Tyndall National Institute
Institiúid Náisiúnta

NiPS Laboratory
Noise in Physical Systems

Considerations for Energy Harvesting Powered WSN Real Life System Integration

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Perugia (Italy) – September 3 – 6, 2019

EnABLES

Tyndall National Institute
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PART 1
EnABLES & Relevance to Today's Presentation

EnABLES

UCC

European Union
European Regional Development Fund

What problem are we solving?

Industry challenge:

The world will have 1 trillion IoT devices by 2025 all needing power

- 100 for every person

Eliminate the need for battery replacement where possible

- Develop energy harvesting solutions and/or find ways to reduce the power consumption of devices

Research excellence challenge:

Collaboratively and concurrently develop application orientated & optimised solutions

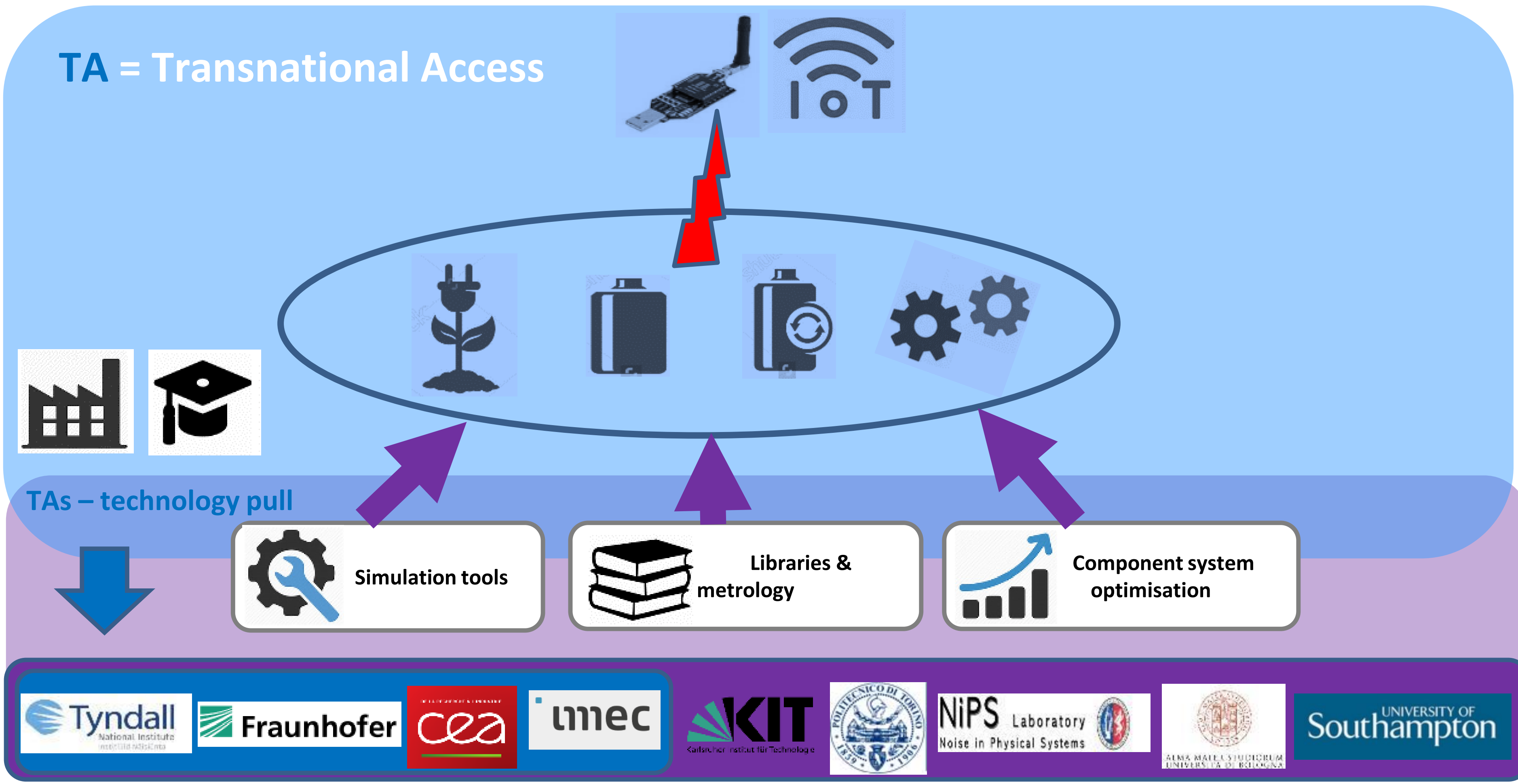
- Get academic and industry developers of energy harvesting components and systems as well as IoT devices to work together
- Accelerate & optimise development of parts and systems
- Parts should be standardised and interoperable

What are we doing about it?

- Building an ecosystem for collaboration starting with EnABLES
  - A €5.2M EU research infrastructure project
  - Creating 'self-sustaining' energy solutions to 'power the internet of things' based on energy harvesting, storage, micro-power management and system integration activities

- Providing external fast track technology access (TA) to expertise and laboratories – over 130 researchers & €2Bn worth of infrastructure
- Fostering internal joint research activities (JRAs) between partners guided by needs & opportunities
- Creating standardised and inter-operable libraries of parts & simulation tools for optimising system level performance
- Using EnABLES to foster a 'starting community'.

Powering IoT Research Infrastructure

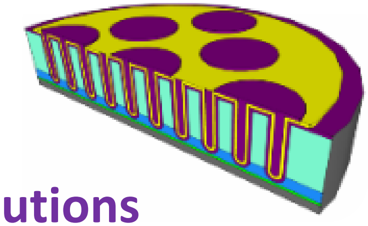


TA & JRA programs

EnABLES

- **Transnational Access program* will enable**
  - Free of charge access to expertise and laboratories
  - Feasibility studies

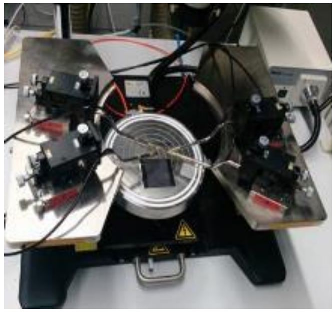
  (paper, simulation, characterisation, proto)

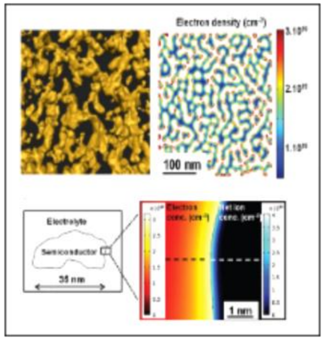


- **Joint research activities will create**
  - System optimised, application orientated solutions
  - De-risked & standardised methodologies and library parts

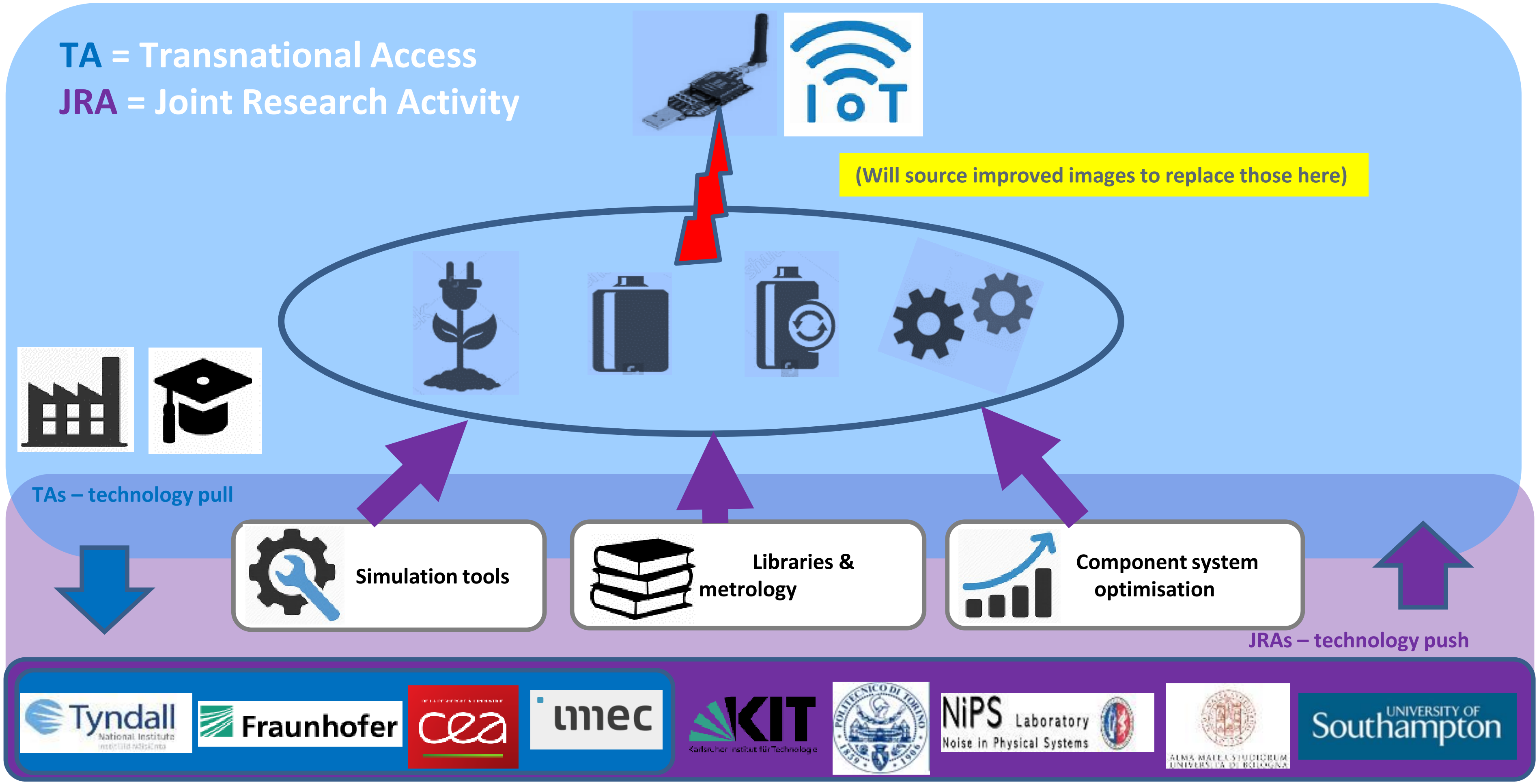
(open source)

*The TA web portal will be launched July 2018



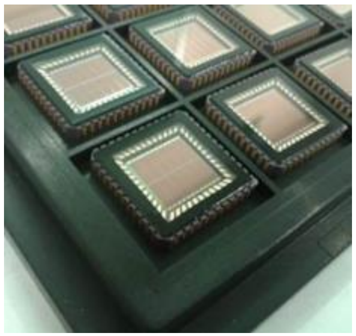


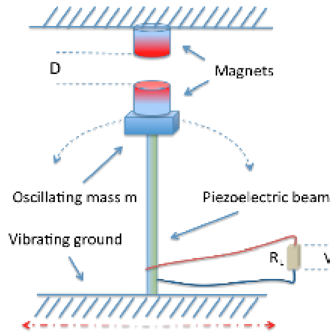
JRAs push and guide technology

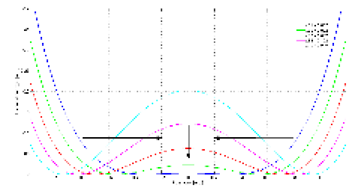


Examples of Technology Available

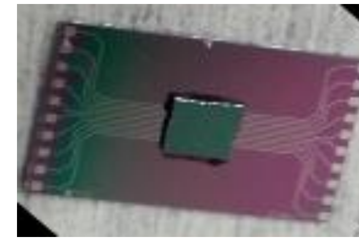
- **Energy Harvesting**





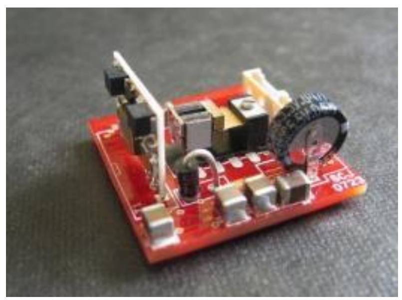


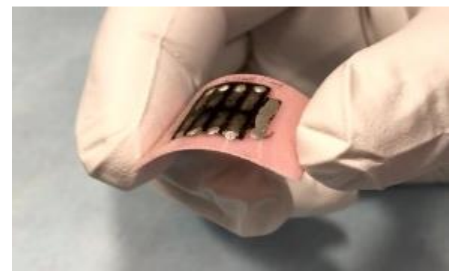
Non-linear EM

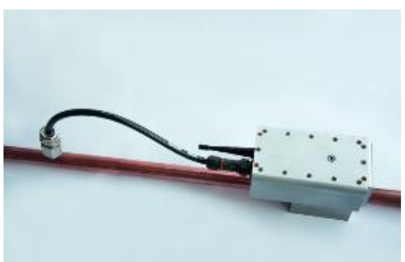


Thermoelectric

Integrated solar

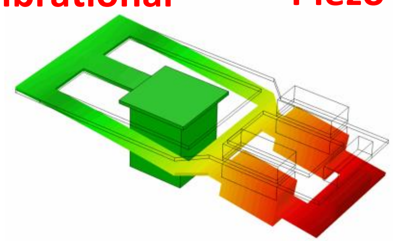




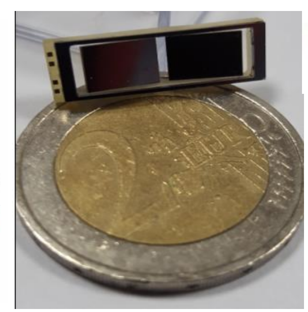


RF

Electromagnetic (EM) Vibrational

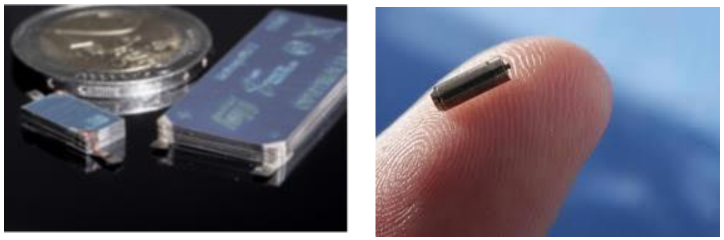


Piezo

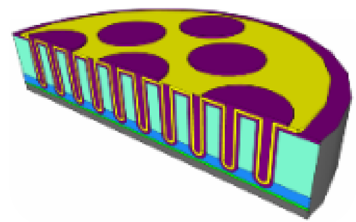


Examples of Infrastructure & Technology Available

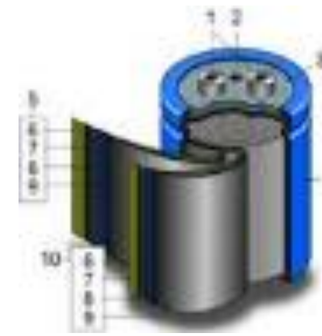
- **Energy Storage**



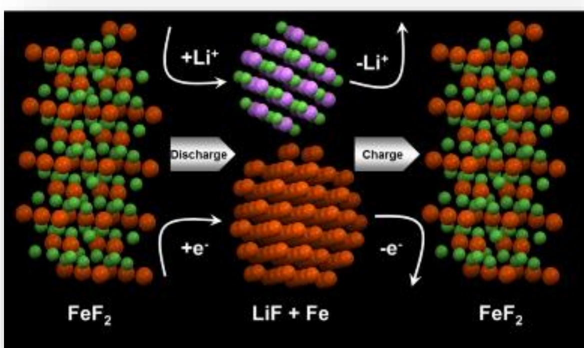
Microbatteries



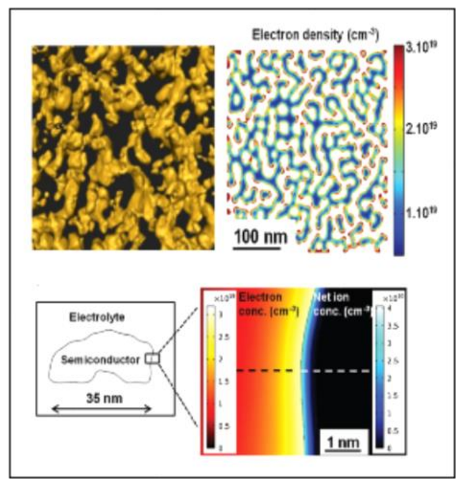
CMOS compatible Supercaps



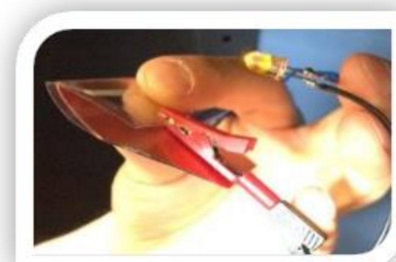
Nanomaterial supercaps



Printed batteries



Battery material simulation

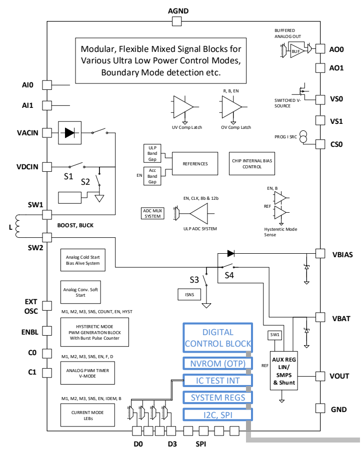


Flexible batteries

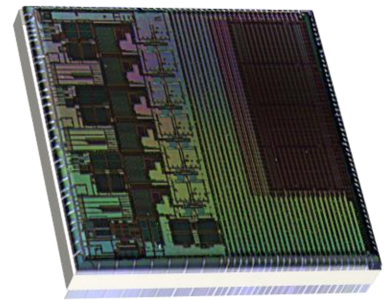
Examples of Technology Available

- **Micro-Power Management (MPM)**

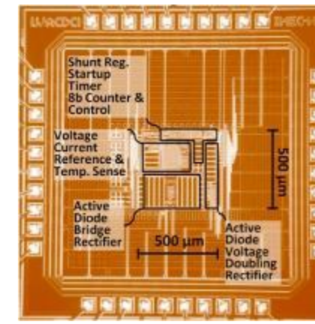
ULP (ultra low power) ASIC



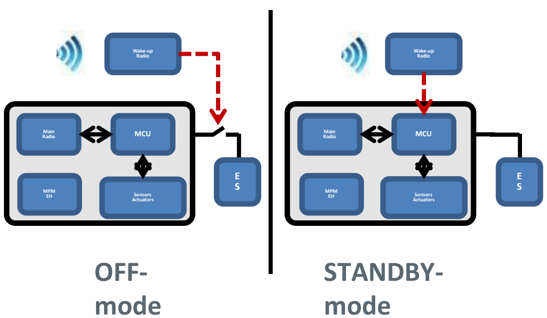
MISCHIEF modular PMIC



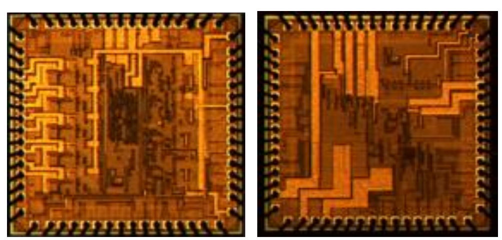
MuseIC



Energy Aware PMIC

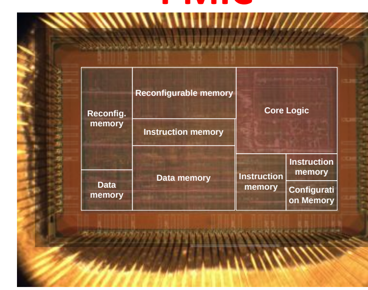


RF MPM



Multi- and Single-source PMICs

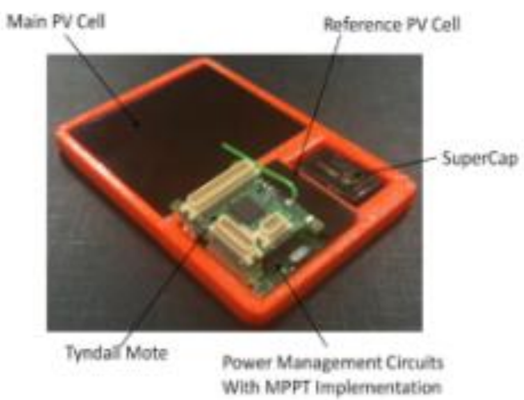
TEG MPM



Near-threshold processor

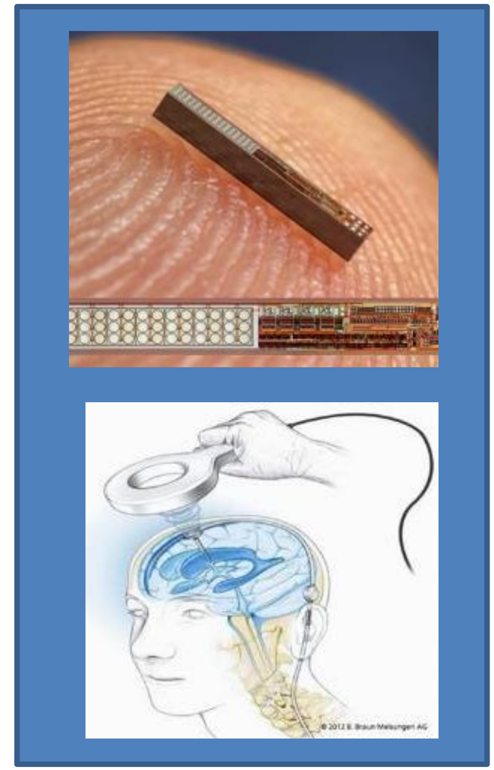
Examples of Technology Available

- **System integration**

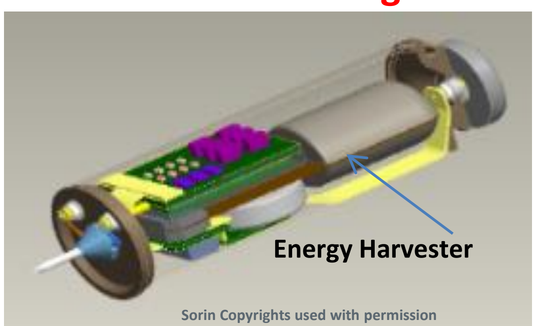


Indoor solar building monitoring

Solar powered window sensor



RF powered sensor

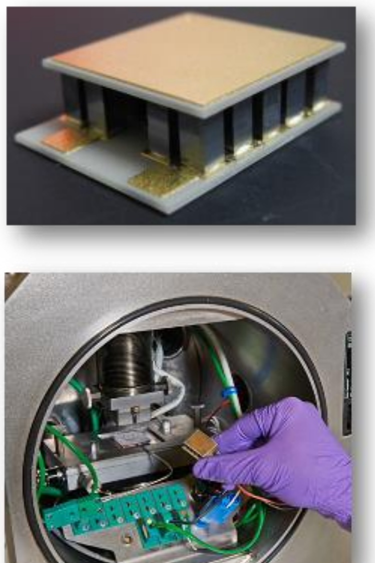


Implantable pacemaker

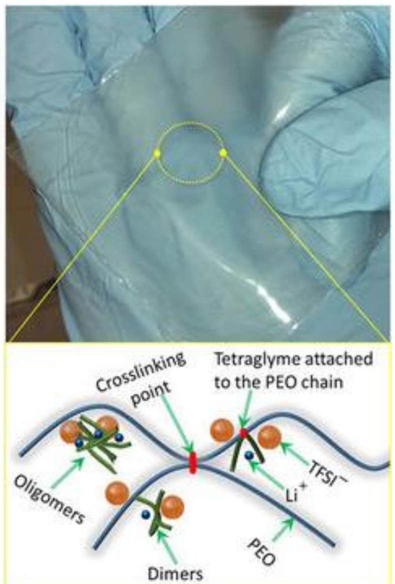
TEG powered sensor

Examples of Technology Available

- **System integration**

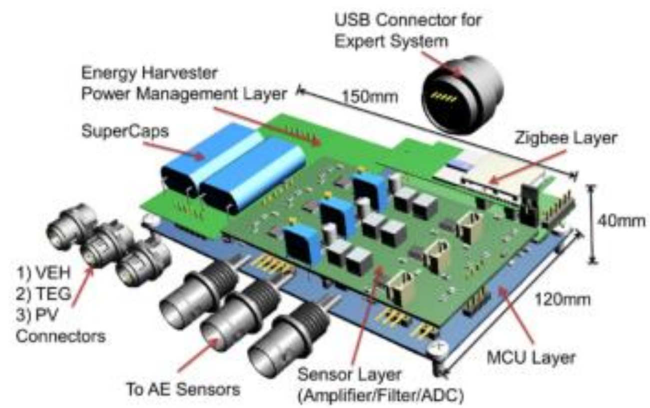


TEG sensor



Flexible battery

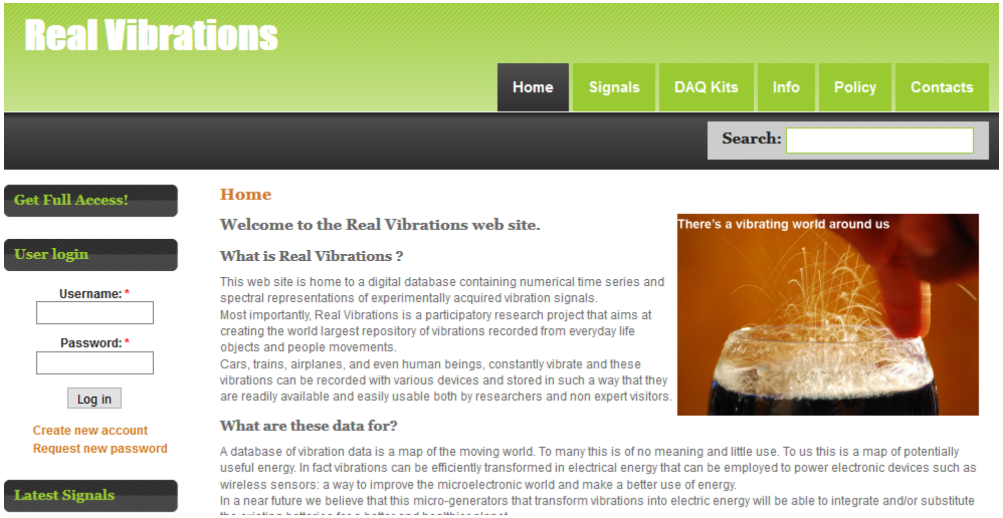
Solar powered IoT device



Multi-source equipment monitor

Case studies

- Virtual access databases already available from Perugia (NiPS) & Southampton
- Standardising, Integrating, Adding



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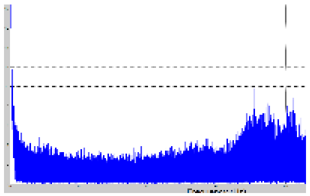
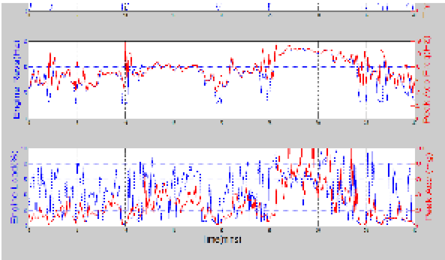
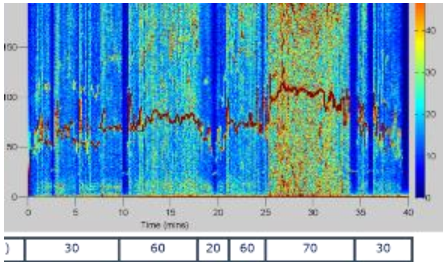
UNIVERSITY OF Southampton







EU Project 730957

Why are we telling you this?

EnABLES is building a 'powering the IoT ecosystem'

Ultimately it needs people like you to be part of this

- *Drive the agenda*
- *Form collaborations & networks*
- *Attract new researchers to this exciting area*

EnABLES PIs giving presentations at this Summer School

'Powering IoT'

Tyndall National Institute
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PART 2

Energy Harvesting Powered WSN

Systems Integration Considerations

UCC University College Cork, Ireland

European Union
European Regional Development Fund

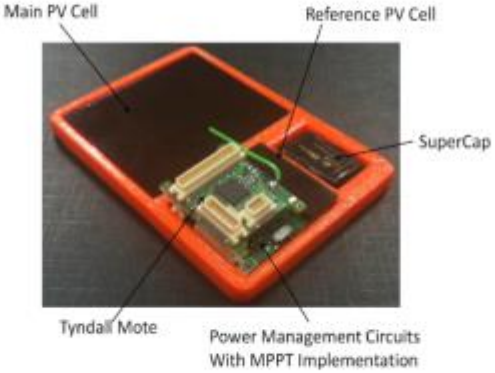
System Integration Contents

- WSN nodes & the Tyndall mote
- Energy Harvesting solutions
- The Energy Harvesting (EH) gap
- Reducing Required Power for EH feasibility
  - Designing for Low Power
  - Energy Conversion & Storage
- Potential Improvements by combining efforts
- Case studies – EH powered mote
  - Thermoelectric, Vibrational & indoor solar
- Summary & Conclusions

Introduction

- **WSN* nodes are ultra low power IoT devices that wirelessly capture data.**
- **Easily retrofitted on, in or near equipment, people and infrastructure**
  - Gather & share additional sensory data & enable better context based monitoring & control
- **Many uses - smart grids, agri-tech, wearables, smart mobility, smart cities**.
  - Asset tracking (equipment, people, goods)
  - Heating and lighting optimisation
  - Conditional monitoring, detecting anomalous behavior enabling predictive maintenance
- **Tyndall has developed a modular platform, used for >50 applications**
- **Major impediment to large scale WSN adoption is need for battery replacement.**
  - Impractical (logistics, access) & uneconomical
  - Also impacts system reliability & data integrity
- **Energy harvesting uses ambient energies as a power source**
  - Eliminates need for replacing batteries
  - (or at least extends battery life)

***Wireless Sensor Network**



- Work presented mainly based on WSN motes for energy efficiency in buildings application but much can be applied for a broader range of applications and ultra low power devices

Rationale

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Why do we need energy harvesting?

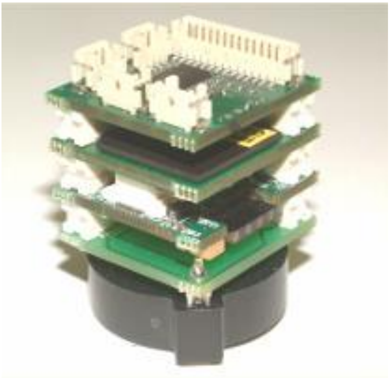
- Eliminate need for battery replacement
- Eliminate/minimize maintenance (deploy & forget)
- Reduce installation costs
  - Initial cost for EH device is higher compared to batteries
  - But initial cost is recovered through increased lifetime of EH devices
- Facilitate large scale deployments (wireless sensors)
- Increase reliability
- Power devices in difficult to access areas
- Condition monitoring
  - Predictive and preventative maintenance

Wireless Sensor Networks (WSN)

Measure temperature, light humidity, presence, CO_2, noise, power, etc.

Why wireless:-

- Easy to retrofit into existing buildings
- Easy to update/change



The challenges:-

- Render easy to install and upgrade
- Add extra sensors without system re-configuration
- Miniaturization to increase reliability, reduce cost & power

The vision:-

- Self configuring, robust
- Low-cost, low power
- Self-powered, maintenance free
- Install with screwdriver

Applications of Tyndall Mote

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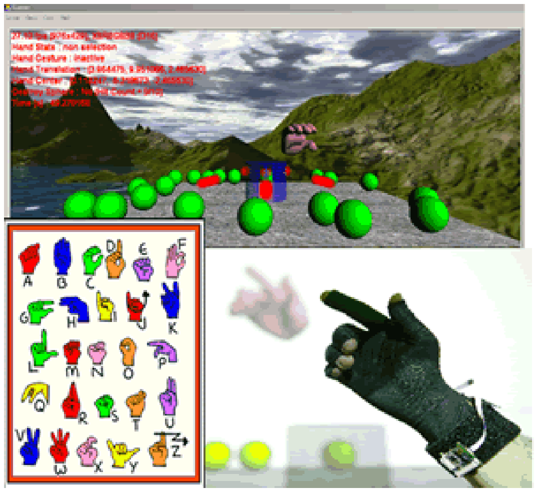
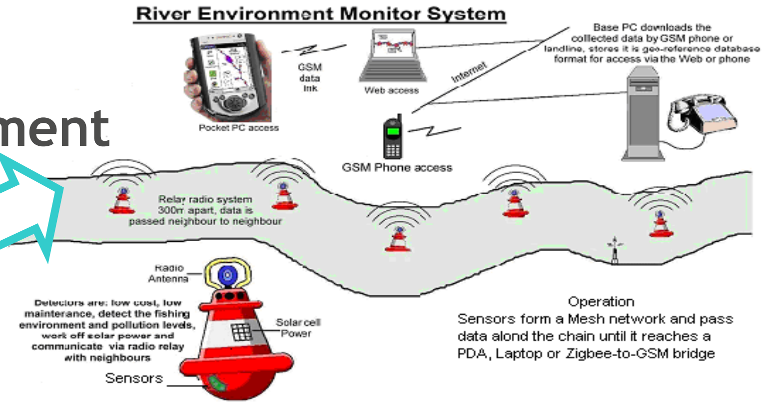
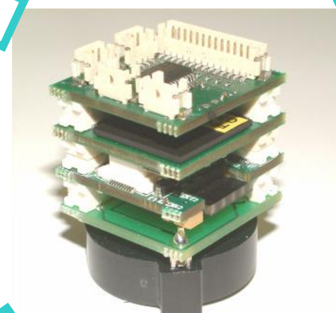


Wearable

Environment



Human Computer Interface



Environmental Monitoring

1"x1" layers

Health

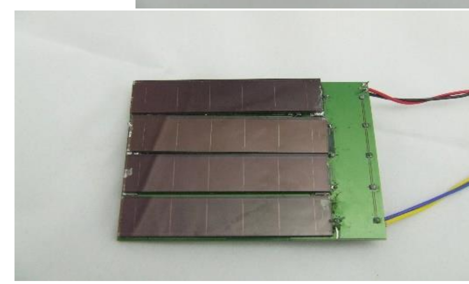
Energy

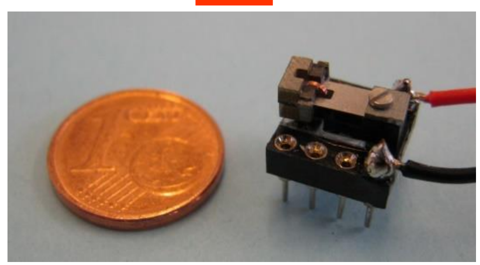
Medical diagnostic (ECG monitor)

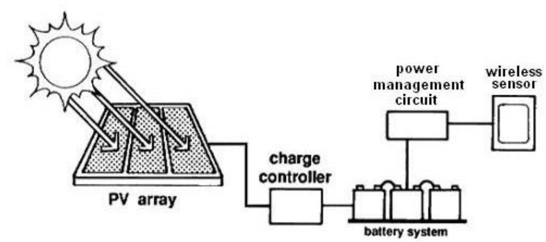
Building Energy Management (BEM)

Some Energy Harvesting Solutions for BEM (Building Energy Management)

BEM EH Sources







Thermoelectricity Generator (TEG)

Vibrational Generator

Indoor High-Efficiency Solar Panel

SYSTEMS - The 'Energy Harvesting Gap'

- Challenge
  - For most applications we have very limited REAL ambient energy sources

- Solution
  - Set realistic target – 50uW (typical for next gen WSN mote)
  - Reduce required power - miniaturization/packaging, low power RF protocols, low power sensors & ICs, low power WS drivers….
  - Increase available power – high efficiency DC/DC, MPPT, low leakage energy storage, smart energy management circuits………
  - Use hybrid solution – extend battery life

- Vision & benefits
  - Everyone working to a common spec & vision
  - World's 1st 50uW credit card sized solar panel + flat battery/storage device + integrated energy management circuit

Living in the real world - The need to Combine Power Sources

- **Challenge**
  - No single EH solutions for all applications
  - Combining of EH sources- potentially could make it ubiquitous
  - Often need to combine with a non-rechargeable power source e.g. high density battery
  - Non necessarily a need to last 'forever'…..Trick is to make power source outlive lifetime of application

- **Solution**
  - Co-designing of different EH solutions
  - Development of adaptable power management circuits e.g. Tyndall MISCHIEF IC (more later)

Living in the real world - Variations in characteristics (impedance, frequency, irradiation, etc.)

- **Challenge**
  - Offer ‘Broadband’ of operation
  - Improved reliability
  - Cover a broader range of target applications
  - Allow for wide variability in ambient energies
- **Solutions**
  - **Multi device design (one for each frequency)**
  - **Tuneable devices - resonant frequency, impedance, storage device voltage**

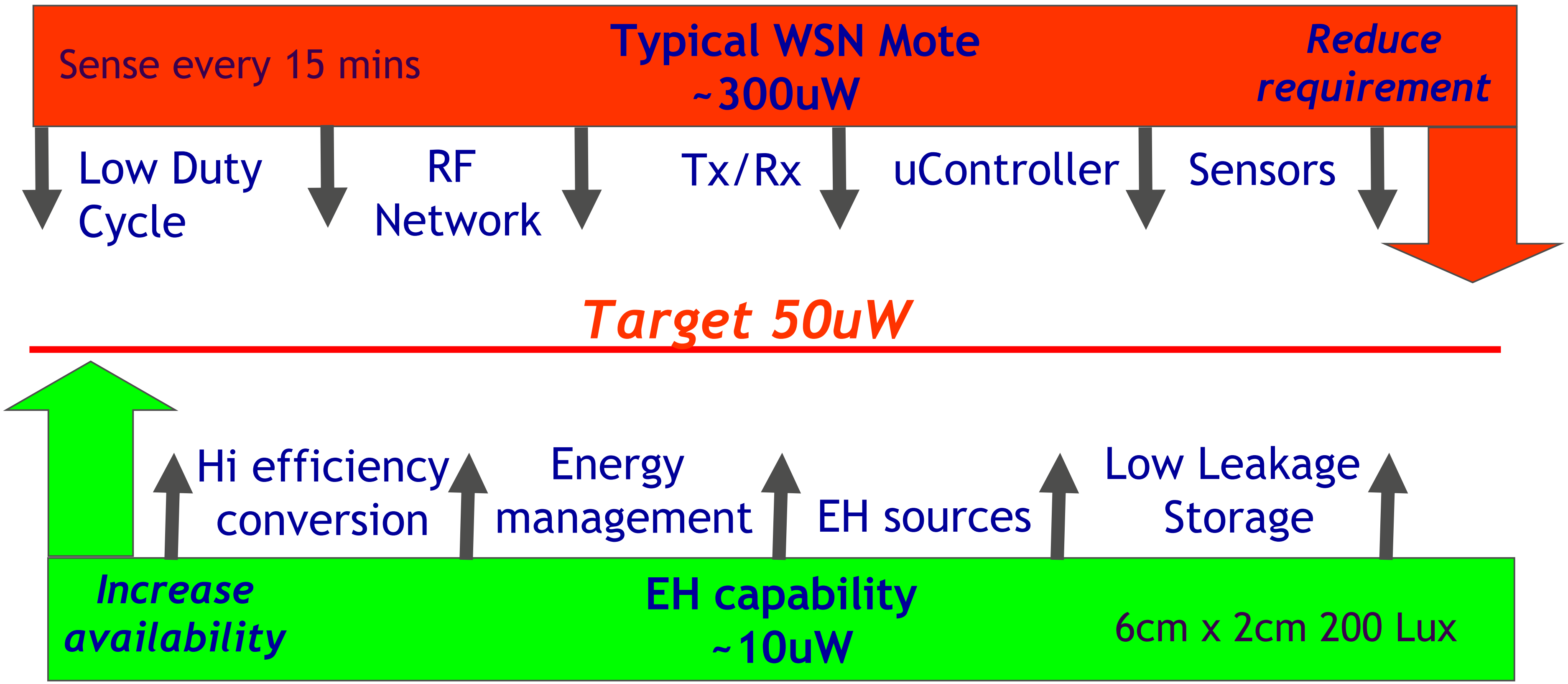
Living in the real world – Data Processing

- **Challenge**
  - Motes need easy to use more powerful software for good user interface
    - actuation and control, data processing
  - This means more power required from the mote
  - How do we interact more closely with SW designers to optimise trade off – power usage Vs capability
- **Solution**
  - Define set of specifications Vs EH capability
    a) Simplify the design where possible
    - ‘Lifeboat model’ for some applications – do as little as possible to get WSN actuation signal out, process elsewhere

    b) Line powered motes for most complicated application, e.g. de-centralised processing capability and/or need to drive actuators.

    c) In some cases at a system level it may make sense to process data locally before transceiving to reduce power consumption in transferring data but only if there is enough energy at source

Energy Harvesting (EH) Gap



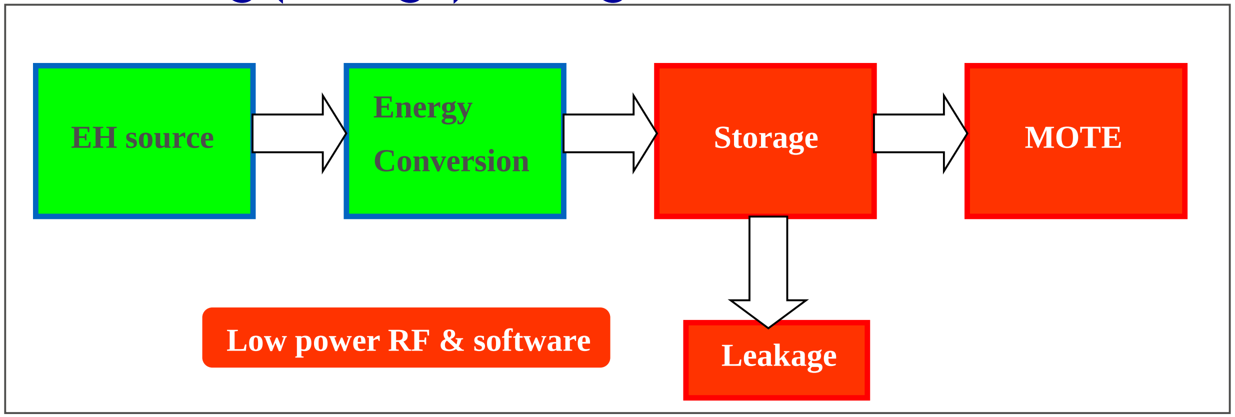
50uW is a reasonable target for BEM:-

- ✓ **Credit card sized indoor solar panel at 200Lux**
- ✓ **Vibration demonstrator already demonstrated (HVAC)**
- ✓ **TEG (thermo electric generator) on a 50deg C heater**

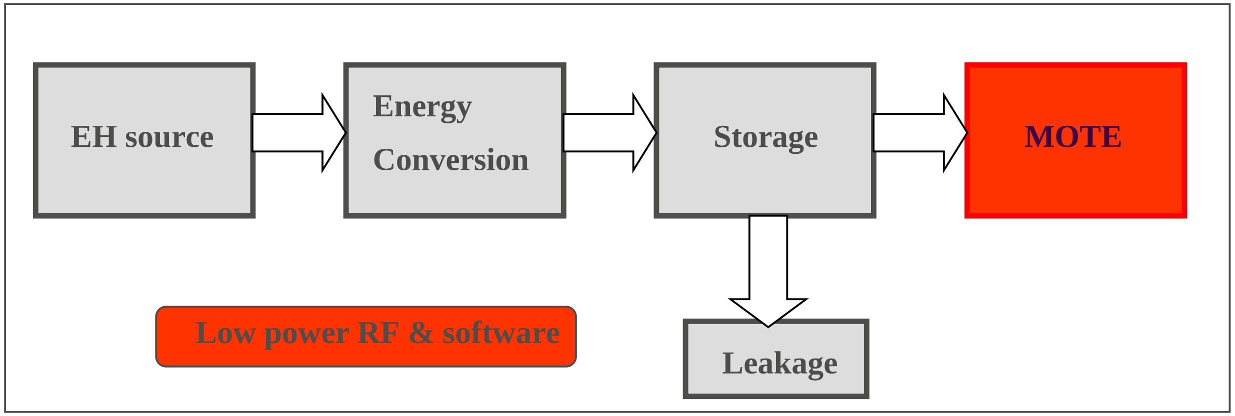
Reducing Power for EH feasibility

- EH research is about
  - Researching new technology EH sources
  - Squeezing as much energy as possible from the EH source

- But it is also about
  - Understanding the application &
    - ✓ Designing low power hardware solutions
    - ✓ Selecting low power RF networks
    - ✓ Selecting low power software
    - ✓ Selecting optimal storage solutions
  - Maximising efficiency of Energy Conversion to a usable voltage
  - Minimising (storage) leakage losses



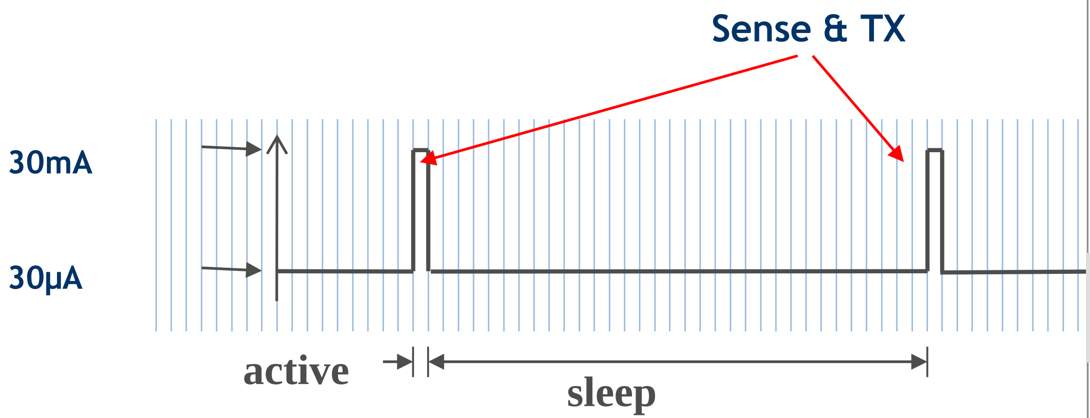
Designing for Low Power



uC
Tx/Rx
Sensors
RF Network
Software

Designing for Low Power

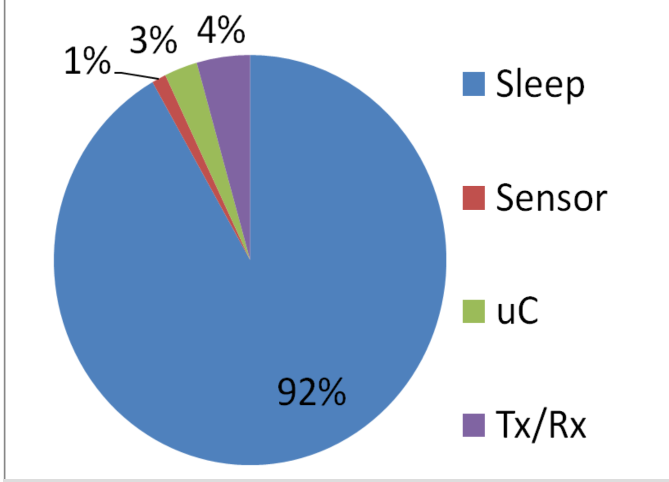
- Microcontroller & Transceiver
  - High sensitivity to Duty Cycle



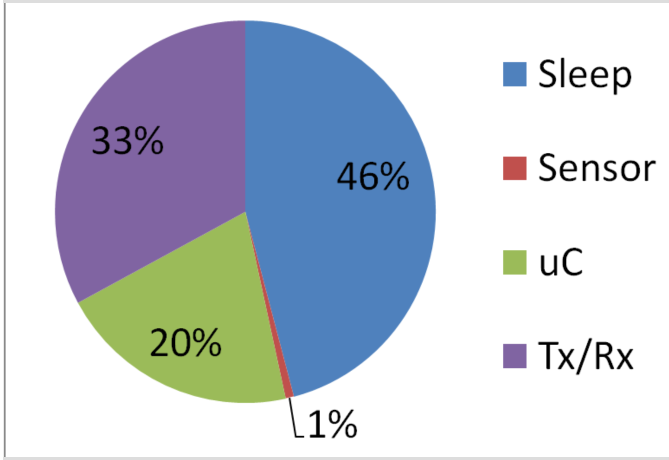
$P_{avg} = (1\text{-}D)P_{sleep} + D(P_{active}) + P_{leak}$

Approx = Sleep Power for D < 0.01%

D = Duty Cycle



Sense every 15 mins
0.01% Duty Cycle



Sense every minute
0.15% Duty Cycle

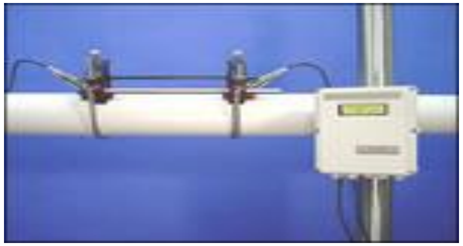
*** Typ BEM values**

Designing for Low Power

- Sensors
  - For low duty cycle, BEM average power is relatively insensitive to sensor selection (temperature, light, humidity)
  - However some require significantly higher power, e.g. ultrasonic gas and water sensors, CO2 sensors, occupancy sensors
  - Some are event rather than time based (e.g. occupancy) so very dependent on how often it is triggered
- RF Network & Software
  - Select low power solutions but understand trade-offs
  - Look at options to 'starve' sensors of power to reduce quiescent power but also Look at time taken for sensors to 'settle'

Light sensor

Ceiling Occupancy Sensors



Ultrasonic sensor

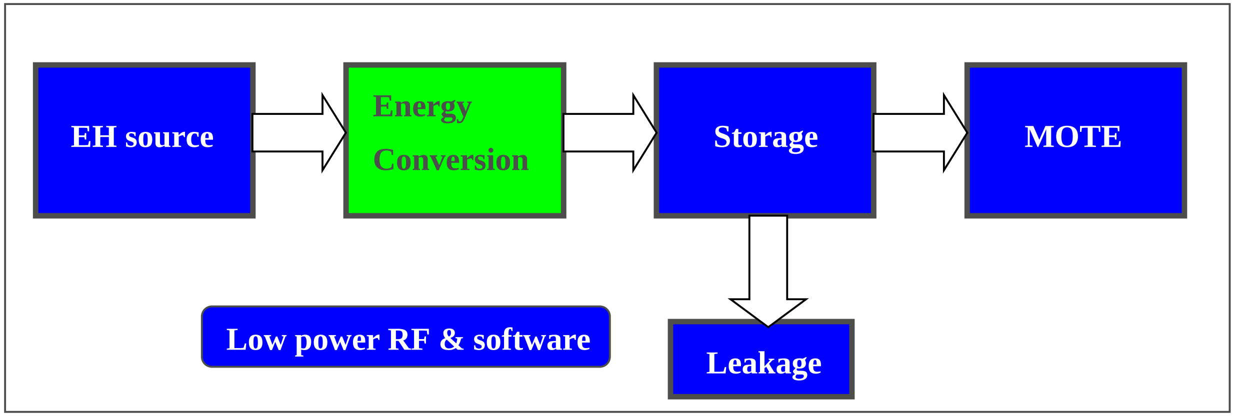
DEVICES/MATERIALS Sensors

- **Challenge**
  - How to power gas and water sensors (ultrasonic, high power)
  - How to power CO2 sensors
  - Continuous sensing required for some apps :- presence, open/close, gas, CO2

- **The good news**
  - Low duty cycle Ok for most applications (once every 15 mins)
  - Typ 93% of the power is for 'deep sleep' mode at this duty cycle

- **Some solution ideas**
  - Develop miniaturized innovative low power sensors (new materials)
  - Accept EH not suitable for some apps
  - 'Adaptive' sensing – system decides on duty cycle + what info to send

High Efficiency Energy Conversion



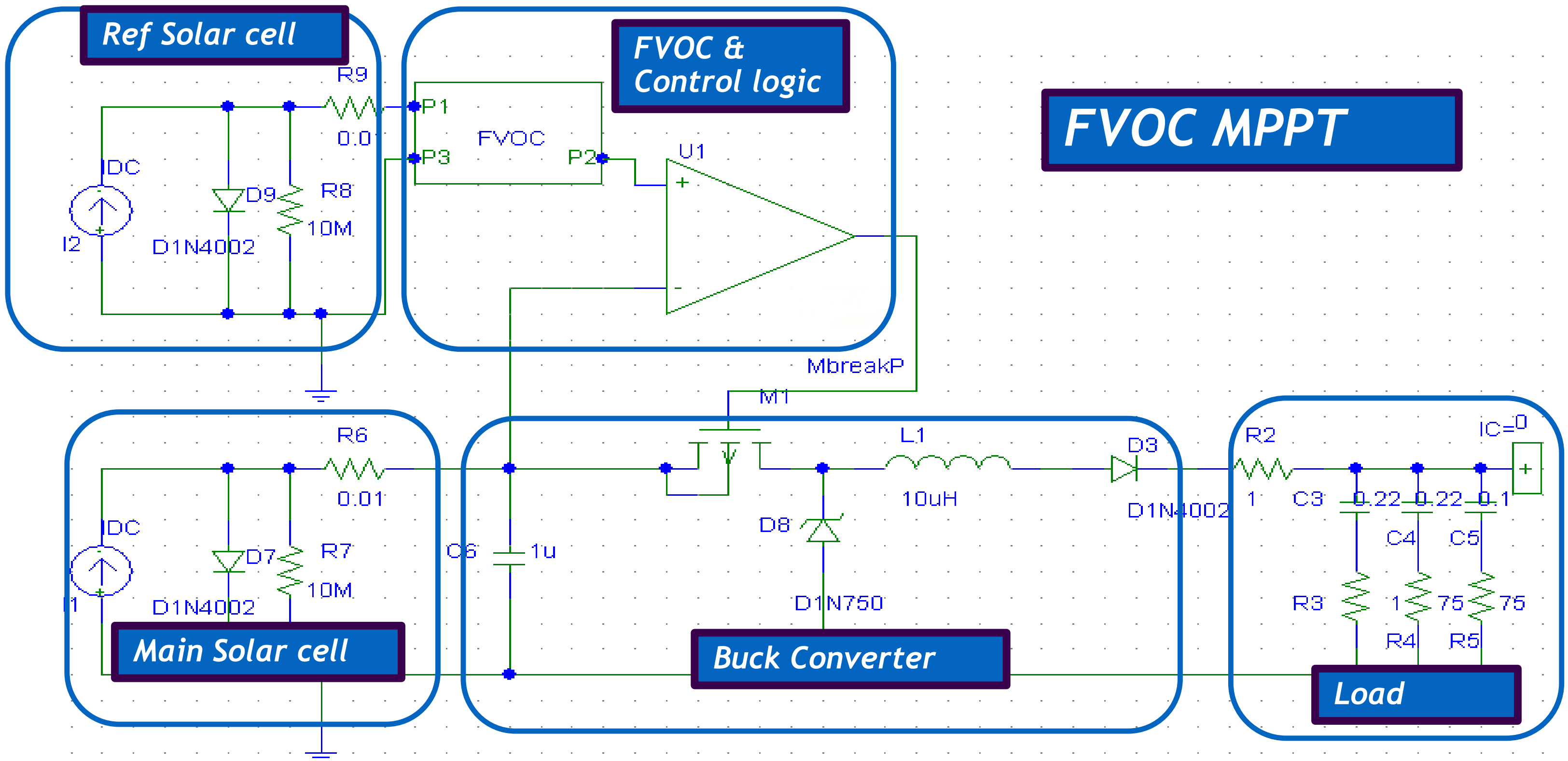
MPPT
DC/DC Convertors

Energy Conversion-MPPT

- **Maximum Power Point Tracking**
  - Load impedance matching technique to optimise conversion of ambient energy to electrical energy
  - For indoor light relatively very little characterisation done
- **Tyndall had developed low power dissipation MPPT solutions for indoor solar applications**
  - Fractional Open Circuit Voltage method
  - Less accurate than other techniques but self power consumption lower

	MPPT Accuracy	Dynamic Response	System Power Consumption	System Complexity
Perturb & Observe	High	Fast	High	High
Fractional Voc	Average	Low	Average	Average
Pre-set load	Low	None	Low	Low

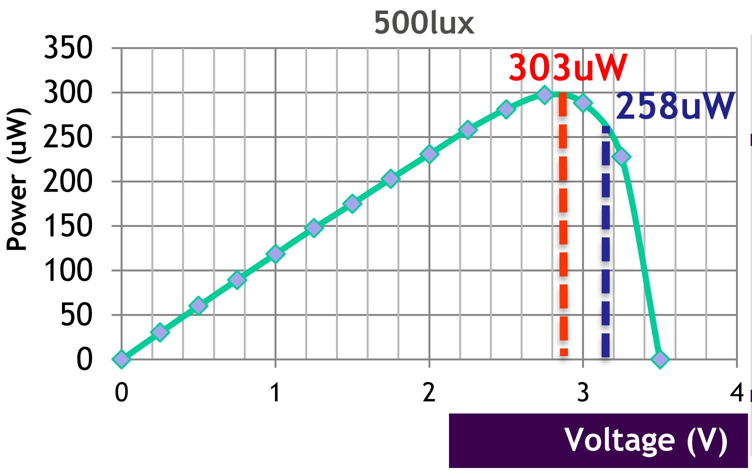
Fractional Open Circuit Voltage MPPT method



- **No DSP unit or microcontroller required in FVOC MPPT**
- **$V_{mpp} \approx k^{*}V_{oc}$ (k ≈ 0.76)**
- **Analog comparator used to control boost converter, tracking the maximum power point**

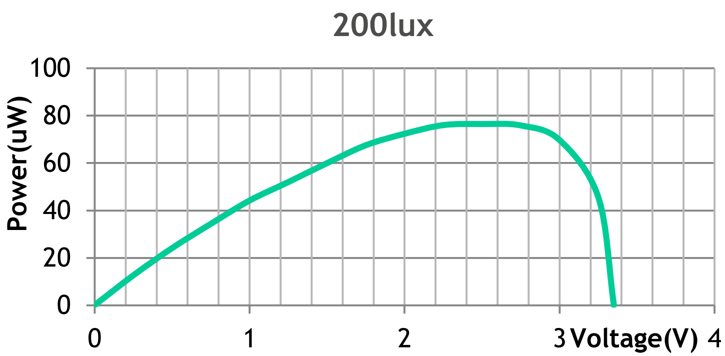
MPPT Results

- For <500LUX any MPPT solution for applications <300uW* requiring >30uW is not worthwhile



MPPT Method	*Perturb & Observe*	*Fractional Open Circuit*	*Optimised Possibility*
P_{MPPT}	303uW	273uW	285uW
$P_{nonMPPT}$	258uW	258uW	258uW
Saving	45uW	15uW	27uW
$P_{MPPTcct}$	300uW	30uW	15uW
Net saving	-255uW	-15uW	12uW

- For <200LUX 90% of peak power is available over relatively large range
- No need for MPPT solution



LUX	*Voltage for 90% Max Power*
500	2.4 - 3.0V
200	1.75 - 3.0V

* 100uW average, 8 hrs…

Energy Conversion – DC/DC

- Convert the Harvested Energy efficiently to a usable Voltage
- **2 most common techniques**
  - IC based DC/DC converter e.g. TI, ST, Maxim, ADI, LTEC, Cypress, GreenPeak
  - Discrete DC/DC e.g. boost converter, e.g. EnOcean or ‘build your own’
- **Problem, conversion efficiency is poor below 100uW**
- **High efficiency DC/DC not extensively researched below 1mW**
  - more difficult to do
  - returns are diminished

  but for EH these savings are significant

- **Key performance issues:-**
  - ✓ Efficiency
  - ✓ Input voltage range
    - $(E = ½ C(V_{start}^2 - V_{finish}^2))$
    - Also many EH system delver low Vout
  - ✓ Low voltage Start-up
  - ✓ Quiescent current
- **Tyndall developing an innovative solution to address this**
  - ‘MISCHIEF’ (ref next few slides)

“MISCHIEF”
Multi-source energy harvesting PMIC

Highest efficiency switch-mode, energy harvesting PMIC, measured @ 10 µW point

- Cold-start and operation over ~1uW to 200mW

Lowest quiescent current (I_Q) in low power regulation mode, <200nA

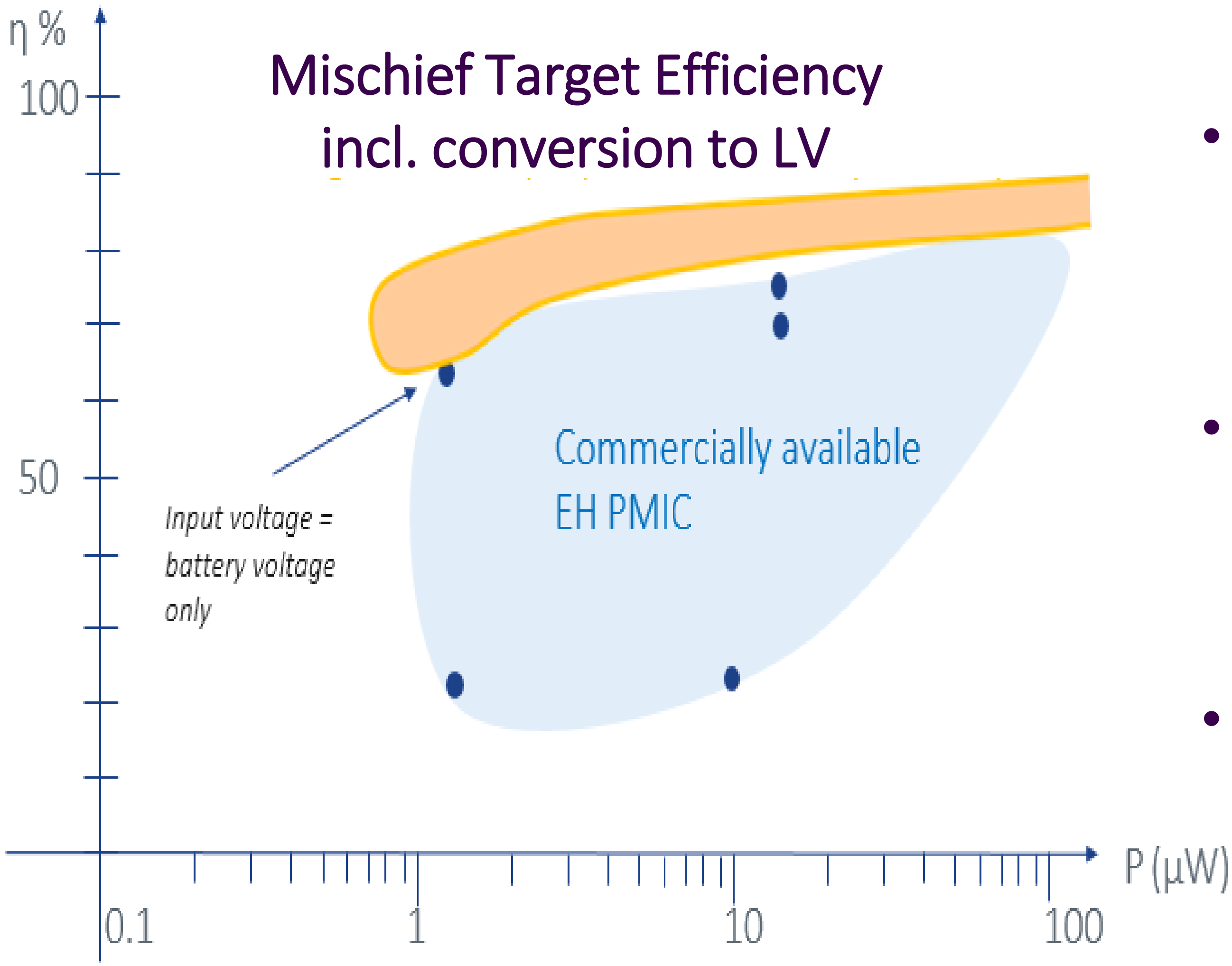
Highest **end-to-end system** efficiency

- Uniquely beginning with both ***Boost and Buck*** modes to both battery voltage (~3V) and LV (~1V8)

Technology Platform proofed for development of:

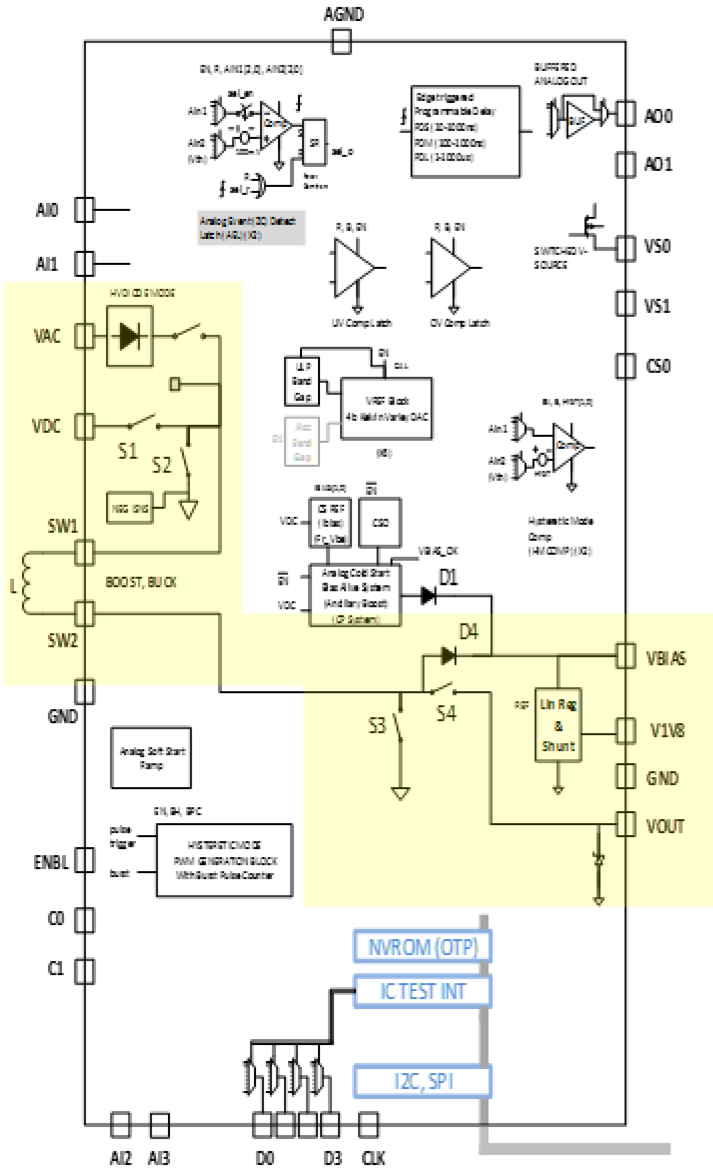
- Next Gen control & features
- (Very much with ***mixed signal*** control approaches)
- Substantially increased power transfer – Vibrational Energy

Highest Efficiency & Next Gen Capability



- 4 Switch Quasi Resonant Buck-Boost topology
- After extensive survey of best available parts
- Highest end-end efficiency over 1uW to 100uW

Mischief Gen. 1 Platform Block Diagram



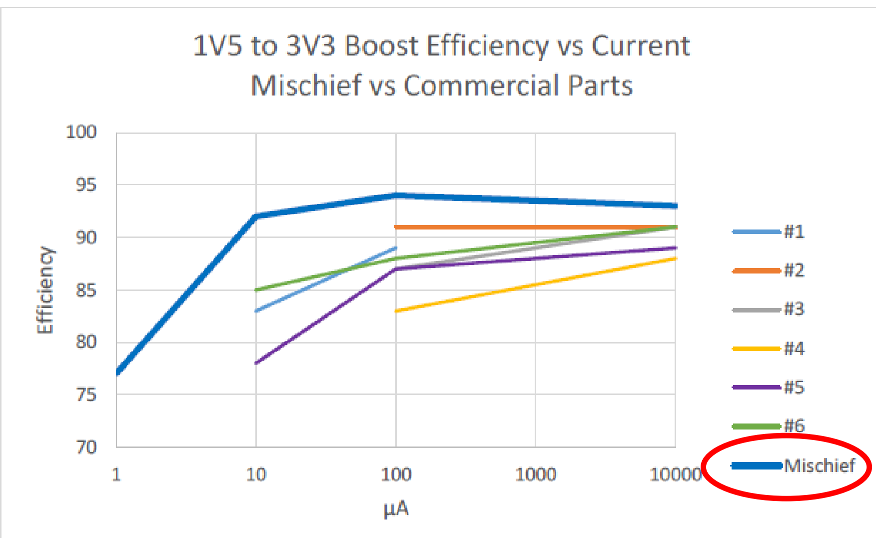
- Modular Flexible Mixed Signal blocks
- Asynchronous and Analog
- Dynamic Power/Speed Control
- Fast Start and Stop Blocks – Efficient Duty Cycling

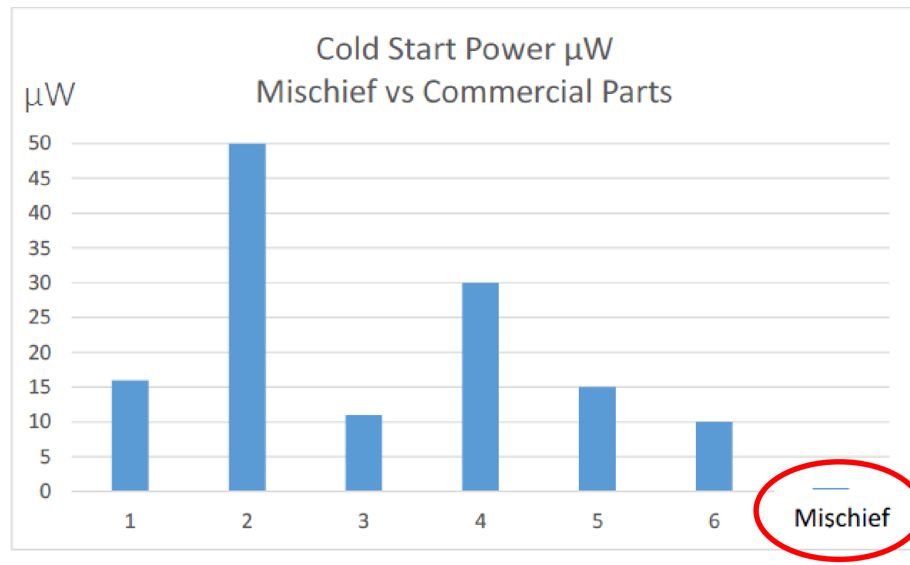
A platform strategy
– interface with Microprocessor or FPGA and will be used for digital state machine development

"MISCHIEF"
Gen 1. Results presented at EnerHarv 2018

Comparison with commercial parts…. 2017
World leading in efficiency, power range, voltage range and quiescent current

Only one part surveyed has buck-boost capability
None have advanced digital configurability (SPI)



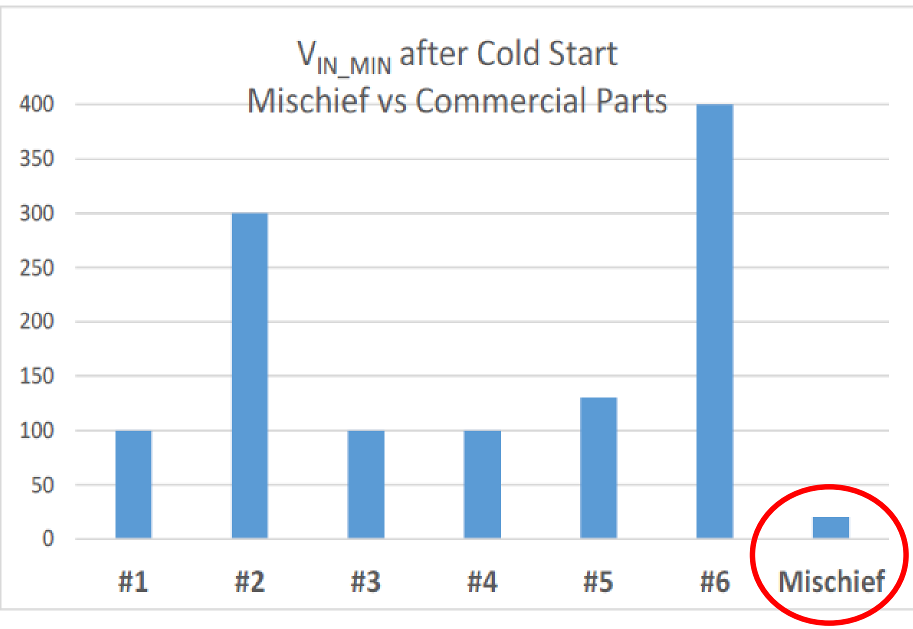


Mischief based on Top Level Schematic Sims (not LVS)

Part nos ADP5090, MB39C831, AEM10940, SPV1050, BQ25504, MAX17220

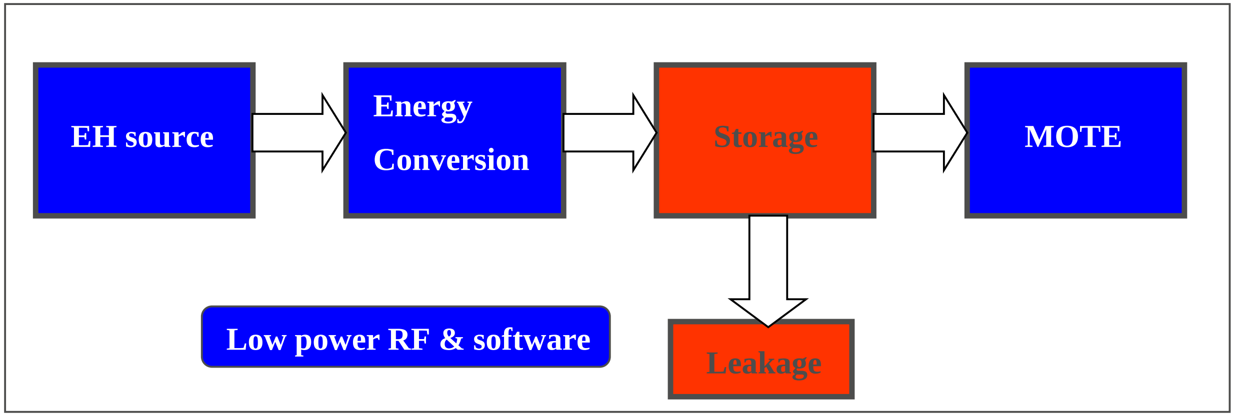
“MISCHIEF”
Results presented at EnerHarv 2018

Low Vin operation after cold start



Marketplace EH PMIC	SPI/ I2C Interface with Host WSN Controller	Topology	Low Output Voltages
#1	No	Boost	No
#2	No	Boost	No (3V+)
#3	No	Cascade Boost, Buck+LDO	Yes
#4	No	Boost, Buck-Boost, LDO	Yes
#5	No	Boost	No (2V+)
#6	No	Boost	No
Mischief	Yes	Buck-Boost	Yes (1V+)

Energy Storage



Cycles
Energy density
Impedance
Transients

Low leakage storage

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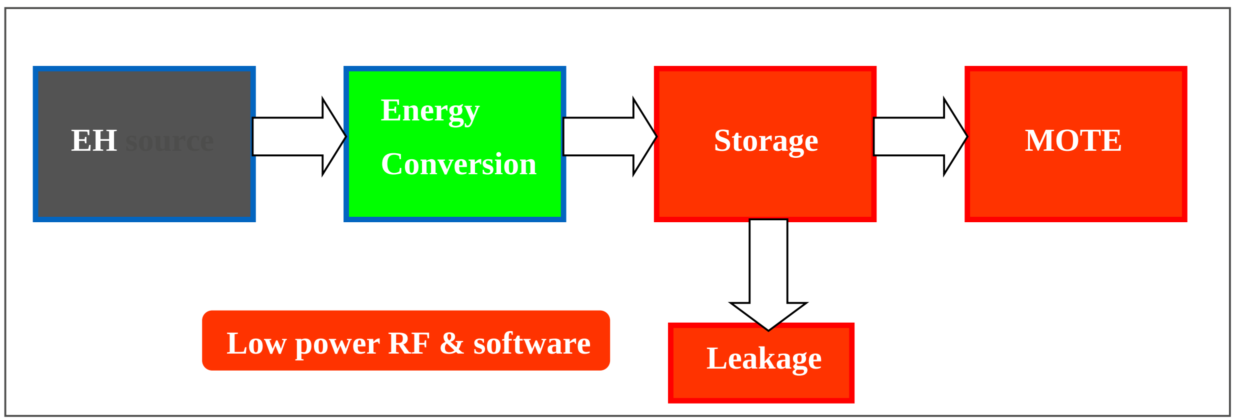
- **Challenge**
  - We may have days, weeks or even months of little or no ambient energy
  - Supercaps have high leakage only suitable for short term storage
  - Thin film batteries at infancy level – temp range, stability, etc.
  - Traditional Batteries – limited life + charge cycles + leakage + ….
  - Low impedance storage solution needed to manage fast transients (e.g. WSN node going from sleep to active)

- **Solution**
  - Supercap technology improving (but not there yet esp. at early stages after storage cycle – 1st few hours)
  - Nanotechnology and next generation materials continue to improve storage device performance – leverage esp. from mobile phone applications market
  - Be careful in mixing and matching devices to cover range of storage needed (low ESR for fast transient)
  - Develop hybrid solutions
  - Combine chargeable and non re-chargeable devices
    - Re-chargeable devices use harvesting energy
    - Dip into non-re-chargeable device only as needed to significantly extend its life
    - Non-re-chargeable batteries have lower leakage and higher density
    - Non-rechargeable battery also good for cold start, covering outage periods, etc.
    - Devise topologies that minimise the need for storage in leaky storage elements
    - Use modelling to determine capability and optimise part sizing , minimise depletion, etc.

Combining efforts



Combining Efforts

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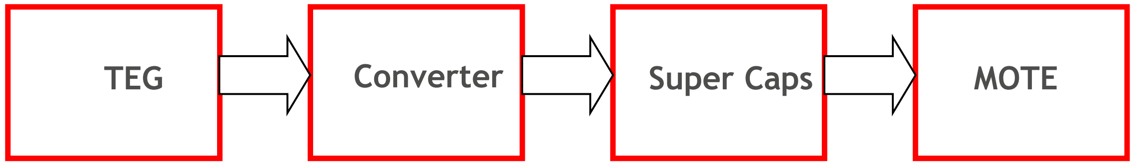
- Demonstration of potential reduction in required power based on sleep current and duty cycle

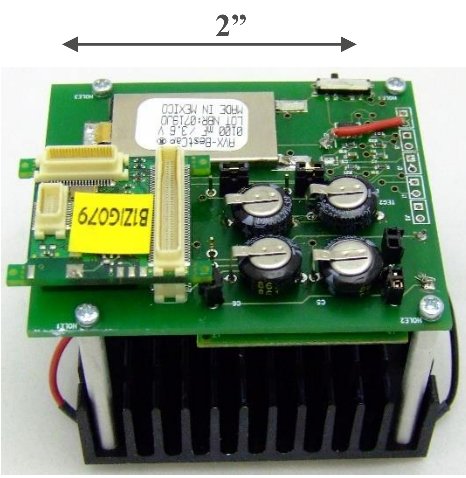
	Sense interval	15 mins	1 min
High sleep current	Duty cycle	0.01%	0.15%
	Sleep uA	30	30
	TRX (active) mA	35	35
	Total average current uA	33	82
	Total power at 40% efficiency uW	**276**	**544**
Low	Sleep uA	5	5
	TRX (active) mA	20	20
	Total average current uA	7	35
	Total power at 50% efficiency uW	**46**	**231**
	Total power at 75% efficiency uW	**31**	**154**

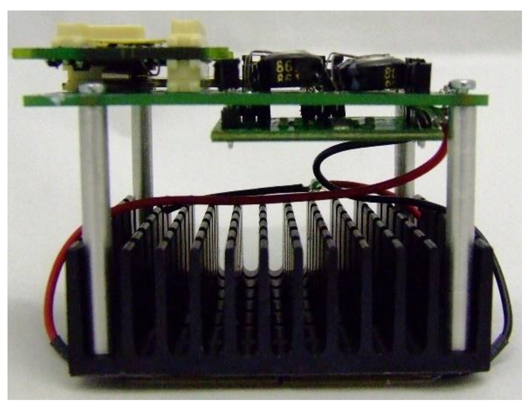
✓ Use low duty cycle
✓ Combine improvements in uC, Tx/Rx and sensors
✓ Understand the application
✓ Improve DC/DC conversion (from batter or EH source)

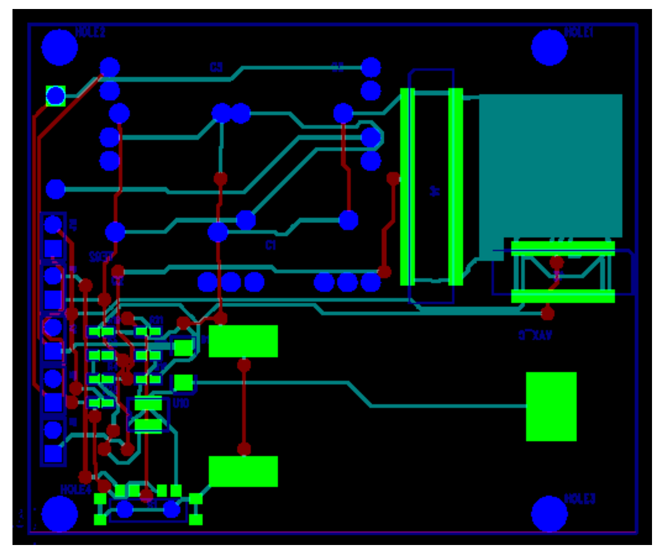
Case Study: TEG Powered Mote



- **TEG: RC-12-6 thermoelectric module*4**
- **DC Converter: Texas Instruments TPS61200**
- **Super Capacitors Bank: Panasonics Goldcap 220mF*4 & AVX Low ESR Bestcap 100mF*1**
- **Mote: Tyndall Zigbee mote**

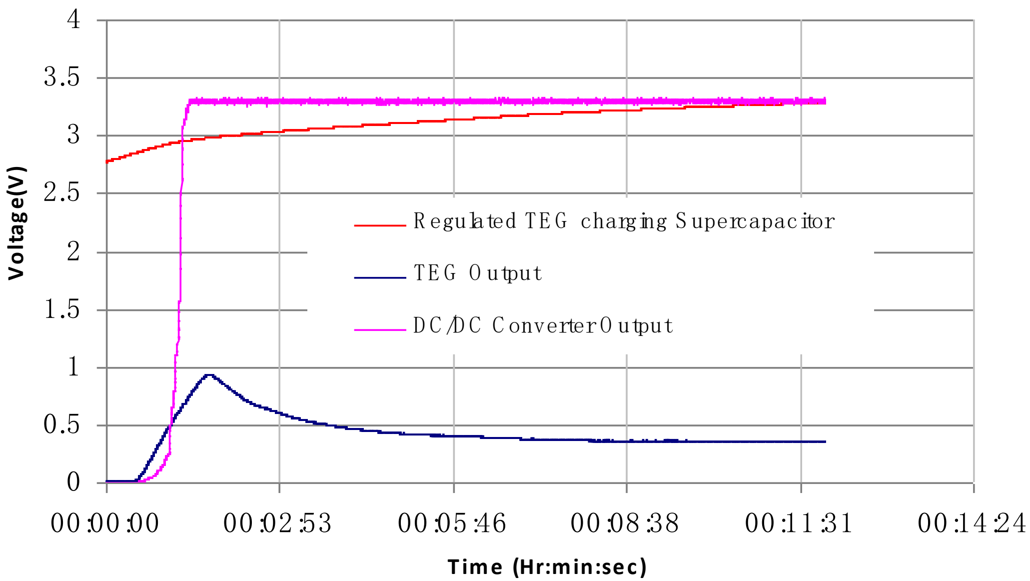






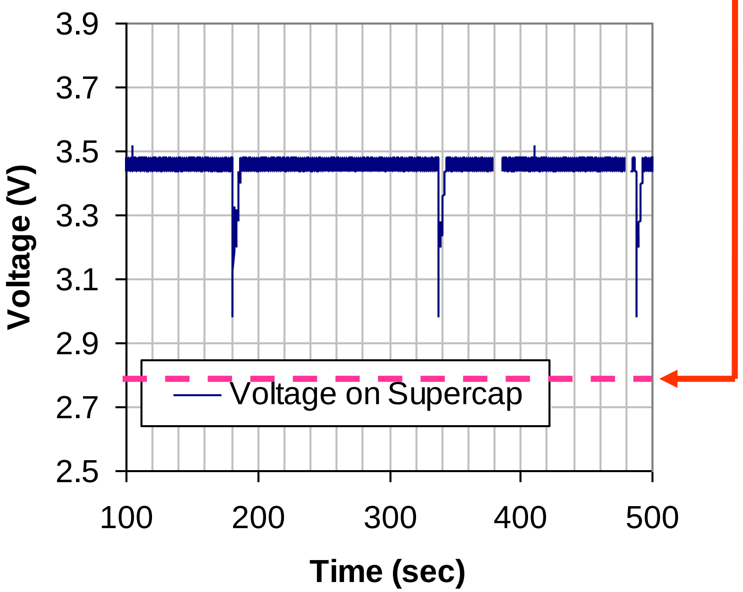
Case Study: TEG Powered Mote

- **TEG with converter can power mote when placed on 70°C radiator (heater)**
- **Mote 0.1% duty cycle**



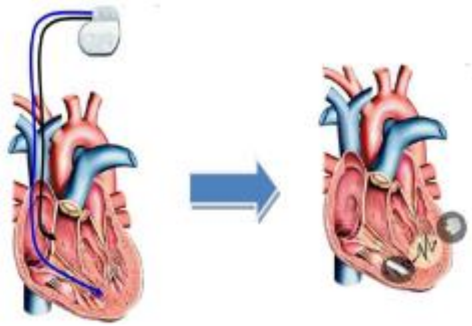
Voltage at start-up

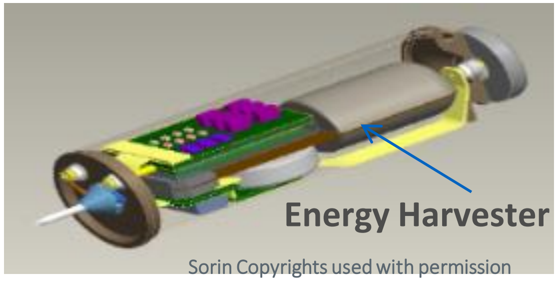
keep load transient above mote threshold voltage



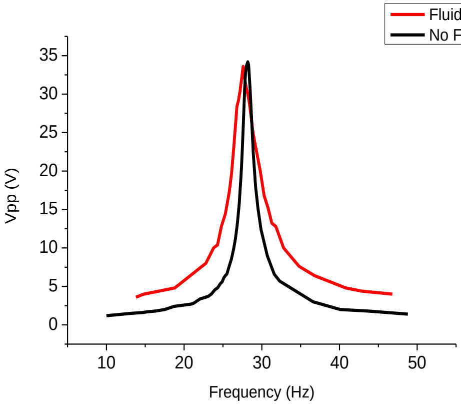
Voltage in steady state

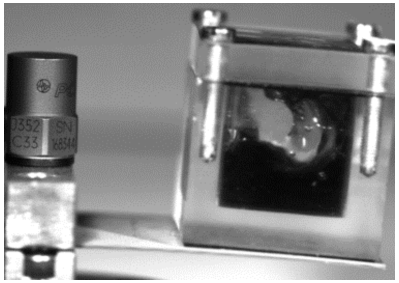
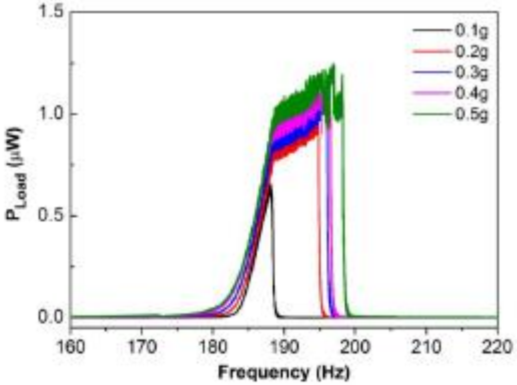
Some Application System Integration Examples

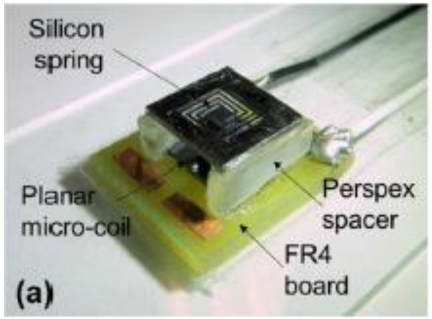




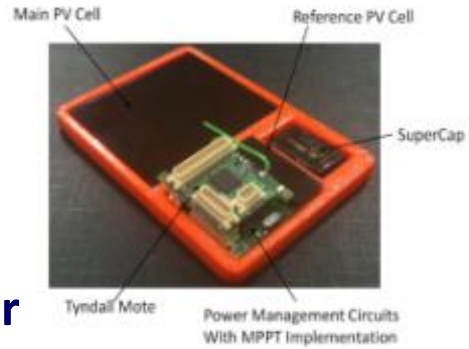
Miniaturisation:- Implantable Energy Harvester



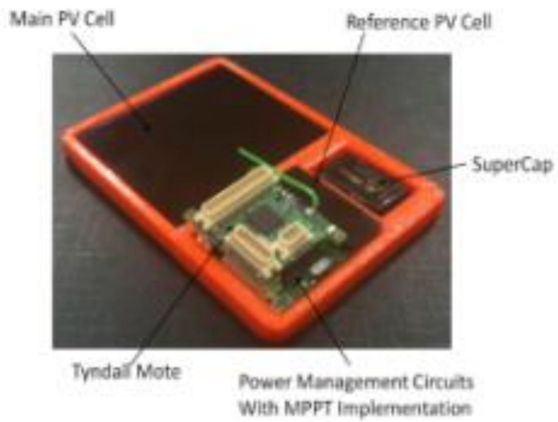


Performance enhancement:- Wide bandwidth Vibrational Energy Harvesters

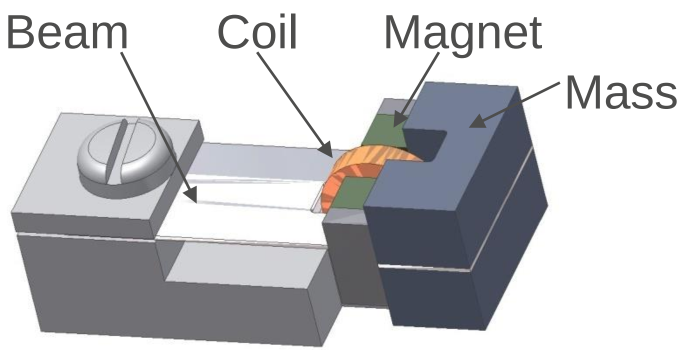
Circuit and system innovation:- Indoor solar energy harvester

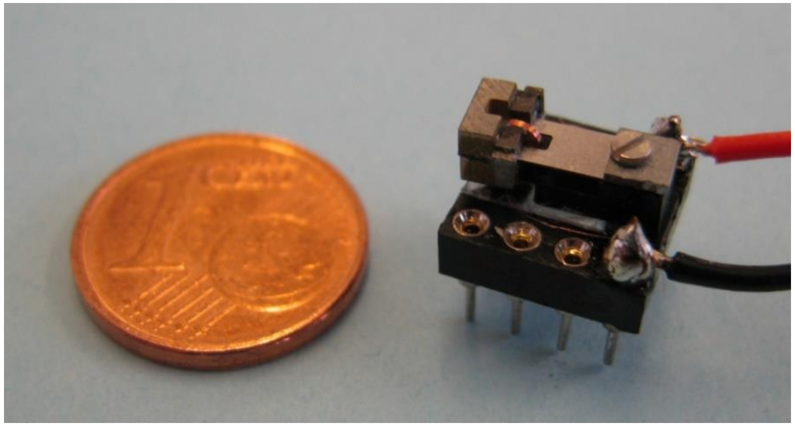
Case study:- Light Powered Mote



- **Indoor solar powered energy harvesting solution**
  - Measure temperature light and humidity indefinitely
  - 10 minute duty cycle
  - Just needs 8hrs of light per day at 250Lux
  - Will operate for 72 hrs in darkness
  - Will self-start within 2hrs
  - Electromagnetic based vibration generator
  - Generated uW average, 600uW peak
  - Deployed in commercial buildings

Case Study:- Higher Power Vibration Powered Mote

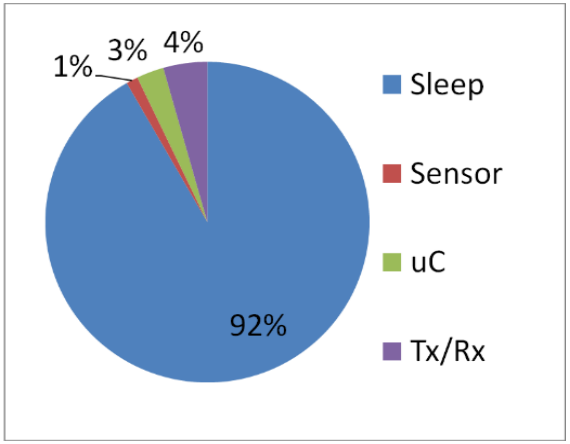




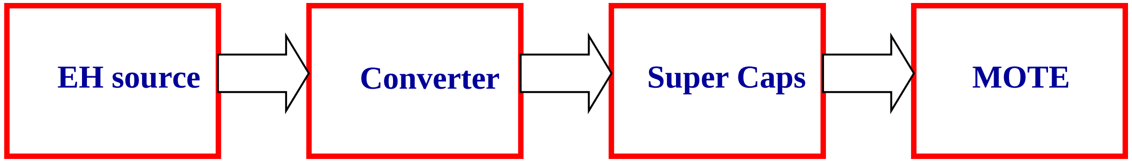
- Example from previous work done under VIBES Project in collaboration with University of Southampton.
  - Electromagnetic based vibration generator
  - Generated 50 uW from 50 Hz, 0.58 m/s^2 vibration
  - Demonstrator device could power a WSN node from vibrations in air conditioning unit.
  - Could measure acceleration and transmit reading approximately every 3 seconds

Summary & Conclusions (part 2)

- EH is critical for self-powering of Wireless Sensor Networks
- EH in real applications requires
  - Lowest possible Duty Cycle
  - Selection & correct use of key components (uC, Tx/Rx, sensors, supercaps)
  - Selection of suitable low power RF network and software
  - High efficiency transfer to usable Voltage (MPPT & DC/DC)



- Successful EH case studies powering Tyndall mote based on
  - Thermoelectric
  - Vibration
  - Indoor solar
- For BEM applications a self-powered mote is possible at 50uW



Design tips

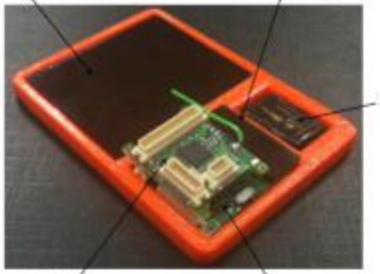
- There is no panacea – design a harvesting solution based on your specific need and fine tune it
- Set realistic targets for your energy source and load
- Turn over every component to explore possibilities for reductions – every nW counts
- Get to know intimately the various power down/idle/sleep modes of your microcontroller
- Look at optimising the impedance of source and load
- Understand variability in ambient energy source and what can be done to give decent power over a broad range
- Use modelling to assess optimal system level performance and do scenarios analysis
- Look at WSN architecture – it is really 'energy harvesting centric' – all opportunities to minimise system level power consumption being used?
- Determine what is the least duty cycle you can use & can it be adapted based on energy available and application needs

PART 3
Target Applications for 'Powering the IoT'

Introduction

- WSN* nodes are ultra low power IoT devices that wirelessly capture data.
- Easily retrofitted on, in or near equipment, people and infrastructure
  - Gather & share additional sensory data & enable better context based monitoring & control
- Many uses - smart grids, agri-tech, wearables, smart mobility, smart cities.
  - Asset tracking (equipment, people, goods)
  - Heating and lighting optimisation
  - Conditional monitoring, detecting anomalous behavior enabling predictive maintenance
- Tyndall has developed a modular platform, used for >50 applications
- Major impediment to large scale WSN adoption is need for battery replacement.
  - Impractical (logistics, access) & uneconomical
  - Also impacts system reliability & data integrity
- Energy harvesting uses ambient energies as a power source
  - Eliminates need for replacing batteries
  - (or at least extends battery life)

*Wireless Sensor Network



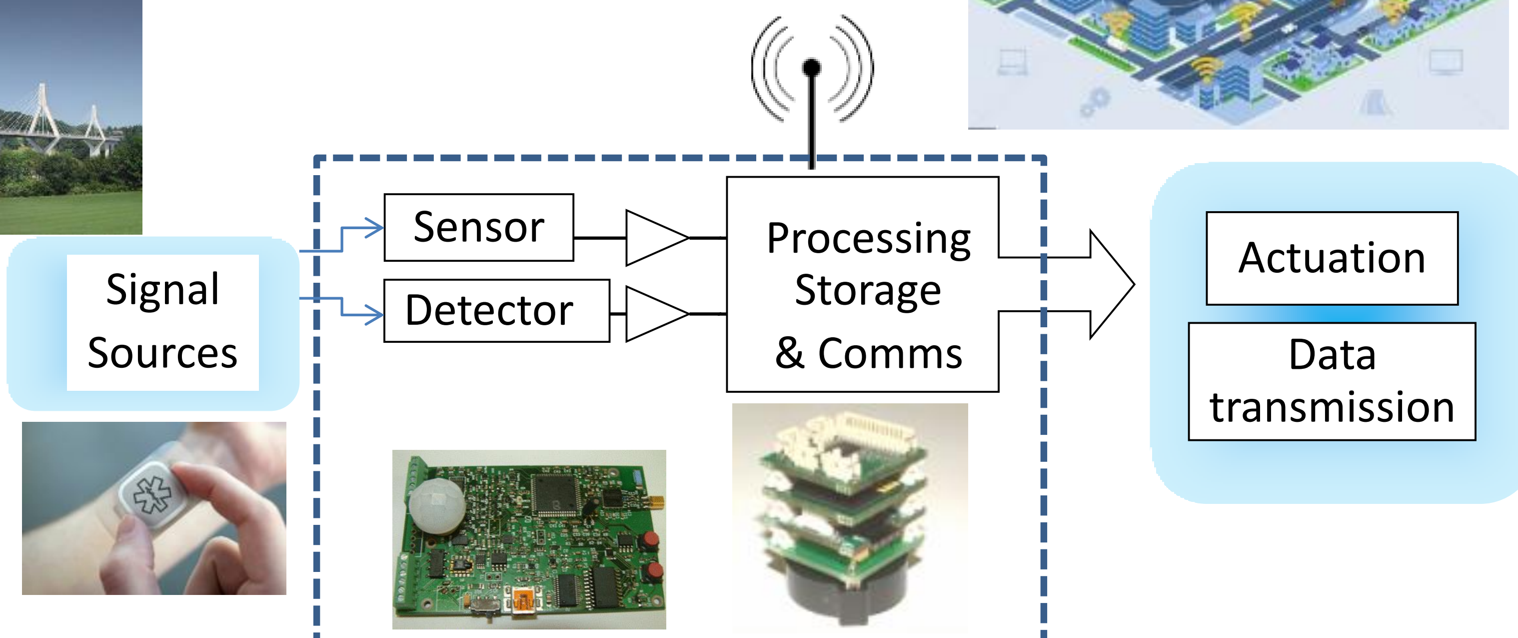
Introduction - IoT WSN Needs & Applications

Take Up No Space **Cost Nothing** **DEPLOY & FORGET**

Last Forever **Zero Power**







Technologies and Applications

Technologies

- We are supplying some combination of
  - **Energy Harvesting* (EH)** platforms,
  - hardware system integration and
  - testbeds

  in several projects

Applications

- Energy Efficiency in Buildings and Micro-grids
- **Conditional Monitoring* (CM)** of Machines, Equipment & Infrastructure
- **Asset tracking***

- Some examples on the following slides

*** Main focus of this presentation**

Tyndall Introduction
National Institute for ICT research & development

- **Host to various research centres**

CONNECT Networks of the Future — MCCI Microelectronic Circuits Centre Ireland — iERC International Energy Research Centre — IPIC Bringing Photonics to Life

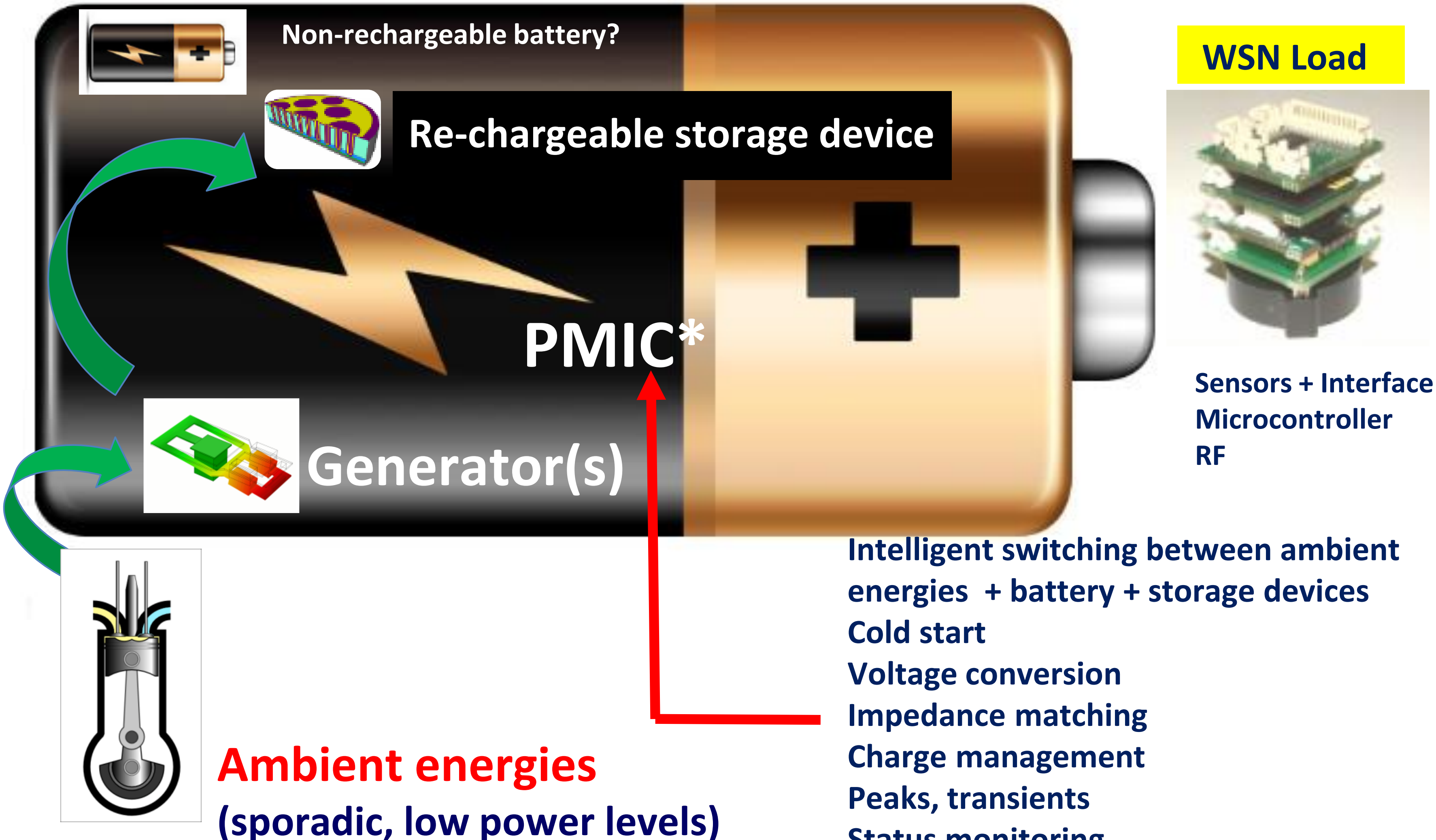
'Things' for IoT *	***Microelectronics***	***Energy Efficiency***	***Photonics***

**** HQ in TCD***

Technology - Energy harvesting

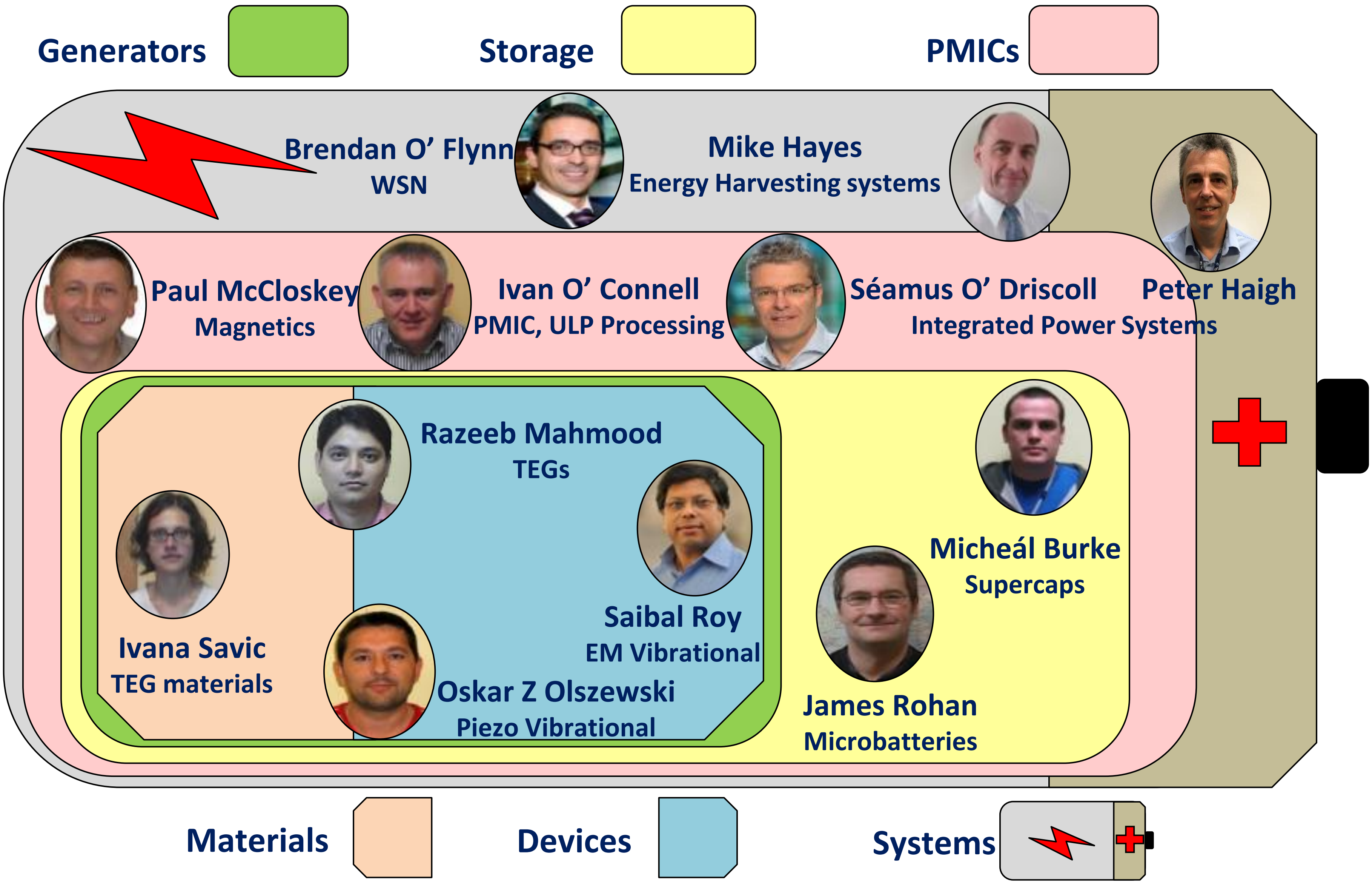
Replacing the function of a battery is not easy

- Complex array of stuff to be integrated



*Power Management IC

Tyndall has an Ecosystem of PIs to address this



A One Stop Shop - Tyndall Energy Harvesting & Storage

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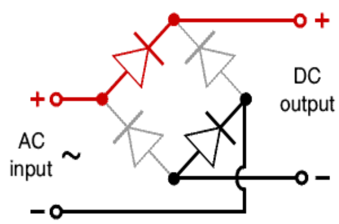
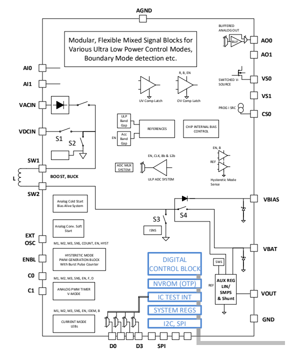
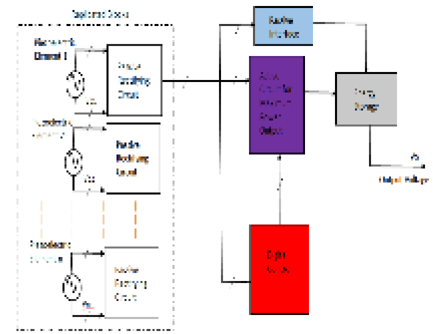
Control

Power Management ICs & Circuits
Multi-source
Self-start
High efficiency

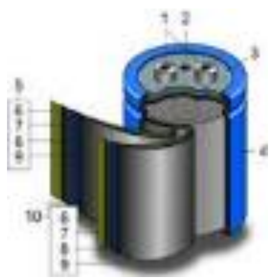


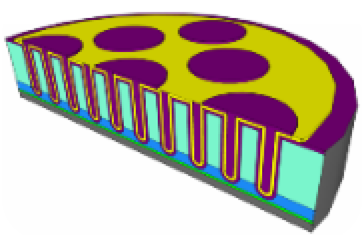


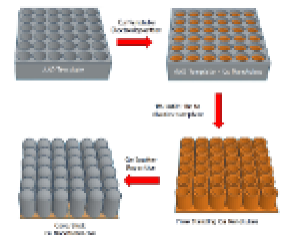


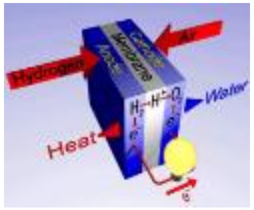
Storage

Supercaps on Silicon
Flexible batteries
Micro-batteries
Nanotube high density



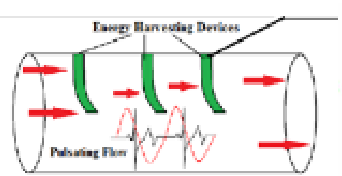


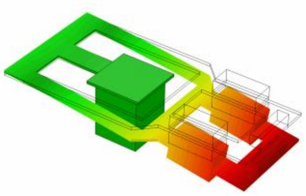


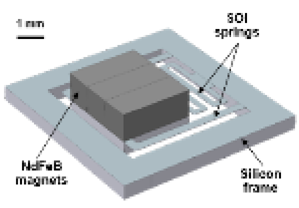


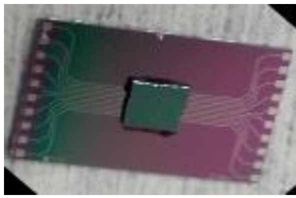
Generation

Generators on silicon
Wide bandwidth vibration
(Electromagnetic & piezo)
High density MEMS
IC integrated highest efficiency TEG materials



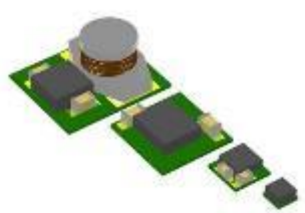


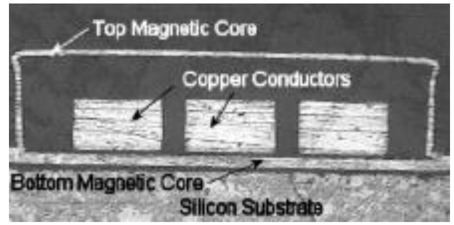


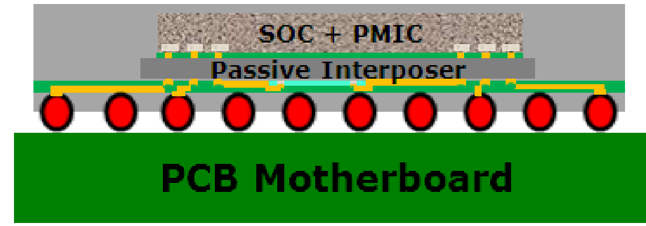


Material, Device & System Integration

Embedded Magnetics

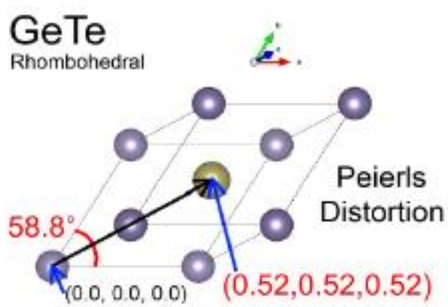




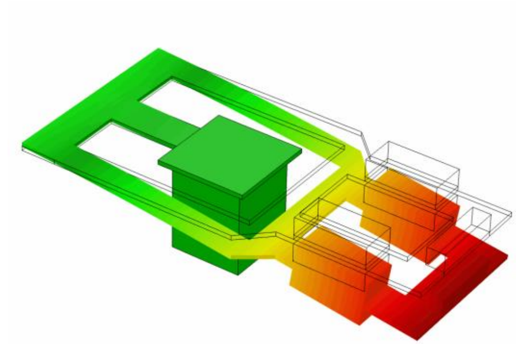


Making magnetics disappear in packages (PSiP) & onto ICs (PwrSoC)

Simulation



Atomic/material



Physical/mechanical

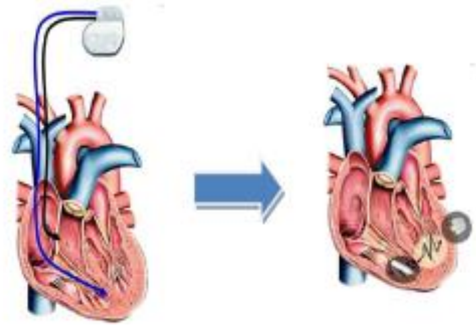
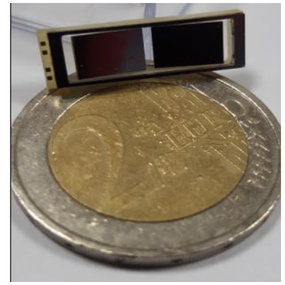
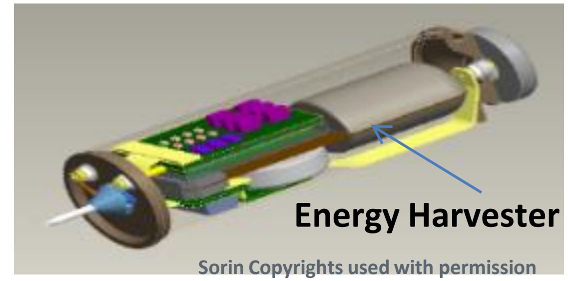
Design/Deployment tool
Circuits (discrete & CMOS)

The Power of Collaboration

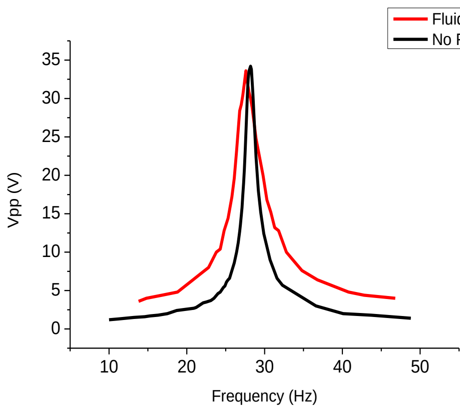
System application optimised parts & devices e.g.

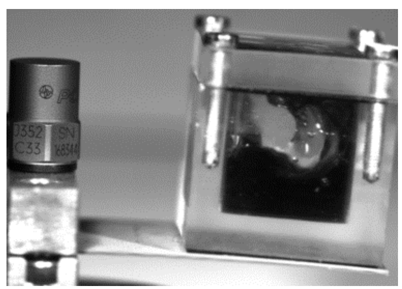
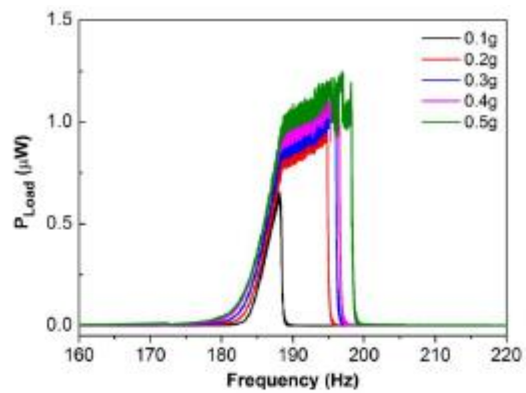
- **Harmonise methodologies & specifications**
- **Compatibility:- Process, Electrical, Packaging**

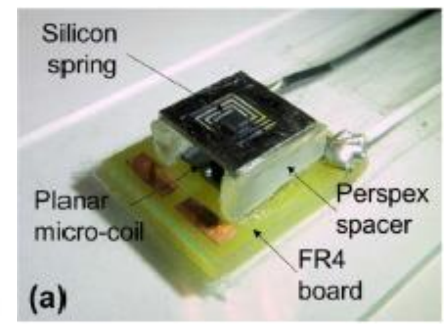
Some Application System Integration Examples

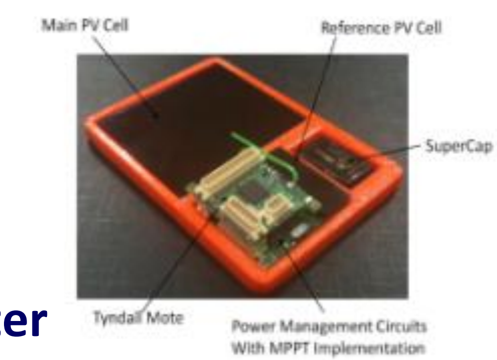
Miniaturisation:- Implantable Energy Harvester





Performance enhancement:- Wide bandwidth Vibrational Energy Harvesters

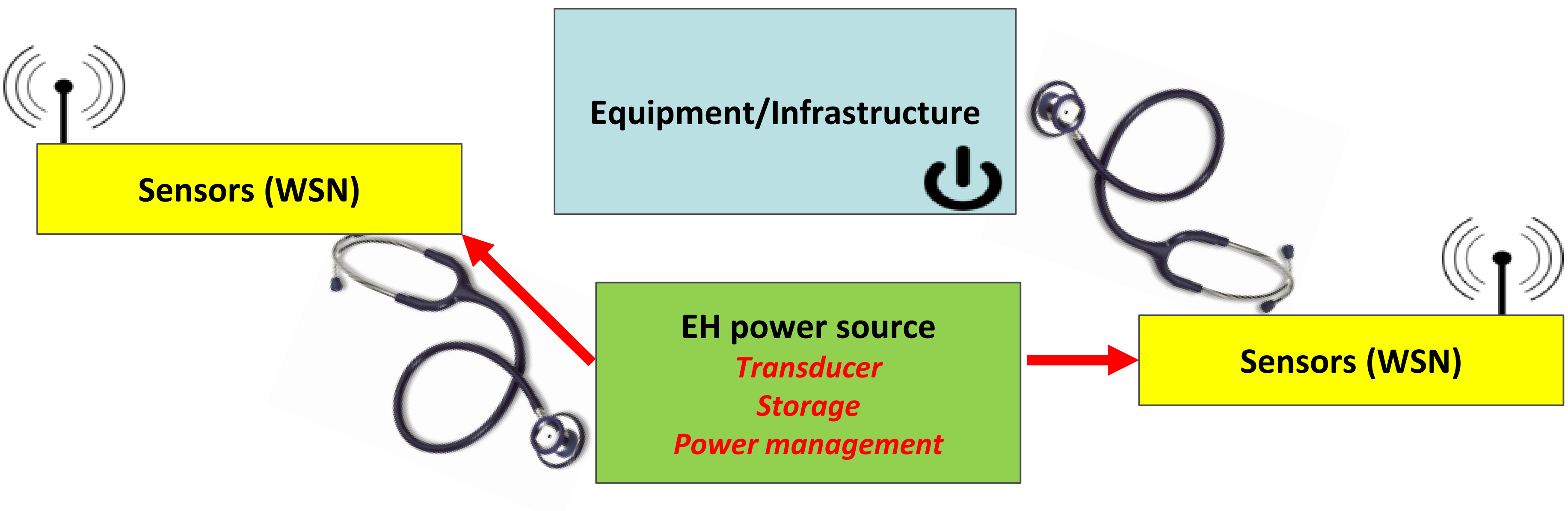



Circuit and system innovation:- Indoor solar energy harvester

Application – Conditional Monitoring

- Smart cities need a **'nervous system'** to check all the equipment & infrastructure is operating as expected
- We call this Conditional Monitoring (CM)
- It often needs **its own independent power source** (battery/energy harvester) so that it can independently report on an anomaly/failure

- Going a layer deeper we may also need Conditional Monitoring of the power source itself



- *Are the transducer, storage element, power management circuit working?*
- *Are we getting enough ambient energy?*
- *Is the WSN operating correctly?*

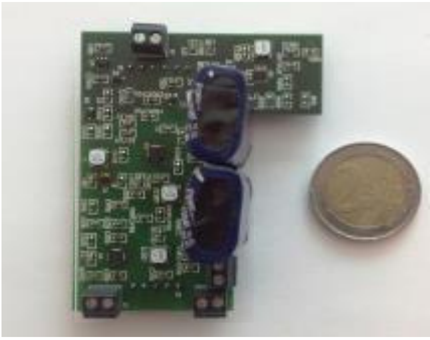
Powering IoT - ICT for Factory Efficiency Examples

MOSYCOUSIS

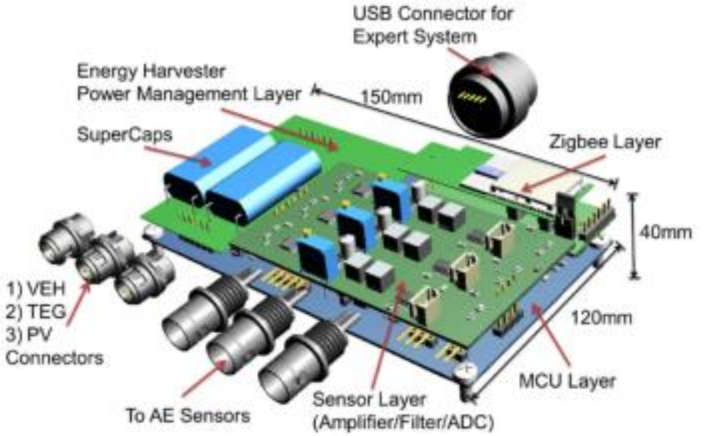
COMPOSITION

Energy Harvesting Application

- Tyndall Hardware developed:-
  Multi-source energy harvester & power management layer



- Consortium development:-
  Acoustic Emissions Wireless Analyser



Impact

- Solution is wireless and non-contact - easy to retrofit
- >2mW (target) of ambient energy harvested (Vibration, thermoelectric, indoor PV)

COMPOSITION

EU FoF project

Tyndall National Institute
Institiúid Náisiúnta

Ecosystem for COllaborative Manufacturing PrOceSses – Intra- and Interfactory Integration and AutomaTION

- Creating a digital automation framework (IIMS) that optimizes the manufacturing processes by exploiting existing data, knowledge and tools to increase productivity and dynamically adapt to changing market requirements.
- This technology acts as the technical operating system for new and existing business connections between factories and their suppliers.
- **Tyndall role:** Supply expertise in WSN at component, device and system integration level for both modelling and real time operation of the use cases (particularly retrofit of self-powered sensors for inter-factory use cases)

Fraunhofer FIT | Boston Scientific | KLEEMANN | CNet
NEXTWORKS | ΕΛΔΙΑ | Tyndall | IN-JET
iti Information Technologies Institute | ATLANTIS | ISMB Istituto Superiore Mario Boella | Atos

(Grant Agreement No 723145)

Use case 1 – Asset Tracking

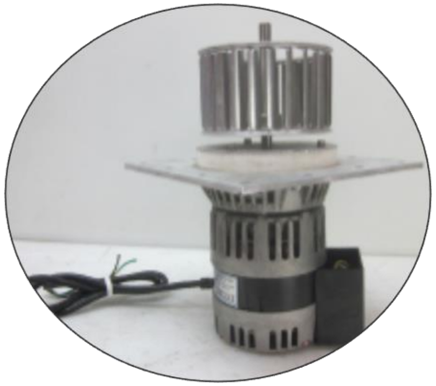
‘Physical security’ – Track & Reduce Loss/Misplacement of Valuable Assets

- Place tags on valuable parts:- Reels, PCBs, headers, test jigs, etc.
  - Direct losses – asset value (e.g. expensive ICs, palladium wires,)
  - Indirect losses - delays to production through being unable to source the asset (test fixture, replacement component reel in stores)
- Good example of cross-functionality needed to solve issues
  - Energy harvesting, WSN, RFID/localisation techniques, data fusion, production equipment & processes, application needs
- Need to devise methodologies that minimise power consumption of the tag for energy harvesting compatibility
- Need to assess ambient energies, e.g. 8 hours of indoor light with a 40x40mm2 cell will on average supply ~ 150uW.

Use case 2 – Conditional Monitoring

Fans (blowers) in SMT reflow ovens wear out

- **Current procedure:-** Fans become noisy and investigated manually
- Some material scrap possible due to oven malfunction & shutdown
- Non-optimised maintenance and process disruption
- Relies on vigilance of operatives
- Expect to see/hear increase from 70-80dB to ~ 90-120dB.



- **New procedure:-** Fan noise will be measured using acoustic sensors
- Predictive failure will reduce scrap caused by oven malfunction
- Retrofitting of self-powered sensors using energy harvesting makes installation easier & maintenance free
- Starting a new project in October doing energy harvesting powered condition monitoring sensors for building integrated PV system

Use case 2 – Conditional Monitoring

Data fusion opportunities & benefits:-

- Use simpler acoustic sensors &/or lower power consumption?
  - Duty cycle of acoustic sensors governed by other data that is already being gathered
  - e.g. change/rate of change of power consumption/ airflow (velocity/volume)
  - e.g. temperature ‘map’ across the oven
- This could also enable earlier replacement of fan and for its replacement to be scheduled in a non-disruptive manner.
- Lower risk of defects due to process variations e.g. change in temperature ‘map’ across the oven if one blower is now less efficient.

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Powering IoT - Energy Efficiency in Buildings and Microgrids

MEB gas

GreenCom

RoWBUST

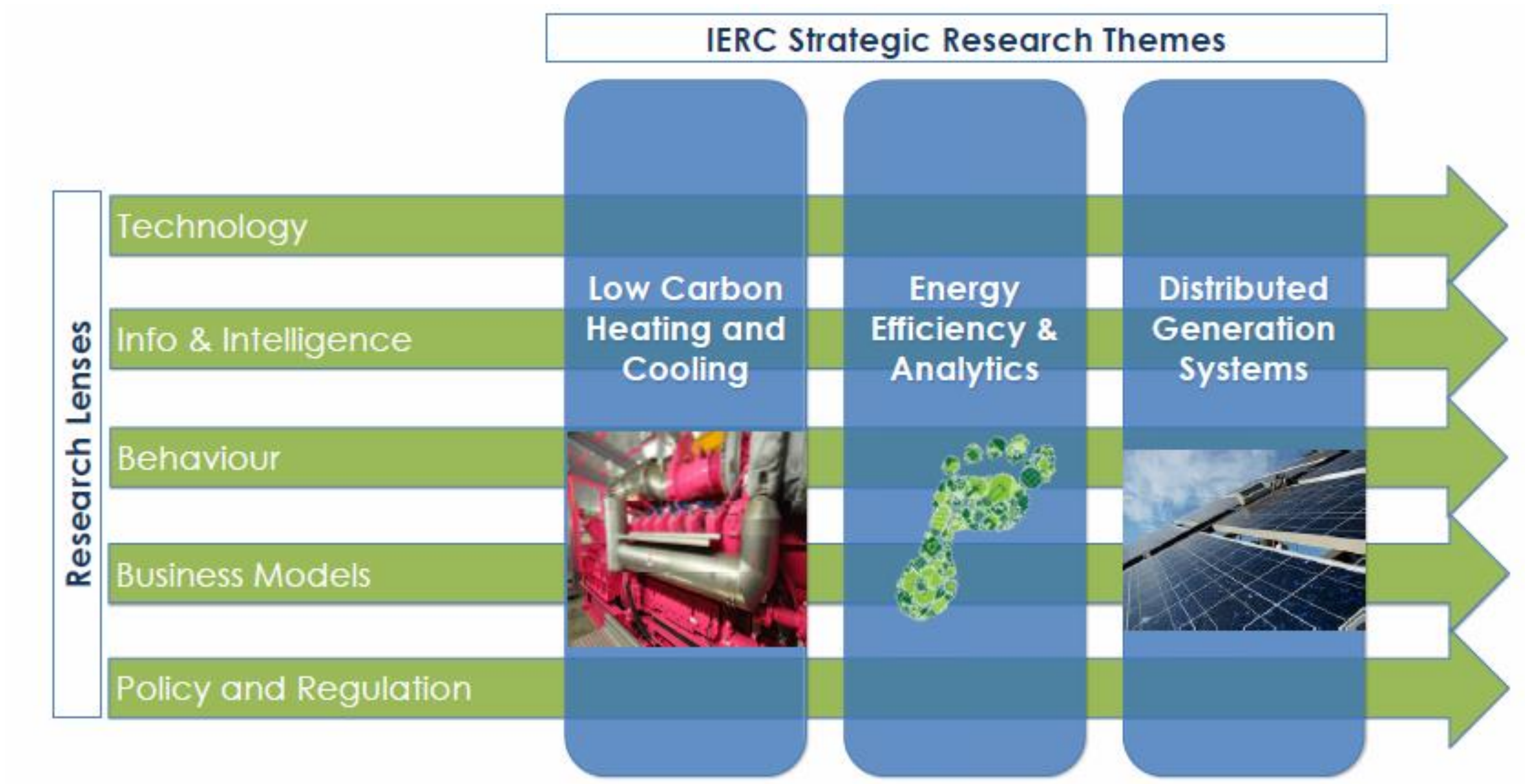
MOEEBIUS

$ReCO_2ST$

UCC

European Union
European Regional Development Fund

IERC Introduction

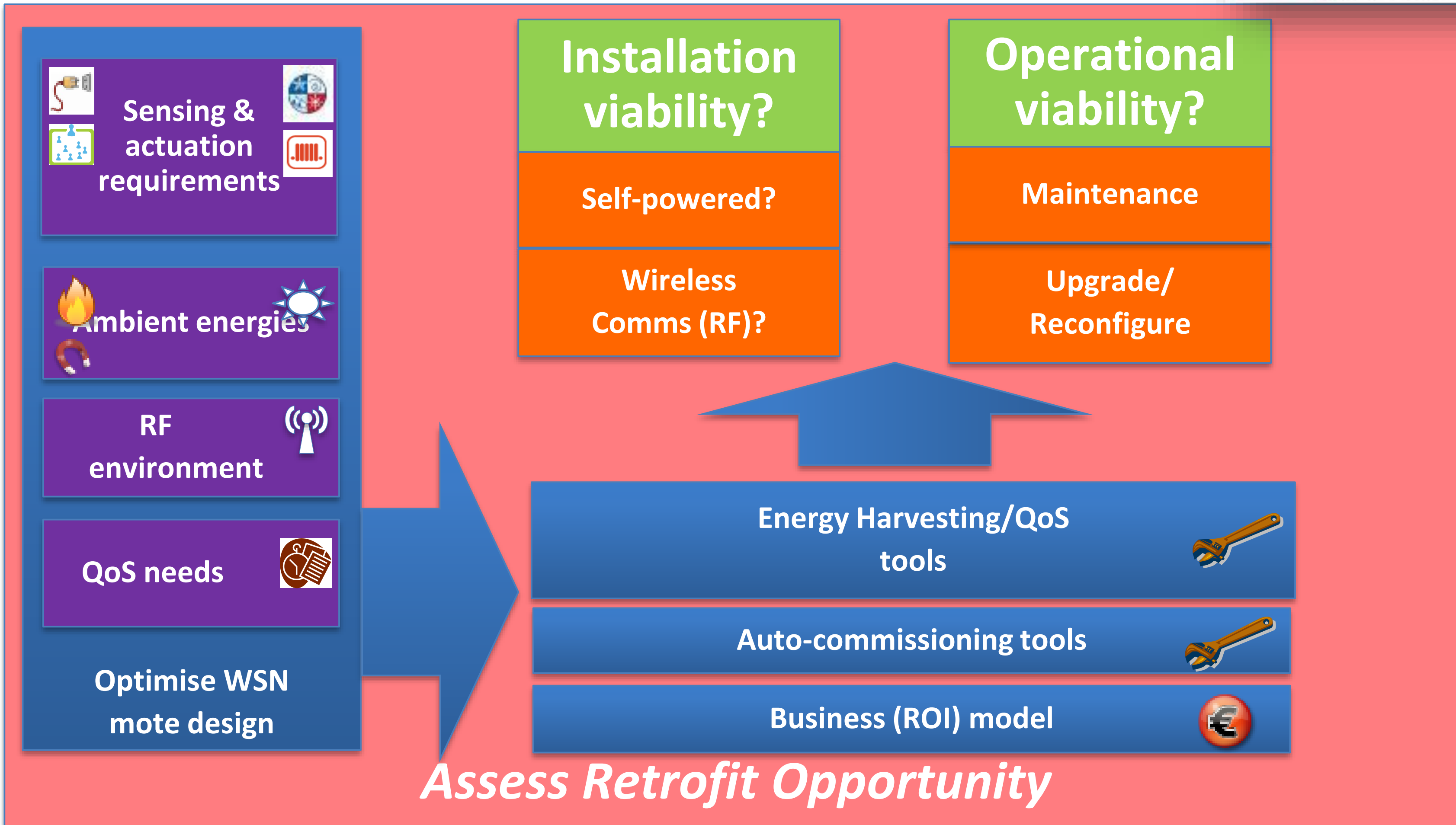


An Irish Government supported, collaborative energy research centre that responds to industry-driven energy challenges within the commercial and residential sectors

Translates industry needs into research objectives to deliver sustainable energy systems solutions

Hosted at Tyndall

ROWBUST –WSN simulation model visual representation



- Developing models to help plan, install and maintain WSN
- Determine if Energy Harvesting can work
- Determine if a good return on investment can be made

Basic Model Energy Harvesting Powered WSN

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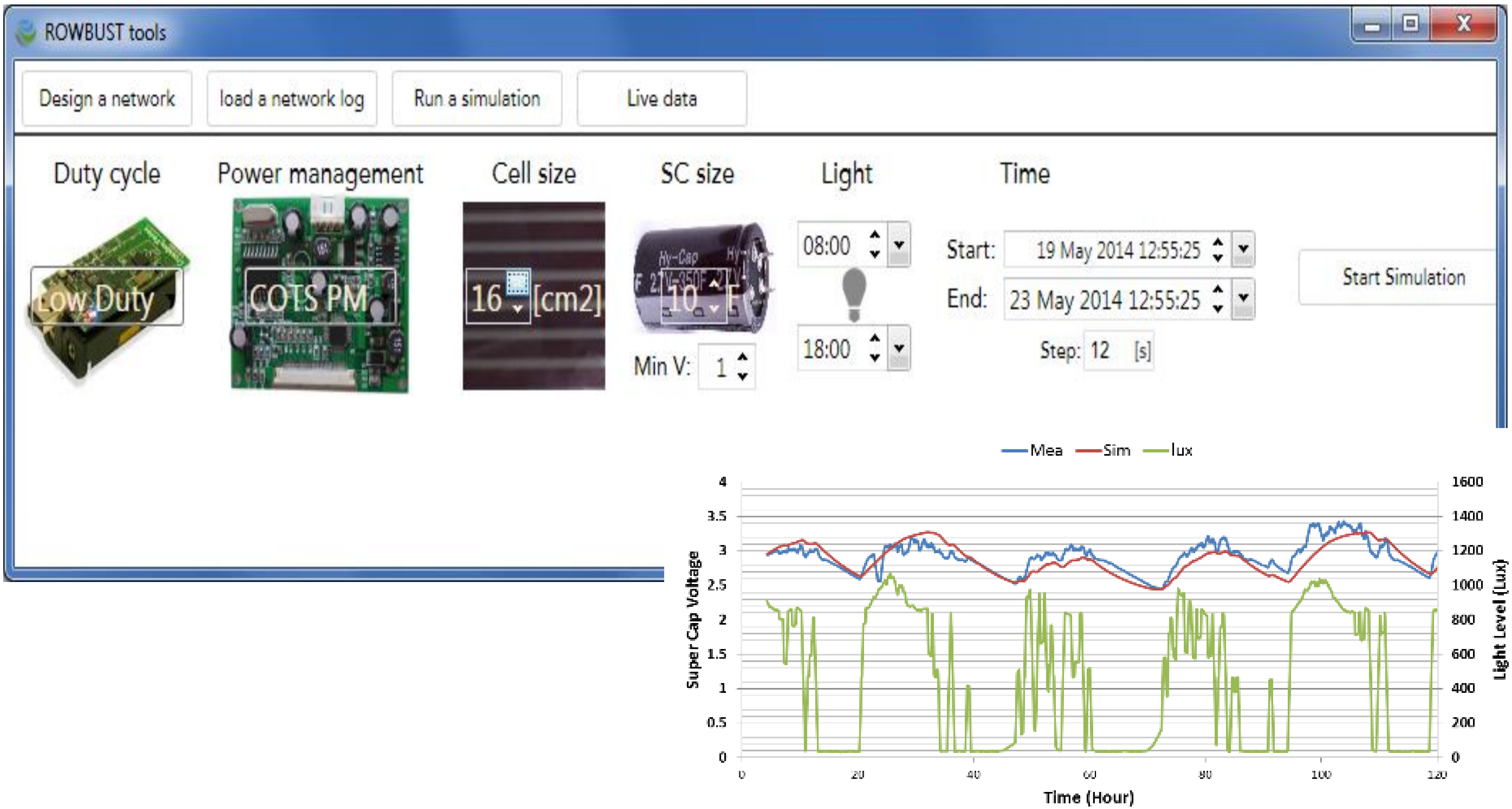
Help installers select hardware components for a potential energy harvesting deployment

No Energy Harvesting or WSN expertise needed



Practical use case –
Battery replace, existing equipment

- Use ROWBUST models to design & build an energy harvesting module ('kit')
- Replace the AA battery pack on Danfoss 'living connect' with the EH kit
- We are already using this on 3 EU projects, COMPOSITION, ReCO2ST & MOEEBIUS**

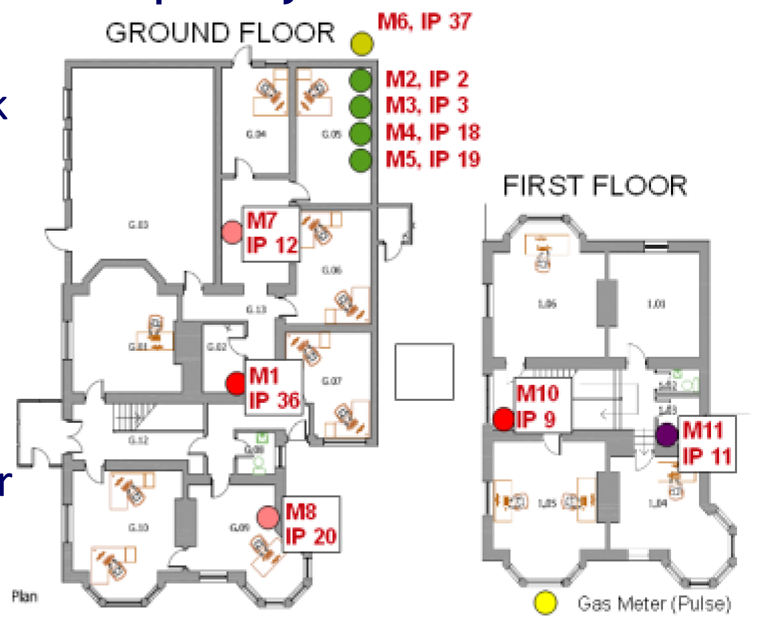
The set temperature can be changed on *living connect®* by using the buttons or on Danfoss Link™ CC.

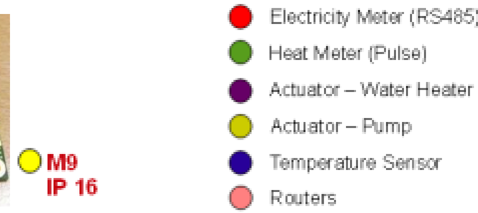
The temperature changes is transmitted to the Danfoss Link™ CC, which will synchronize other *living connect®* thermostats in the same room.

** Modelling for Optimisation of Energy in Buildings – Tyndall WSN & EH activities

ME3Gas Pilot – Crossleigh House UCC

- **Show inter-operability of Wireless Hardware, business GUI & ME3Gas middleware**
- **Demonstrate actuation & control capability**

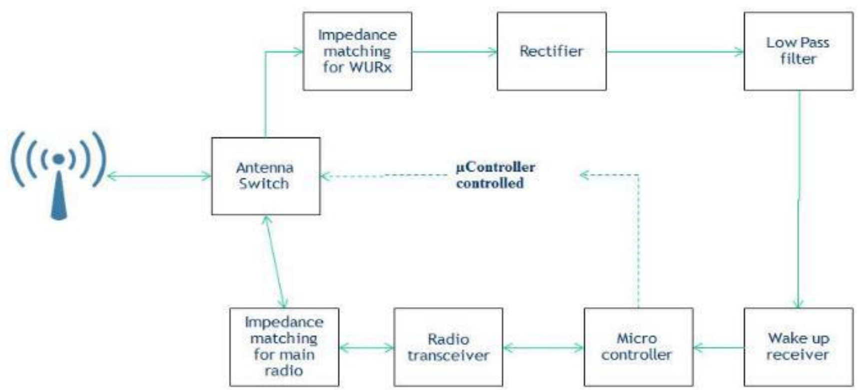




- Hosted by Tyndall & Arup Cork
- Measure temperature, light, humidity, heat pump energy, electricity
- Wireless sensors control radiators and under-sink water heater
- **Energy harvesting** powered independent wireless sensing of gas usage

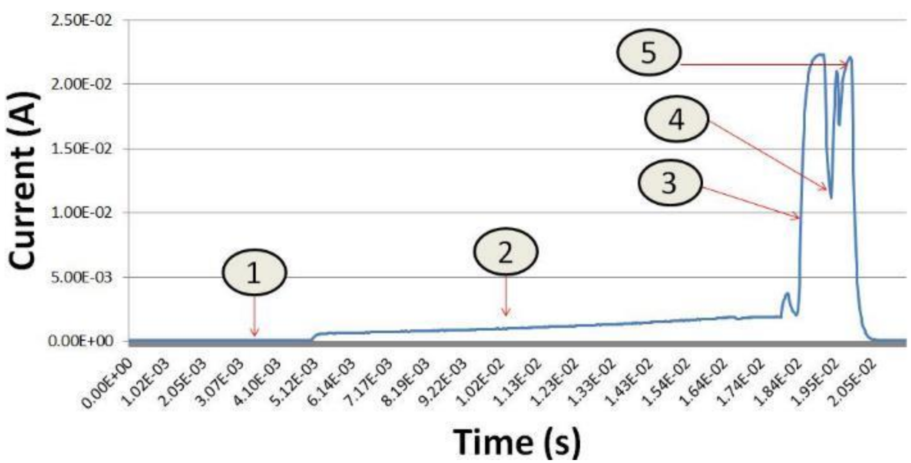
Tyndall task - How to improve reliability of WSN architectures?

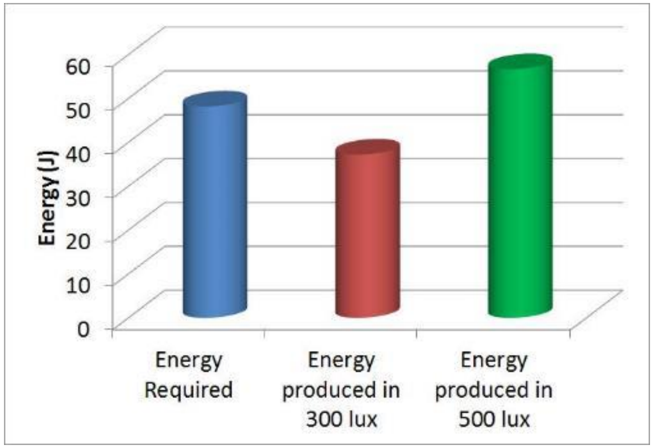
- Did a series of experiments on low power listening (LPL) WSN architectures to determine reliability and energy harvesting compatibility
- Enables devices to be in listening mode and capable of reacting to events rather than just waking up at given intervals
- Conventional devices use 'duty cycling' - go into sleep mode in order to save battery and wake up periodically
- Duty cycling unsuitable for 'event based' applications – PIR, safety, security, etc.



Some results – Energy harvesting compatibility for a selected LPL solution

Stage	Duration (s)	Average Current (A)	Consumed power
(1) Sleep Mode		18.6μA	
(2) Oscillator stabilise	13.4ms	1.2mA	40.2μW
(3) RX mode	717μs	17.7mA	31.7μW
(4) Receive to Transmit transition	389μs	14.2mA	13.8μW
(5) Transmit mode	369μs	19.1mA	17.6μW
(6) Transition to sleep mode	451μs	12.5mA	14.1μW





(Credit card sized indoor solar panel)

Conclusion – could self power a WSN device in LPL mode with around 400lux (lower if PV panel made larger)

Acknowledgements

- This work was sponsored by the following projects

MISCHIEF **ITOBO**

- I would like to take this opportunity to thank the ICT4EE team at Tyndall.

Thank You

Tyndall