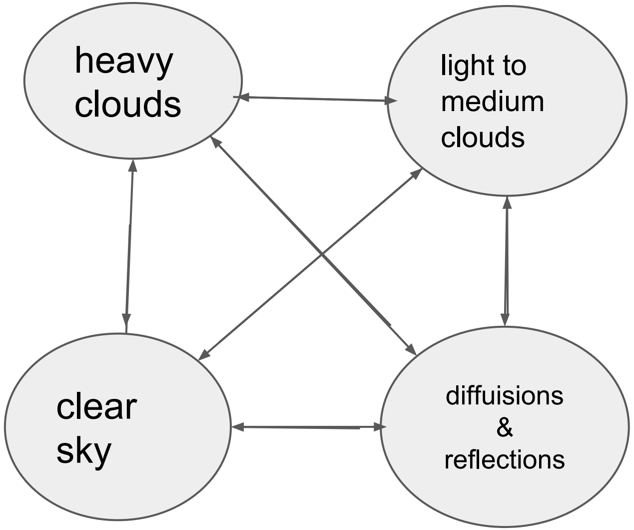
Discrete-time semi Markov process



- Sojourn time distribution for each state $\mathbf{f_i}$
- Distributions of values of α for each state: $\mathbf{g_i}$
- f_i and g_i , for i ∈ {1, 2, 3, 4} will be fitted to empirical distributions of the sojourn times and values of α

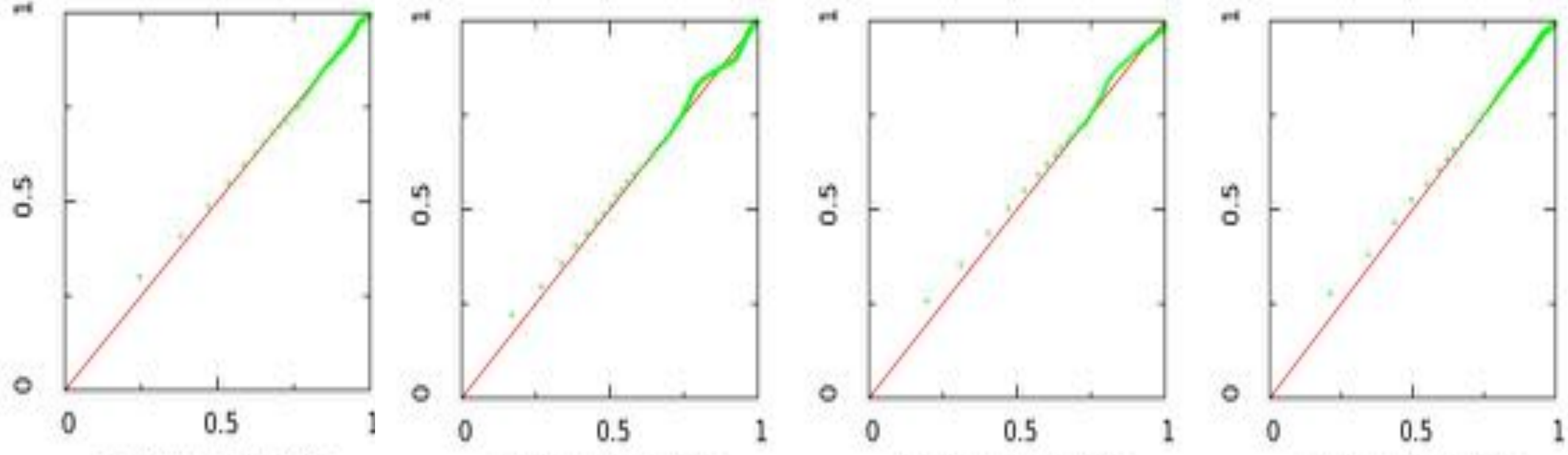
Modeling the clear sky index α

➢ k-means for α to define the different weather conditions-> metric Davies doublin index -> k =4



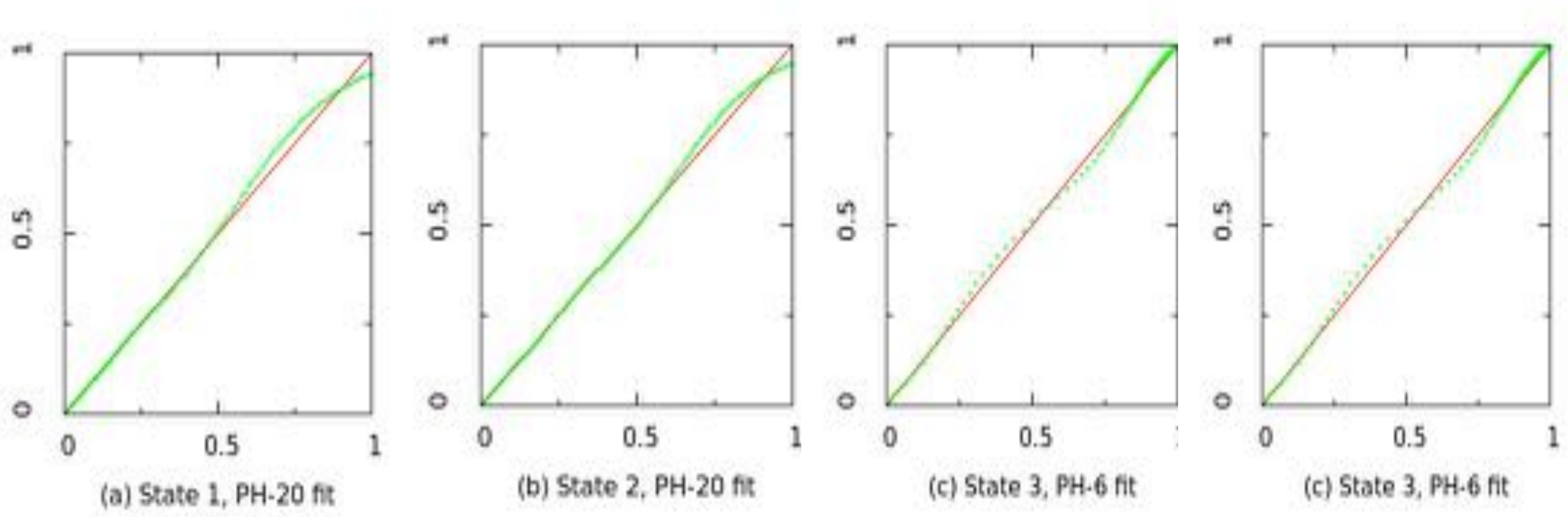
Range of values of α	State	Physical Interpretation
[0,0.44152)	1	heavy clouds between the sun and the surface
[0.44152, 0.81639)	2	medium to light clouds between the sun and the surface
[0.81639, 1.4343)	3	clear sky
[1.4343,3)	4	High reflection and diffusion in the atmosphere

Probability plots of the phase-type fitting for sojourn times in each state

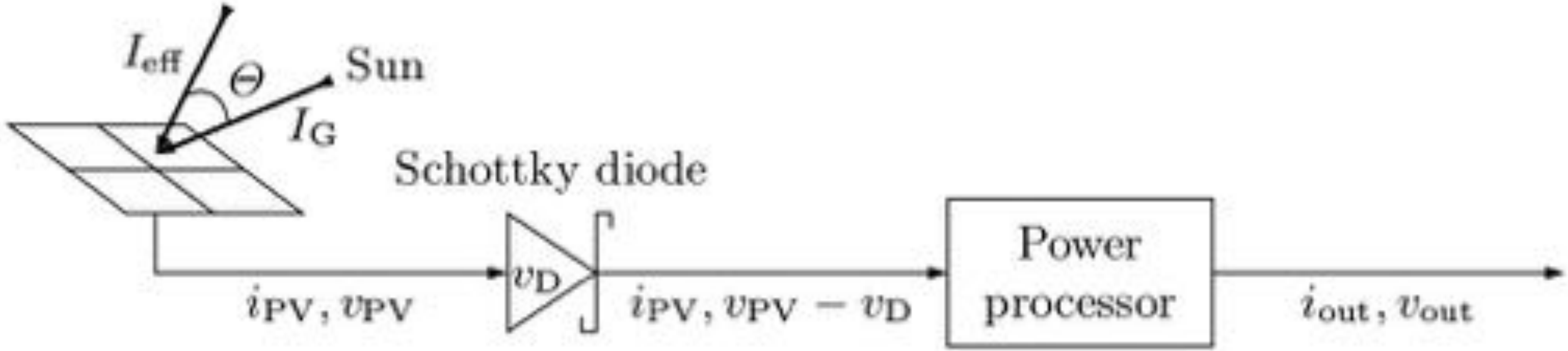


(a) State 1, PH-5 fit (b) State 2, PH-6 fit (c) State 3, PH-6 fit (d) State 4, PH-6 fit

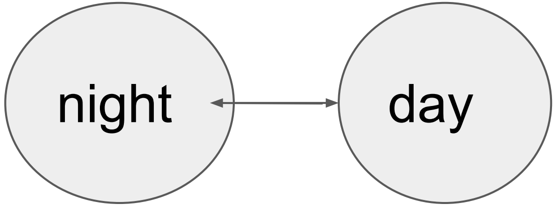
Probability plots of the phase-type fitting for α values in each state



Modeling the Harvested Power



On-off model [3]



- Per hour solar irradiance data for LA, from NREL [1]
- Model the output current (ι_{out})
- 2-state semi-Markov process
- Split the data according to an arbitrary threshold
- Output current grouped by month
- Kernel smoothing techniques to estimate time duration and output current distributions
- Day state -> generate current *constantly*
- Night state -> output current =0

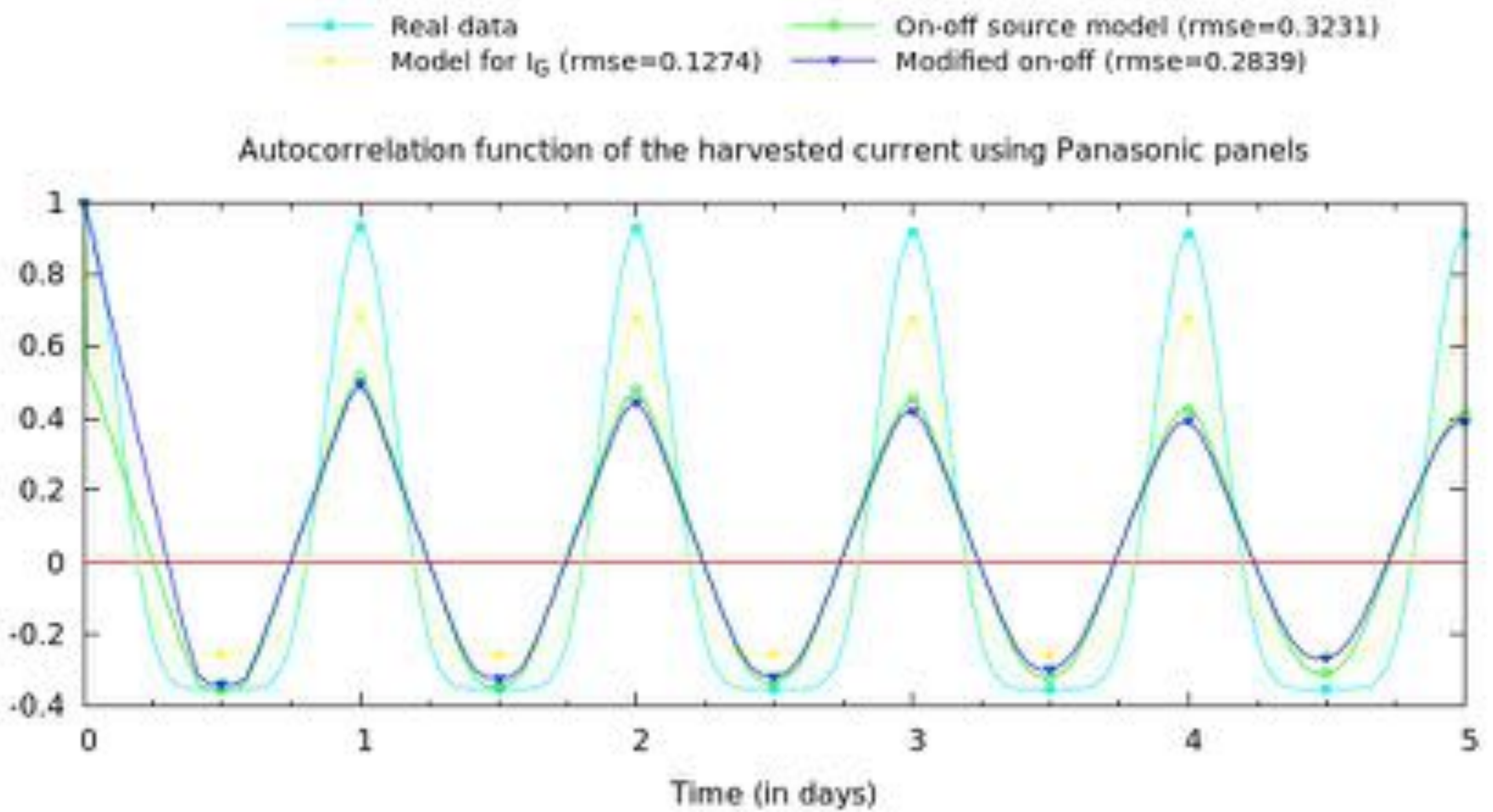
Modified on-off model

➢ Day state -> *resample* (every 10 minutes) from the current distributions until a transition occurs

Comparison

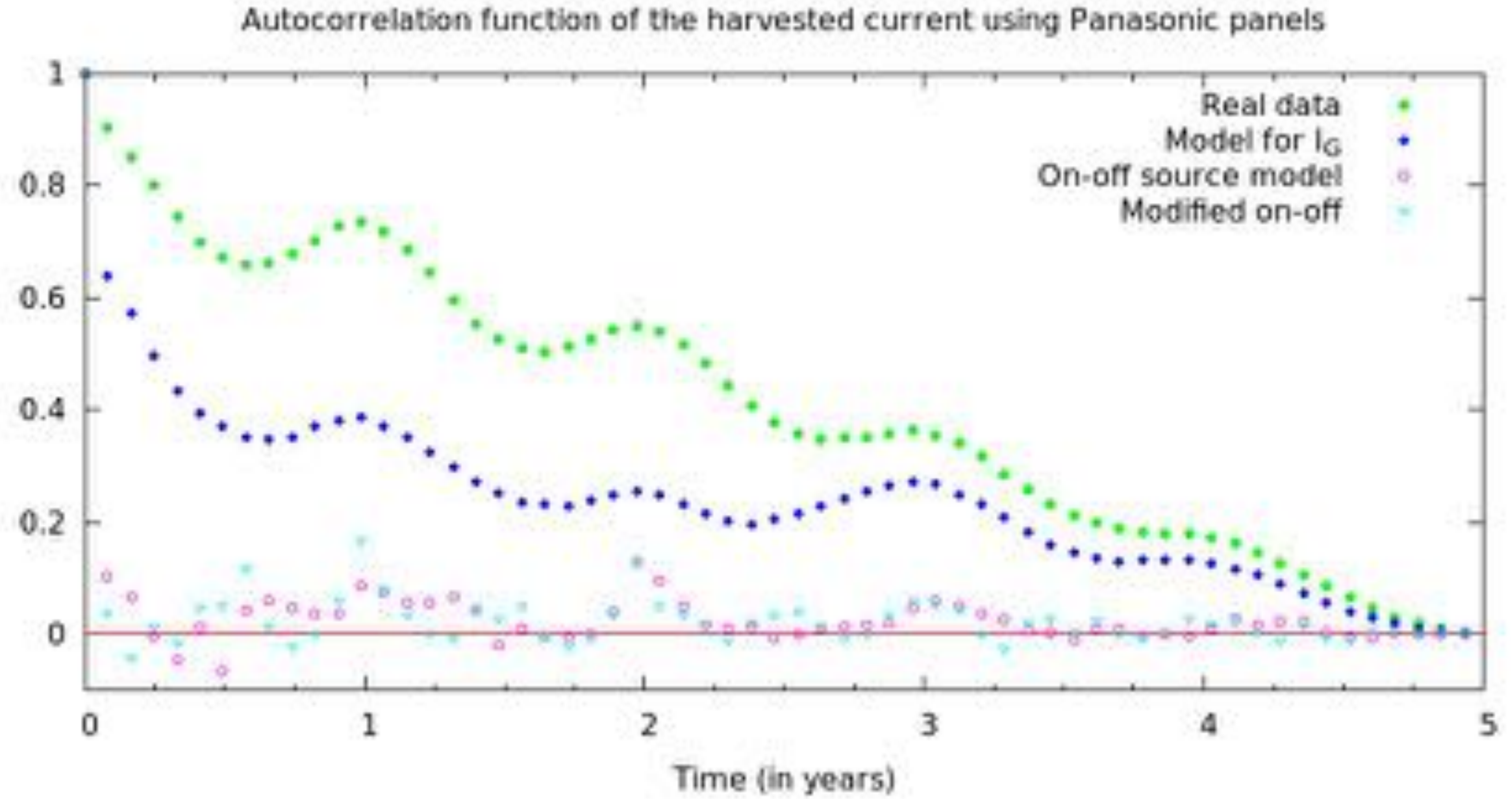
- Use 5 years empirical data
- Generate 5 years synthetic data from
  - Irradiance model
  - On-off model [3]
  - Modified on-off model
- Metrics
  - Autocorrelation
  - periodogram

Results (1/3)



Real data
On-off source model (rmse=0.3231)
Model for I_G (rmse=0.1274)
Modified on-off (rmse=0.2839)
Autocorrelation function of the harvested current using Panasonic panels
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
0
1
2
3
4
5
Time (in days)

Results (2/3)



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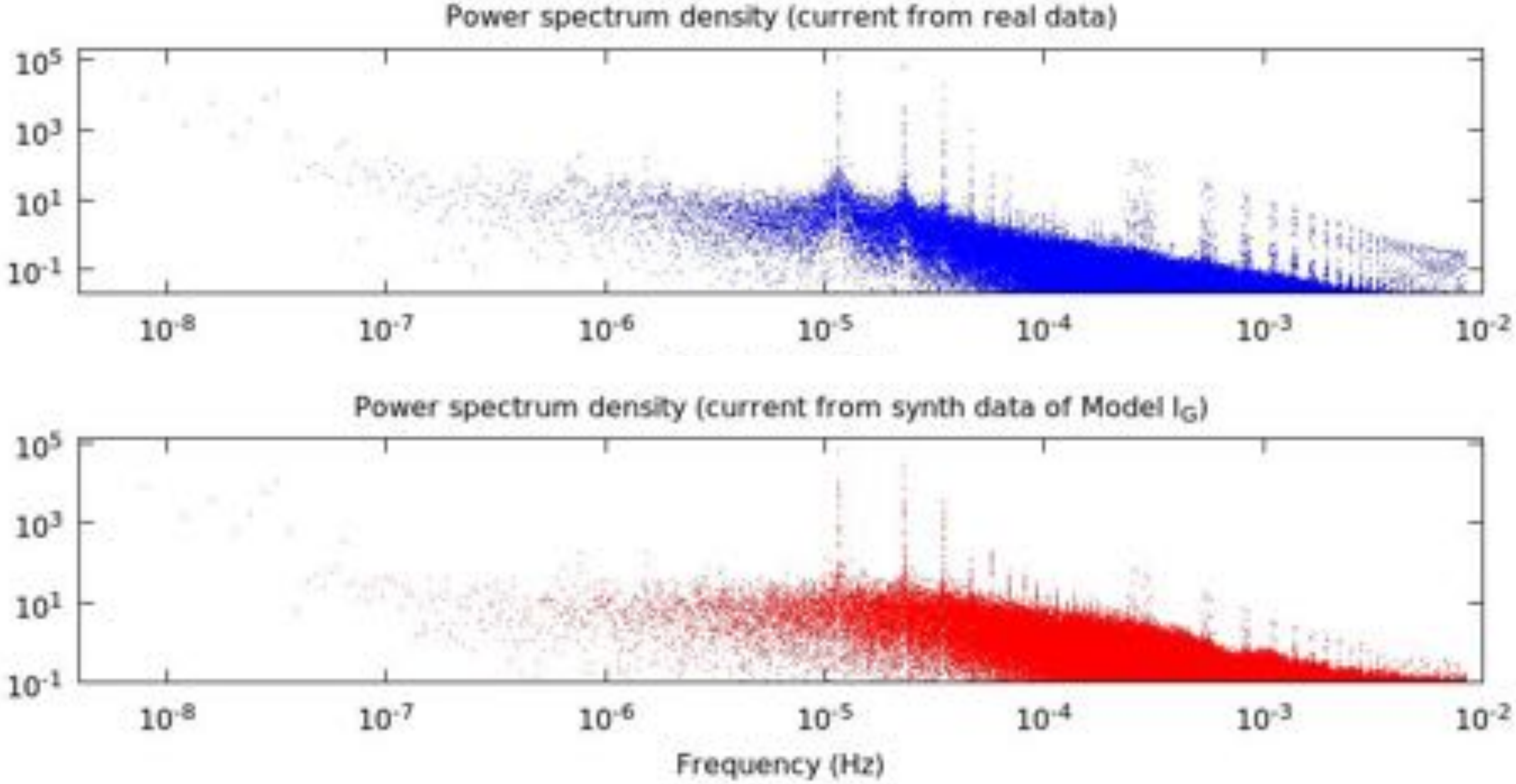
Results (3/3)


Power spectrum density (current from real data)
10^5
10^3
10^1
10^-1
10^-8
10^-7
10^-6
10^-5
10^-4
10^-3
10^-2
Power spectrum density (current from synth data of Model I_G)
10^5
10^3
10^1
10^-1
10^-8
10^-7
10^-6
10^-5
10^-4
10^-3
10^-2
Frequency (Hz)

Conclusions

- ➢ Our solar irradiance model is able to generate synthetic data that exhibits most of the frequency peaks of real data
- ➢ Our solar irradiance model captures small time scales fluctuations as would be needed by ICT applications
- ➢ Autocorrelation functions and periodograms of empirical and synthetic traces -> very well performance
- ➢ Our model can be used not only in the mathematical analysis of energy harvesting communication/computer systems and in their simulation.

Thank you!!!

References

1. Andreas, A., Wilcox, S.: Solar Resource & Meteorological Assessment Project (SOLRMAP): Rotating Shadowband Radiometer (RSR); Los Angeles, California (Data). Report DA-5500-56502, NREL (2012
2. Bird, R.E., Hulstrom, R.L.: A simplified clear sky model for direct and diffuseinsolation on horizontal surfaces. Tech. Rep. Technical report SERI/TR-642-761,Solar Energy Research Institute (February 1981)
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4. Van Heddeghem, W., Lambert, S., Lannoo, B., Colle, D., Pickavet, M., Demeester, P.: Trends in worldwide ICT electricity consumption from 2007 to 2012. Computer Communications 50, 64–76 (September 2014)
5. D.Politaki, S. Alouf, "**Stochastic Models for Solar Power**". In proceedings of EPEW 2017, Berlin, Germany, August 2017. (it will be appeared)