Batteryless, Ambiently-Powered Internet of Things That Think: An Asynchronous Message Passing Approach

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Special thanks to P.N. Alevizos

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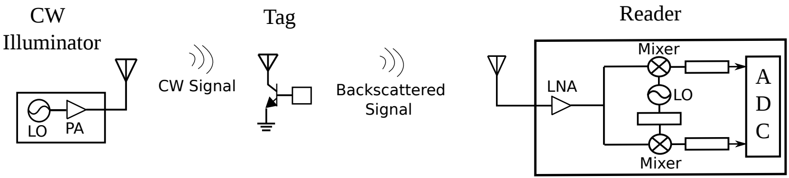
Agenda

1. IoT: Backscatter Sensor Networks
2. Batteryless IoT: Ambient μPower
3. IoT That Think: (Asynchronous) Message Passing
   - Architecture
   - Toy Example
   - Richness of Inference/Message Passing Algorithms

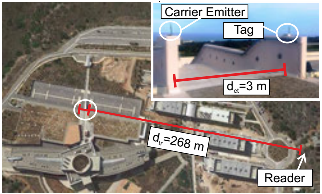
Principle of Tag Reflection

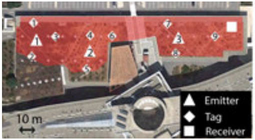


- Monostatic Architecture (RFID): illuminator + reader = same unit (common local oscillator - LO) [1], [2], multi-antenna monostatic [3].
- Bistatic Architecture (WSNs/ambient): illuminator $\neq$ reader (distinct units).

[2] G. Vannucci, A. Bletsas, and D. Leigh, "A software-defined radio system for backscatter sensor networks", IEEE Trans. Wireless Commun., vol. 7, no. 6, pp. 2170-2179, Jun. 2008. Conf. version [1] at IEEE PIMRC 2007, Athens, Greece.
[3] J.D. Griffin and G.D. Durgin, "Gains for RF tags using multiple antennas", IEEE Trans. Antennas Propag., vol. 56, no. 2, pp. 563-570, Feb. 2008.

Backscatter Range/Coverage CAN be VASTLY improved!



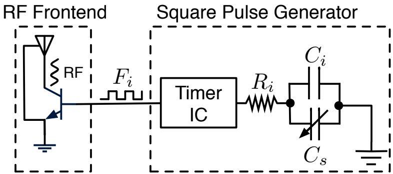


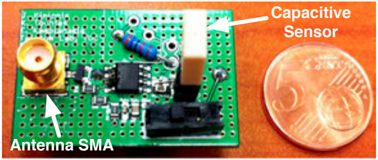
- $P_{\mathrm{TX}} = 13$ dBm, semi-passive tags, NF=$7-12$ dB (SDR) or NF=$3-4$ dB (embedded) [4].
- Multistatic coverage of 3500 m^2 with only 3 emitters [5], [6], [7].
- Monostatic coverage much smaller!

Signal Processing Milestones in Backscatter Radio

- 2004-07: Noncoherent symbol-by-symbol detection with MSK - pulse shaping and multiple access with receiver-less tags [1], [2].
- 2011: Bistatic sniffing [8] (IEEE RFID-TA 2011 2nd Best Student Paper Award).
- 2012-14: Bistatic architecture, noncoherent symbol-by-symbol detection with FSK [9], [10], [11], [12].
- 2014-15: Bistatic architecture, coherent symbol-by-symbol and coherent channel-coded sequence detection with FSK [13], [14].
- Coherent FM0 Gen2, GNU Radio Reader Open Source [15].
- 2015-16: Noncoherent, uncoded sequence detection with FSK (also applicable to GEN2/FM0) [16] [17] (IEEE ICASSP 2015 Best Student Paper Award).
- 2014-17: Noncoherent, channel coded sequence detection/small packet [7], [18], [19], [20].
- 2018: Extensions to ambient setups (modulated illumination).

Backscatter Radio Sensing: Greenhouse Humidity [21, 22]





- Principle: capacitor changes $\Rightarrow$ freq. of backscattered signal.
- Cost:$\sim$ 3Euro (quantity of 1), Power: 220μWatt, RMS: $1-2\%$ RH.
- Networking: simple, multiple-access (FDMA).

[21] E. Kampianakis, J. Kimionis, K. Tountas, C. Konstantopoulos, E. Koutroulis, and A. Bletsas, "Wireless environmental sensor networking with analog scatter radio & timer principles", IEEE Sensors J., vol. 14, no. 10, pp. 3365-3376, Oct. 2014. Conf. version [22] received IEEE Sensors Conf. 2013 distinction.

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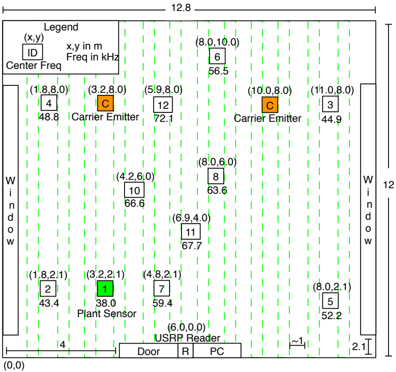
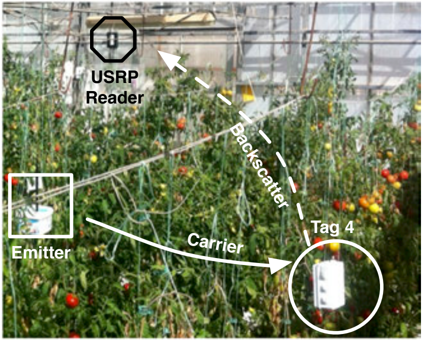
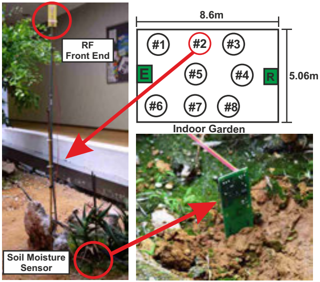
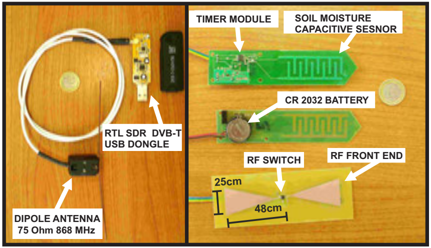




Backscatter Radio Sensing: Soil Moisture [23, 24]

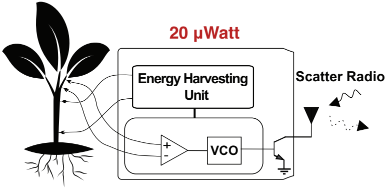


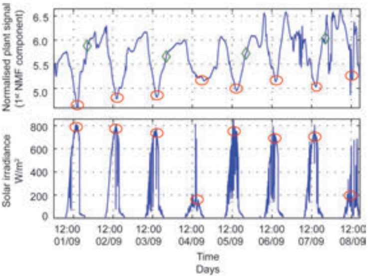


- Principle: capacitor changes $\Rightarrow$ freq. of backscattered signal.
- Cost:$\sim$ 5Euro (quantity of 1), Power: $\sim 100\mu$Watt, RMS: 1.9% RH.
- Networking: simple, multiple-access (FDMA).

[23] S. N. Daskalakis, S. D. Assimonis, E. Kampianakis, and A. Bletsas, "Soil moisture scatter radio networking with low power", IEEE Trans. Microw. Theory Techn., vol. 64, no. 7, pp. 2338-2346, Jul. 2016.

Backscatter Radio Sensing:Plant=Sensor=Battery [26],[25]





- Transmit EP with backscatter FM. Use Plant as Battery.
- EP signal is correlated with solar irradiance and plant watering!

[25] C. Konstantopoulos, E. Koutroulis, N. Mitianoudis, and A. Bletsas, "Converting a plant to a battery and wireless sensor with scatter radio and ultra-low cost", IEEE Trans. Instrum. Meas., vol. 65, no. 2, pp. 388-398, Feb. 2016. Conf. version at IEEE Sensors 2013 [26].

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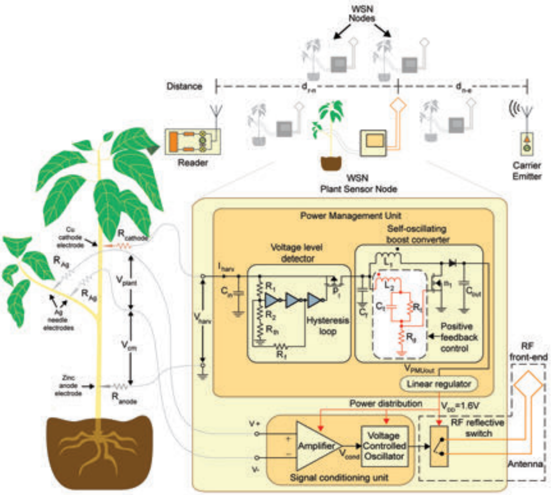
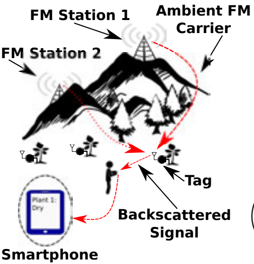
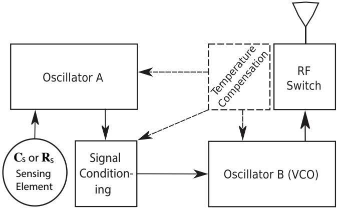
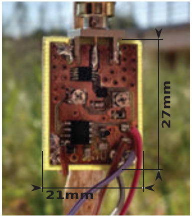


Ambient FM with μWatt Sensors & Smarphone Transmit Diversity Reception [27]



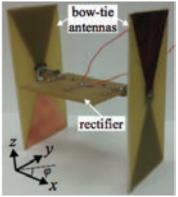


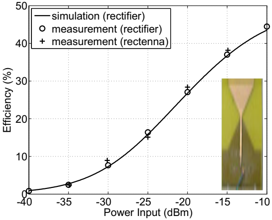


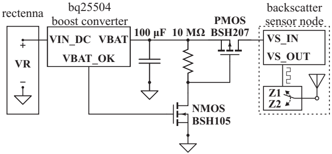
- $12 - 24\mu$W *continuous, non-duty-cycled operation)!*
- Tag-smartphone range: 26m, FM emitter-tag range: 6.5km!

[27] G. Vougioukas and A. Bletsas, "24μW 26m range batteryless backscatter sensors with FM remodulation and selection diversity", in Proc. IEEE RFID Techn. and Applications (RFID-TA), Warsaw, Polland, Sep. 2017.
Best Student Paper Award.

RF Energy Harvesting is limited by Harvester's sensitivity [29], [30]







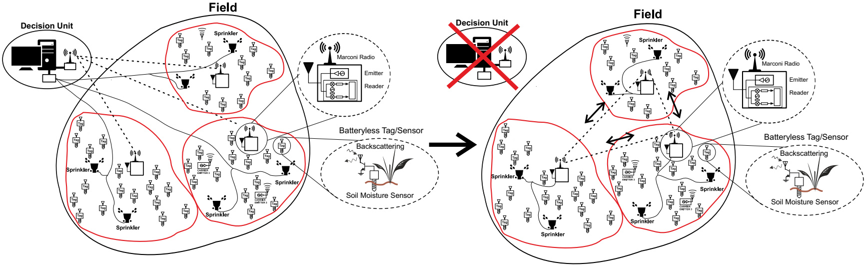
- RF energy harvesting circuitry is not "very sensitive"!
- RF harvesting sensitivity improves by 3 dB every $\sim$5 years [28].

Ambient micro-Energy Densities

	Energy Source	Ambient Energy Availability	Current-Technology Offered Electric Power (after conversion, incorporating efficiency)
1	Light/ Solar	35mWatt/cm^2	**135mWatt** (Polycrystalline Blue Solar Cell 5.4cm x 4.3cm, efficiency 16.5%)
2	Kinetic/ Vibration		**20mWatt** (PMG FSH Electromagnetic transducer)
3	Thermal		**1mWatt** (Thermoelectric Generator, 25° C @ 200Ωhm load)
4	Chemical/ Biologic	Voltage from an Avocado plant (*persea americana*) 60 cm tall	**1.15μWatt** @ 21° C, 12.00 pm **1.05μWatt** @ 19.5° C, 16.00 pm
5	RF	0.1μWatt/cm^2 (GSM band)	**0.88μWatt** (efficiency 6%, dipole antenna)
6	RF	-40dBm/FM station (FM band)	**0.018μWatt** (efficiency 3%, harvesting from six FM stations)
7	RF	-40dBm/FM station (FM band)	**0.003μWatt** (efficiency 3%, harvesting from one FM station)

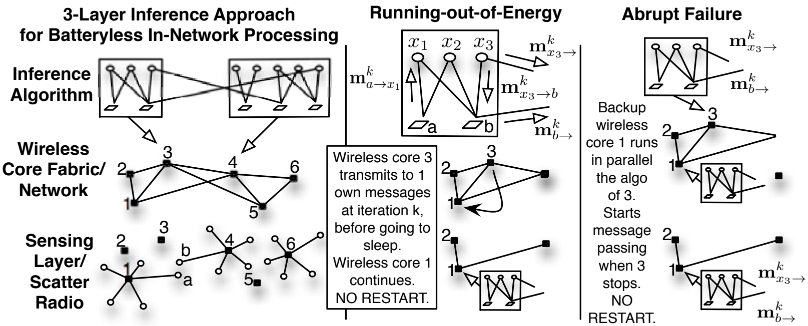
- Fixed available power per square (or cubic) cm.

Motivation: Ambiently-Powered In-Network Processing



- Key Idea 1: Large surface (or volume) can collect vast amounts of ambient power!
- Key Idea 2: distribute computation in surface (or volume) via message passing/inference!

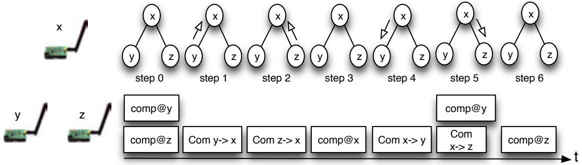
Basic Idea/Network Architecture



$$\mathbf{m}^{k+1} = \mathbf{F}(\mathbf{m}^k) = \left[F_1(\mathbf{m}^k)\ F_2(\mathbf{m}^k) \ldots\ F_{2EM}(\mathbf{m}^k)\right]^T$$

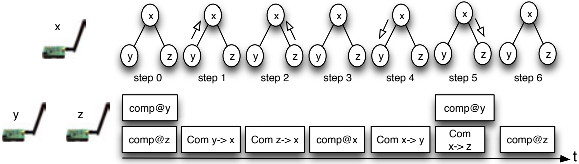
$$\mathbf{m}^{\pi(k+1)} = \mathbf{F}\left(\mathbf{m}^{\pi(k)}\right) = \left[F_1(\mathbf{m}^{\pi(k_1)})\ F_2(\mathbf{m}^{\pi(k_2)})\ \ldots\ F_{2EM}(\mathbf{m}^{\pi(k_{2EM})})\right]^T,\ \pi(k_j) \le t_k$$

Toy Example



	Step 0	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	
$$\begin{bmatrix} 1 & -2 & 3 \\ -2 & 1 & 0 \\ 3 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} -6 \\ 0 \\ 2 \end{bmatrix}$$				comp μ_x $h_{x\to y}$ $J_{x\to y}$ $h_{x\to z}$ $J_{x\to z}$	TX $h_{x\to y}$ $J_{x\to y}$	TX $h_{x\to z}$ $J_{x\to z}$		x
	comp $h_{y\to x}$ $J_{y\to x}$	TX $h_{y\to x}$ $J_{y\to x}$				comp μ_y		y
	comp $h_{z\to x}$ $J_{z\to x}$		TX $h_{z\to x}$ $J_{z\to x}$				comp μ_z	z
$$\begin{bmatrix} J_x & J_{xy} & J_{xz} \\ J_{yx} & J_y & J_{yz} \\ J_{zx} & J_{zy} & J_z \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} h_x \\ h_y \\ h_z \end{bmatrix}$$	y: $3A+4M$ z: $3A+4M$	$\text{TX}_y:\beta$ $\text{RX}_x:\beta'$	$\text{TX}_z:\beta$ $\text{RX}_x:\beta'$	x: $10A+9M$	$\text{TX}_x:\beta$ $\text{RX}_y:\beta'$	$\text{TX}_x:\beta$ $\text{RX}_z:\beta'$ y: $2A+M$	z: $2A+M$	

Toy Example - Serial Scheduling

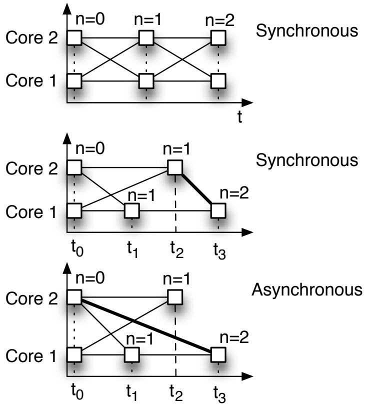


- Computation Energy cost: 300μWatt @1MHz, 64 instruction (clock) cycles/per flop $\Rightarrow$ **19.2** nJoule/flop.
- Communication Energy cost: $L = 96$ bits per pair of real numbers, @1Mbps $\Rightarrow$ **80** pJoule/bit.
- "Harvest energy-and-then-operate" (duty-cycling) to match power consumption needs.

Gaussian Belief Propagation (GBP) message passing for the above 3x3 setup completes within:

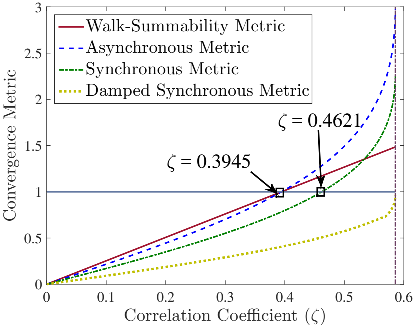
- **38.0** sec with RF energy harvesting from FM.
- **0.78** sec with RF energy harvesting from GSM.
- **0.60** sec with bioelectric energy harvesting from 60cm-tall avocado plants.

Synchronous vs Asynchronous Scheduling



[31] D. P. Bertsekas and J. N. Tsitsiklis, Parallel and Distributed Computation: Numerical Methods. Upper Saddle River, NJ, USA: Prentice-Hall, Inc., 1989.

Could asynchronous scheduling be helpful?

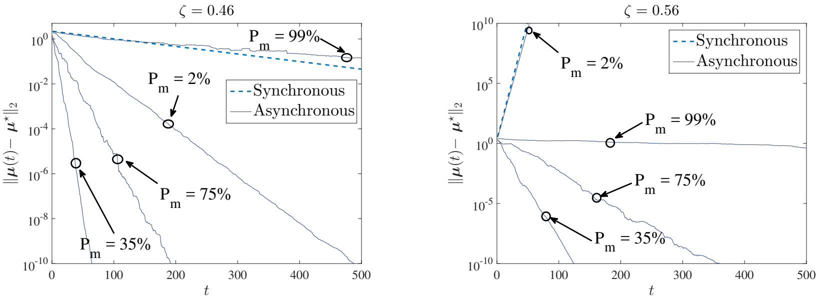


$$\mathbf{Px} = \mathbf{h}, \mathbf{P} = [p_{ij}], p_{ij} = \begin{cases} 1 & \text{if } i = j \\ \zeta \cdot a[i,j] & \text{if } i \neq j \end{cases}$$

Synchronous: necess. and suffic. cond's. Asynchronous: suffic. cond's.

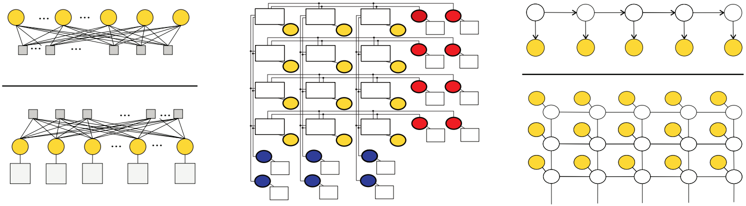
Reproduced from Q. Su and Y.C. Wu, On Convergence Conditions of Gaussian Belief Propagation, IEEE Trans. Signal Process., vol. 63, no. 5, pp. 1144-1155, Mar. 2015.

Our result: Asynchronous operation helps batteryless IoT That Think (BIoTTT)!



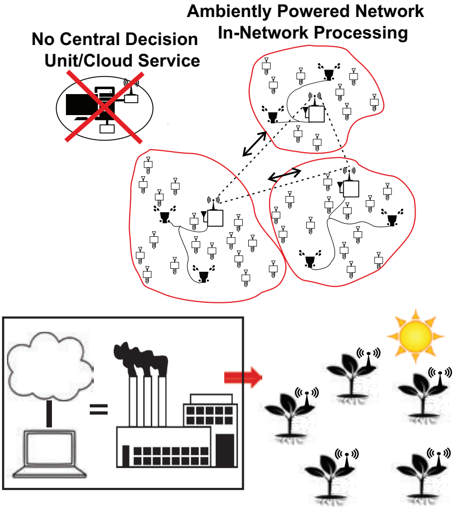
- Asynchronous operation may accelerate convergence!
- Asynchronous scheduling matters!
- We propose *stochastic* asynchronous scheduling.

Richness of Inference/Message Passing Algorithms



- Message passing can describe a rich variety of fundamental signal processing algorithms!
- Examples: Kalman Filtering, Viterbi, channel (de)coding, clustering, compression, signal de-noising/reconstruction, matrix completion, constraint satisfaction, HMMs and many more...

Cloud-free, private, ambiently-powered computing!



[1] G. Vannucci, A. Bletsas, and D. Leigh, "Implementing backscatter radio for wireless sensor networks," in *IEEE PIMRC*, Athens, Greece, Sep. 2007.

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[4] G. Vougioukas, S. N. Daskalakis, and A. Bletsas, "Could battery-less scatter radio tags achieve 270-meter range?" in *Proc. IEEE Wireless Power Transfer Conf. (WPTC)*, Aveiro, Portugal, May 2016, pp. 1–3.

[5] K. Tountas, P. N. Alevizos, A. Tzedaki, and A. Bletsas, "Bistatic architecture provides extended coverage and system reliability in scatter sensor networks," in *Proc. International EURASIP Workshop on RFID Technology (EURFID)*, Rosenheim, Germany, Oct. 2015, pp. 144–151.

[6] P. N. Alevizos, K. Tountas, and A. Bletsas, "Multistatic scatter radio sensor networks for extended coverage," *IEEE Trans. Wireless Commun.*, 2018, accepted, to appear.

[7] P. Alevizos, "Intelligent scatter radio, RF harvesting analysis, and resource allocation for ultra-low-power internet-of-things," Ph.D. dissertation, School of ECE, Technical University of Crete, Chania, Greece, 2017, advisor: A. Bletsas.

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[12] ——, "Increased range bistatic scatter radio," *IEEE Trans. Commun.*, vol. 62, no. 3, pp. 1091–1104, Mar. 2014.

[13] N. Fasarakis-Hilliard, P. N. Alevizos, and A. Bletsas, "Coherent detection and channel coding for bistatic scatter radio sensor networking," *IEEE Trans. Commun.*, vol. 63, pp. 1798–1810, May 2015.

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[28] G. D. Durgin, "RF thermoelectric generation for passive RFID," in *Proc. IEEE RFID*, Orlando, FL, May 2016, pp. 1–8.

[29] S. D. Assimonis, S. N. Daskalakis, and A. Bletsas, "Efficient rf harvesting for low-power input with low-cost lossy substrate rectenna grid," in *2014 IEEE RFID Technology and Applications Conference (RFID-TA)*, Tampere, Finland, Sep. 2014, pp. 1–6.

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THANK YOU! Questions?

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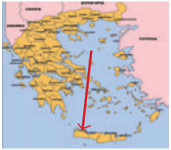
Εκπαίδευση και Διά Βίου Μάθηση
Ειδική Υπηρεσία Διαχείρισης
Με τη συγχρηματοδότηση της Ελλάδας και της Ευρωπαϊκής Ένωσης

ΕΣΠΑ 2014-2020
ανάπτυξη - εργασία - αλληλεγγύη



TU Crete is located at north-west of Crete, Greece!