Yogesh Ramadass, Texas Instruments, Energy Harvesting: Past, Present and Future

The area of energy harvesting has seen significant interest in academic circles over the past decade and a half. A host of research articles have been published looking into various aspects of energy harvesting from power sources and energy storage to power management IC's and low-power loads. The introduction of specialized harvesters, unique storage devices and commercial ICs geared for energy harvesting applications is helping the technology move from academic environs into commercial adoption promising a future of self-powered electronics in applications geared towards improved quality of life, industrial automation and connected health to name a few.

In this talk, I will explore the last ~15 years of the energy harvesting industry to understand how we got to this point in the ecosystem of the industry and the key technological advancements being pursued to continue to propel the commercial adoption into the future.

Eric Yeatman, Imperial College London, Alternative Powering Methods for Miniature Wireless Sensors

As wireless electronic devices continue to proliferate, removing the maintenance burden of battery replacement or wired recharging becomes ever more attractive. Wireless sensors present a particularly compelling application, as in many desired applications they will be large in number, and difficult to access for maintenance, while having modest power requirements. At Imperial College we have developed a variety of alternative powering methods, including kinetic energy harvesters, dynamic thermoelectric harvesters, resonant inductive charging systems, and ultrasonic power delivery. In this talk we will present these methods, and discuss their current and potential performance capability, their suitability for specific applications, and likely future developments.

Ausrine Bartasyte, FEMTO-ST, From Green Piezoelectric Materials to Designed Hybrid Piezoelectric Energy Harvesters

At present, many different ferroelectric ($PbZr_{1-x}Ti_xO_3$ (PZT), $BaTiO_3$ (BTO), $K_{1-x}Na_xNbO_3$ (KNN), etc.) and non-ferroelectric (AlN, ZnO) piezoelectric materials in the form of films, nanostructures and ceramic/crystals bonded on wafers are explored for the fabrication of piezoelectric vibrational energy harvesters (PiViEHs). However, in future, PZT maybe has to be replaced by lead-free materials, even for thin films. Ferroelectric material, such as $LiNbO_3$ (LN) presents FoM similar to that of PZT. Moreover, LN is compatible with high-temperature applications of transducers (up to 1000 °C) and EHs (at least up to 500 °C) while PZT, BTO and KNN loss their piezoelectric properties at these temperatures. However, the application of these materials in PiViEHs is still very little studied and considerable efforts have to be done towards their integration to the conventional processing of MEMS.

Hybrid harvesters (i.e. ones which combine more than one type of harvesting transducer) have had increasing interest in the literature but the bulk of the work has simply involved adding multiple individual transducers placed into one package. Our research concerns the possibility of using an individual transducer element to scavenge multiple types of energy, i.e thermal and vibration. It was reported that combining piezoelectric and thermal effects could amplify the displacement in piezoelectric actuators, which therefore demonstrates that generated charges can be increased with a structure dedicated for hybrid harvesting.

Dhiman Mallick, Tyndall National Institute, Broadband Vibrational Energy Harvesting using Nonlinear Systems

The ‘Internet of Things (IoT)’ envisions a world scattered with physical sensors that collect and transmit data about almost anything and thereby enabling intelligent decision-making for a smart environment. The technological limitations of electrochemical batteries for powering ‘IoT’ devices has led to research into harvesting alternative ambient energy sources like mechanical vibrations due to its wide abundance in nature. However, limited applications of conventional resonant devices under most practical environments involving frequency varying inputs, has gushed the research on wideband transducers recently. Such a solution needs to be cost-effective to the consumer market, and topologies need to address unique application environments.

This talk will outline some of the disruptive solutions using nonlinear systems to address these challenges, employing Meso-/Micro-/Nano-technologies for developing Vibrational Energy Harvesting (VEH) devices on 3D printed polymer, micro-machined FR4 (PCB) and batch fabricated silicon with wide bandwidth of operational capability. By mechanical topological variation, ~80 Hz operational bandwidth is obtained from a MEMS device, 40 times higher than that of a linear counterpart, which is benchmarked using a novel figure-of-merit. The fundamental phenomenon of multi-stability limits many nonlinear oscillator based applications including energy harvesting. To address this, an electrical control mechanism is introduced which significantly (35 times) improves the energy conversion efficiency over a wide bandwidth in a frequency-amplitude varying environment using only a small energy budget. Some of the solutions described here could potentially enable autonomous and ubiquitous sensor nodes within the web of ‘IoT’, while opening the scope for new application spaces.

Jane Cornett, Analog Devices, Optimization of Chip-scale Thermoelectric Energy Harvesters for Room Temperature Energy Harvesting Applications

Thermoelectric energy harvesters (TEHs) are devices capable of converting low levels of heat into electrical power on the order of 10s to 100s of µWs. The chip-scale TEHs developed by Analog Devices, Inc. (ADI) are designed to power a wireless sensor node or other small device from thermal energy sources close to room temperature. These devices are based on bismuth telluride- (Bi2Te3-) related compounds (one of the best thermoelectric materials at room temperature), and make use of an ADI-patented device architecture designed to optimize the temperature gradient across the thermoelectric materials. In this talk, we will present design and modeling, thermoelectric material improvement and process development of the ADI chip-scale TEHs, and the role that each of these steps plays in device optimization. In addition, we will present a machine health monitoring wireless sensor node powered entirely by TEH—a physical example of thermoelectric energy harvesting in action. Thermal and mechanical design of the sensor node around the TEH will be discussed, highlighting the importance of material choice both thermally in series and in parallel with the thermoelectric device. The system architecture and component selection to enable ultra-low-power operation and compatibility with energy harvesting will also be described.

Brandon Lucia, Carnegie Mellon University, Reliable Software and Programming for Intermittent Energy-Harvesting Systems

Emerging "intermittent computer systems" operate using energy harvested from their environment, even from low-power sources like ambient radio-frequency energy. These systems will be a key enabler of emerging implantable medical devices, IoT applications, and nano-satellites. However, these computer systems operate intermittently, only as environmental energy is available. Intermittent operation makes systems unreliable and extremely difficult to program and debug. In this talk I will describe how intermittent computer systems run software in an unfamiliar and unintuitive "intermittent execution model". I will summarize the main software programming and debugging challenges that stem from the intermittent software execution model, including memory inconsistency, lack of forward program progress, and difficulty meeting I/O timeliness constraints.

I will then discuss our recent efforts developing system, programming language, and software development toolchain support to address the challenges of intermittent computing. I will describe Chain and Alpaca, two related programming languages that provide programmers with a simple, task-based programming model, while using static and dynamic analysis to ensure data remain consistent, despite power interruptions. I will describe EDB -- the Energy-interference-free Debugger -- which is the first hardware/software system designed to help programmers debug intermittently executing software running on energy-harvesting devices. EDB provides new debugging capabilities, allowing debugging a target running on harvested energy without interfering with its energy supply. EDB provides abstractions that link high-level software events (e.g., code watchpoints) and low-level energy events (e.g., input voltage variation), which are useful for understanding intermittent execution (mis)behavior.

I will close by discussing an upcoming full-system deployment effort centered around a novel, energy-harvesting nano-satellite platform that integrates many of our recent hardware and software developments.

Mehmet Ozturk, North Carolina State University, Flexible Thermoelectric Generators with Bulk Thermoelectric Materials and Stretchable, Low-Resistivity Liquid Metal Interconnects

Thermoelectric generators (TEGs) that can convert waste heat into electricity are of great interest for a variety of applications ranging from self-powered wearables to industrial applications with continuous sensing needs. For many of these applications, flexible TEGs that conform to the shape of the heat source are highly desirable. For wearables, a flexible TEG would provide a better contact to the skin and reduce the thermal contact resistance between the body and the device. A variety of approaches have been previously proposed for manufacturing flexible TEGs. Unfortunately, none of these approaches were able to produce flexible TEGs that were able to rival the performance of their rigid counterparts.

In this talk, we will review a novel approach to flexible thermoelectric generators that can rival the performance of their rigid counterparts. We will provide the details of the manufacturing process and summarize our current efforts on system optimization through modeling and development of new materials with high or low thermal conductivities as needed in different parts of the modules. We will also provide on-body measurements of the electrical power generated under different ambient conditions and a live functional demonstrations of flexible TEGs.

Luis Martins, Boston Scientific Limited, COMPOSITION – Industry 4.0 IoT Device Retrofit and Energy Harvesting Use Cases

COMPOSITION is an EU 'Factories of the Future' project led by Fraunhofer FIT that develops inter-operable systems for inter and intra-factory collaborative systems. Boston Scientific Limited (BSL) Clonmel is working with Tyndall in determining potentially where IoT devices can be retrofitted in or near equipment and infrastructure in their medical device factory to improve energy and resource efficiency. The presentation will focus on the 2 high priority use cases selected

(i) sensors for tracking high value assets (high value component reels, test fixtures, measurement and inspection equipment)

(ii) condition monitoring of reflow oven fans for predictive maintenance by detecting fan wearout (using acoustic and power sensors)

To date the work has focused determining the appropriate types of sensors and wireless infrastructure on selecting commercially available and emerging platforms. Systems have already been installed in BSL gathering reference data and prototyping both use cases. The next stage involves determining to what extent IoT device power consumption can be reduced (based on hardware platform selection, sensor data granularity & duty cycle and data gathering infrastructure) to extend battery life and also if ambient energies are available potentially for device self-powering.

Denis Pasero, Ilika, Review of Energy Storage Solutions for IoT Edge Nodes

This paper will describe the challenges in meeting specifications placed on autonomously powered, wireless sensors for Internet of Things applications, and will review available storage options including conventional lithium ion batteries, coin cells, Li-polymer pouches, other liquid-electrolyte chemistries, solid state batteries and supercapacitors.

Trends towards miniaturisation are desirable for most applications where sensors would ideally be "invisible", which is not always achievable for incumbent technologies like conventional lithium batteries due to the level of packaging required to prevent the liquid or polymer electrolyte from leaking out, even though new coin cells of few mm^3 now exist. At the mm-scale of implantable medical devices, solid state batteries offer variable sizes and shapes but energy density does not yet compare well with coin or pouch cells, although this paper will describe ways of stacking cells to increase density. High accumulated energy densities and long life may be achieved by combining secondary power sources with harvested energy if the capacity of the former can be matched with the efficiency of the latter. To become truly autonomous, both on day to day basis (24/7 operation) and for long times, energy buffers need to be efficient at storing electrical current, with on-going work taking place to improve the efficiency of caps and supercaps for example. On the other hand, it is often advantageous to combine these high power components with high energy, low leakage components like solid state batteries.

Finally, the various storage alternatives will be compared in terms of cost and operational demands (such as high temperature for industrial sensors or bio-compatibility for medical devices).

Pierre Mars, CAP-XX, Using Supercapacitors to Manage Your Power

This presentation will outline the properties of supercapacitors that designers should be aware of and provide case studies using supercapacitors with low power energy harvesters such as small solar cells, RF charging, and a vibration transducer which provide sub mW power to enable wireless sensors to transmit data at high power from ~50mW for BLE to watts for cellular transmission.

Thomas Fletcher, Cambridge Display Technologies, Progress in Printable Energy Harvesting and Storage Devices

Many applications such as wearables and autonomous wireless sensors will require the development of a new generation of thin and flexible/conformable power sources. In addition to flexible energy storage, the use of energy harvesting will be required to circumvent the need for labour intensive battery replacement for autonomous systems. To address these needs, CDT is developing a number of energy harvesting and storage technologies, including printable thermoelectrics, battery/supercapacitor hybrids and organic photovoltaics. In this talk, we will give an overview of the status of these technologies, with special focus on the recent progress in the area of thermoelectric generators.

Roberto La Rosa, ST Micro, A System on Chip for Energy Harvesting and Wireless Power Transfer

This talk is motivated by the continuous development of IoT (Internet of Things) infrastructure and applications, which are paving the way to advanced and innovative ideas and solutions, some of which are pushing the limit of state-of-the-art technology. The increasing demand of WSN (Wireless Sensor Nodes) which need to be capable of collecting and sharing data wirelessly, while often positioned in places hard to reach and service, motivates engineers to look for innovative solutions of energy harvesting and wireless power transfer to allow battery-free sensor nodes. RF harvesting and wireless power transfer, due to the pervasiveness of RF energy, that can reach out of sight places, could be a key technology to wirelessly power IoT sensor devices, that in order to be ubiquitous, need to be wires, maintenance free, battery free and low cost enough to be used almost anywhere. A System on Chip is presented to be used either as RF power receiver and as a Ultra Low Power high performance power management for multi source energy harvesting. Several different possible applications examples are shown.

Katherine Kim, Ulsan National Institute of Science and Technology (UNIST), Power Circuitry Design Considerations for Photovoltaic Energy Harvesting Applications in Uneven Lighting Conditions

Photovoltaic (PV) cells are widely used to provide renewable energy to the ac electric grid, but they are also viable power sources for lower power energy harvesting applications. In outdoor applications, PV cells can provide a high amount of power compared to vibration, thermal, or RF-based transducers.

Thus, PV power is appropriate for many wearable or mobile tracker applications. However, these kind of application have a high probability of experiencing uneven lighting or partial shading. Traditionally, PV cells are connected in a series string, but it is well known that imbalances in the PV cell powers can result in extremely low system efficiency.

This work focuses on enabling PV power for emerging wearable and mobile tracking applications, where non-uniform light intensities are expected over multiple PV cells. The key to enabling PV power for these applications, is to reinvestigate the PV cell and power converter configuration. A parallel connection, rather than a series connection, along with the concept of differential power processing (DPP) is explored to enable PV power for wearable applications. This work will review the existing connection and converter solutions for PV energy harvesting application and compare them to the proposed technique through simulation and experimental results.

Seamus O'Driscoll, Tyndall National Institute, ULP Energy Harvesting PMIC for Smart Sensor Node

A PMIC to efficiently convert and manage power from various ambient energies and optimally delivers to an energy storage device or smart sensor system voltage rail is presented. It features a monolithically integrated power path with an external inductor and delivers high efficiency from input powers as low as 1uW. The 4-Switch Quasi-Resonant Buck-Boost topology appears to be unique and enables maximised overall system efficiency for an IoT node incorporating RF communication, energy harvesting, storage, sensor interface and signal processing.

The control architecture is based on modular mixed signal control blocks which create a flexible low cost platform enabling next generation power processing and signal interface features applicable to maximising efficiency with either DC (TEG, PV) or AC (both electromagnetic (EMT) and piezoelectric (PZT) vibrational) energy source.

An overview of the topology, control circuits and PWM mode choices is presented. Analog control blocks achieve the combined objectives of efficient duty cycling and low quiescent operating current. 1st valley quasi-resonance is achieved for both buck and boost modes. A cold start charge pump block creates the IC bias and this block in itself may create a 1V8 rail system rail from a 200nW energy source. The IC is implemented on 180nm Silicon-on-Insulator process. Simulation results projecting better than state-of-the-art efficiency and lower quiescent current will be presented for powers greater than 1uW.

Peter Woias, IMTEK-University of Freiburg, Energy-autonomous Systems Based on Thermoelectric Energy Harvesting: application-oriented system design and integration

Thermoelectric energy conversion is excelling over other concepts of energy harvesting with a number of advantages, making this technology suitable for a large range of applications: Thermoelectric generators (TEGs) use no moving parts, they can be designed in a robust fashion, are long-lasting and tap the almost ubiquitously available reservoir of waste heat. However, when designing an energy-autonomous system powered by thermoelectric energy harvesting, a number of specific problems will arise that are mostly related to an application-specific optimization of the thermal and electric interfaces at the TEG. The presentation will discuss these aspects using a global thermal/electrical model of a TEG harvesting system, including all thermal and electrical interfaces and subsystems. A focus will be on the necessity of special step-up converters to boost low voltages – typically only a few 10 mV – from a TEG operated in a low-ΔT-scenario, e.g. when harvesting from human or animal body heat. Considerations on electrical load matching will discuss the problem of delayed system start-up after an unavoidable brown-out of thermal energy, present e.g. in a car that has been parking for a longer period of time. The effect of rapid dynamic temperature fluctuations on the thermal system design of a TEG will be demonstrated in an application scenario for infrastructure monitoring.

Peter Spies, Fraunhofer IIS, Micro-Energy Management for Broadband Energy Harvesting Systems

The energy management in self-powered wireless sensor systems is a key component with a board range of functions. It has to work with a wide input range of current and voltage levels from different harvesters to enable a large spectrum of applications and use-cases. It has to provide a maximum efficiency in form of low leakage currents and enabled by maximum power point tracking and low resistance devices. It has to manage one or several kinds of energy storage devices, providing also a crude state-of-charge information. Finally, it has to control the application depending on the availability of sufficient energy.

In the presentation key functional block like DC-DC converters for thermoelectric harvesters, AC-DC converters for piezo-materials, micro-battery management and energy control functions are explained and results from implementations on ASIC or PCB level are provided. To extend the operation range, bipolar input stages and maximum-power point tracking are employed in the designed energy management modules. Examples of self-powered wireless sensors in condition monitoring and tracking application prove the functionality of the introduced circuits.

Alex Weddell, University of Southampton / ARM, Energy Harvesting in Future Integrated IoT Devices

Energy harvesting is attractive, as it will allow IoT devices to be installed without the costs and inconvenience of installing wiring or replacing and disposing of batteries. However, we found as much as 28x difference between the worst and best case conditions over four days from an indoor solar-powered system in a fixed location. To address this, a variation-aware model for light harvesters has been developed, leading to better design-time verification of power converter circuits which are needed for maximum power point tracking (MPPT) and voltage level conversion.

For a given energy budget, conversion losses limit performance, and in typical systems it is common to have two converters optimized for different operating conditions (i.e. on the input and the output from the energy storage device). This multi-converter design can reduce the overall operating efficiency, resulting in less energy available for sensory activities. Furthermore, these converters show severe performance degradation for low available energy levels, leading to poor utilization of harvested energy e.g. when lighting is dim and hence power is scarce. To overcome these problems, a Selective Direct Operation (SDO) technique with a single reciprocal converter was developed and implemented along with an ultra-low power CPU and digital logic to prove a complete sub-system running industry standard sensor benchmark software.

Measured results demonstrate a 16% increase in energy utilization and 30% increase in compute cycles. The harvester and circuit co-design methodology resulted in a sub-system shown to execute the software benchmark with as little as 200lux of indoor lighting for two hours per day. The work completed thus far has delivered a sub-system that can operate effectively down to 50 Lux of continuous light or 20°C of temperature differential.

Stephen Savulak, United Technologies Research Center, Perspectives on Energy Harvesting for Aerospace Sensors

Certain qualities of energy harvesting naturally lend themselves for use in aerospace sensors. This talk will review, from a supplier perspective, some of the advantages of using EH devices in this space, including avoiding costly aircraft re-certifications and placing sensors in previously inaccessible locations. Also to be examined will be the unique challenges for the components and circuits for energy harvesting in aerospace applications, both overcome and yet to be solved. This discussion will also touch on the need and opportunities to minimize sensor module power consumption for energy harvesting compatibility or at least battery life extension and size minimization.

Ivan O'Connell, Tyndall National Institute, Methodologies for Reducing ULP Device Power Consumption

Based on experience gained in the development of CMOS devices at MCCI with industry partners & awareness of recent research advances Dr. O' Connell will propose a methodology for exploring opportunities to reduce power consumption of ULP devices based on the application need. These are categorised as Static Power Consumption, Dynamic Power Consumption, Process Technology, & Architectural decisions.

To optimise Edge IoT devices for ULP consumption, minimising the power consumption for the end solution requires a multi-factorial approach, where individual block performance is leveraged against the overall system performance.

Francesco Carobolante, G2nd Systems, The Future of the Energy Harvesting Ecosystem

From large scale to miniature scale, energy is always obtained by a harvesting process: yet, the ubiquitous intelligence envisioned by the proponents of the Internet of Things requires that we re-tool our technology arsenal and cope with the challenges of extremely low energy levels. Moore's law helped us increase logic circuits efficiency but it is not sufficient: a much broader range of disciplines need to be brought together to enable a successful ecosystem: from material science to manufacturing methods, from low power computing to ultra-low power sensing and communication, from software enabling intermittent computing to HW and SW co-design to ensure privacy and resilience to cyber-attacks.

It takes a village – a village of technologies – to bring to life the vision of ubiquitous intelligence that we have been painting as the Internet of Things. We need the concurrent and collaborative synergy of multiple disciplines to be able to use all the tools and maximize the final system performance.

This is what our ecosystem is all about and the objective of EnerHarv and its organizers. Seeing the bigger picture, involving all the stakeholders early, getting them to work together, figuring out which tools and technologies can help achieve the vision.

POSTERS

Valeria Nico, University of Limerick, Multiple Degree-of-Freedom Vibrational Energy Harvester Multi-VIBE

A D-battery scale Multiple-Degree-of-Freedom vibrational energy harvester (Multi-VIBE), which employs velocity amplification to enhance the power scavenged from ambient vibrations, is presented. The device comprises two masses relative oscillating one inside the other between four sets of springs. The resonant frequency of the device can be modified using a sliding cap that affects the height of the device. Electromagnetic transduction is used: seven coils are embedded in the external mass while the second mass is made of two NdFeB magnets. A power management circuit based on a voltage rectifier and a DC/DC converter is used to power a LoRaWAN sensor node. The proposed device shows a wider frequency bandwidth and higher output powers compared to the vibrational energy harvesters that are commercially available. Predictive maintenance, self-optimizing production, and automated inventory management and railway monitoring are key sectors driving the development of UL harvester.

Heiko Reith, IFW Dresden, Integrated Micro-Thermoelectric Modules for Local Heat Management

MISSING

William Ferguson, University of Exeter, Auxetic Enhancement of Vibration Energy Harvesting

We have developed a simple auxetic (negative Poisson's ratio) energy harvester to increase the power output available from small tensile strain excitations (<300 με in the range of 1–20 Hz). We found that this produced around 11 times more power than an equivalent plain harvester under the same excitation.

Peter Woias, IMTEK-University of Freiburg, Thermoelectric Energy Harvesting for Powering Wireless Sensor Nodes: from low-temperature to high-temperature applications

MISSING

Watcharapong Paosangthong, University of Southampton, Performance Comparison Between Different Materials and Operation Modes of Triboelectric Nanogenerator

In this project, the output performance of different triboelectric materials, such as Al, PET, PE, Kapton, PVC and PTFE, were investigated and explicitly compared for all four fundamental operation modes. The four operation modes are freestanding triboelectric-layer mode, lateral sliding mode, single-electrode mode and vertical contact-separation mode. The results show that for all operation modes, the TENG with the PTFE film delivers by far the highest output performance. At the frequency of 3 Hz, the load of 10 MΩ and the force of 5 N in the freestanding triboelectric-layer mode, the TENG with PTFE/Al substrates exhibits the maximum output performance with an RMS voltage of 9.30 V, an RMS current of 0.93 µA and an average power of 8.66 µW corresponding to a power density of 2.7 mW/m2, followed by the lateral sliding mode, whereas the contact-separation mode and the single-electrode mode produce much lower power.

Ausrine Bartasyte, FEMTO-ST, ITN ENHANCE - Piezoelectric Energy Harvesters for Self-Powered Automotive Sensors: from Advanced Lead-Free Materials to Smart Systems (2017-2021)

The Initial Training Network ENHANCE will provide Early Stage Researchers (ESRs) with broad and intensive training within a multidisciplinary research and teaching environment. Key training topics will include development of energy harvesters compatible with MEMS technology and able to power wireless sensor. Applied to automobiles, such technology will allow for 50 kg of weight saving, connection simplification, space reduction, and reduced maintenance costs - all major steps towards creating green vehicles. Other important topics include technology innovation, education and intellectual asset management. ENHANCE links world-leading research groups at academic institutions to give a combined, integrated approach of synthesis/fabrication, characterization, modeling/theory linked to concepts for materials integration in devices and systems. Such a science-supported total engineering approach will lead towards efficient piezoelectric energy harvesters viable for the automotive industry. ESRs will focus on this common research objective, applying a multidisciplinary bottom-up approach, which can be summarized by : "engineered molecule- advanced material- designed device - smart system". ENHANCE also seeks to intensify the relationship between academic and private sectors, and to train highly skilled young researchers for new materials and device technologies. Both are essential to provide a strong European lead over the rest of the world in this highly competitive industry.

James Rohan, Tyndall National Institute, Nanoscale Cathode Materials for High Power Microbatteries

Commercial wireless sensors in use today typically utilise large non-rechargeable batteries as the energy source and as such require frequent battery replacement. Hybrid devices with combined energy harvesting and storage could enable intervention-free operation over the lifetime of the device [1]. Silicon integrated on-chip energy storage is an attractive goal for the hybrid solution but is limited to low power and energy outputs in the typical 2D planar thin format demonstrated to date.

One of the issues with solid state thin film microbatteries is the high resistance of the electrolyte which can lead to significant potential drop when powering devices during operation and interrogation. The ability to provide high currents in a small form factor is a critical need for the development of realistic long life devices.

In this work we will correlate the results from Comsol finite element simulations and electrochemical data showing material utilisation for a non-porous additive-free sputtered nanoscale LiCoO2 cathode and the influence of electrolyte type on the output characteristics.

Raphaël Salot, CEA-Leti, EnSO (Energy for Smart Objects) EU Project

EnSO has set up a unique European ecosystem in the field of high-performance autonomous miniature energy-harvesting power sources for IoT market in Europe.

The scope of project encompasses energy solutions for powering “smart” objects in Smart Society, Smart Health and Smart Energy key applications. EnSO is developing high reliability assembly technologies of shapable and customisable micro batteries, energy harvester and power management building blocks, and set up a competitive high volume production. The project aims to demonstrate the competitiveness of EnSO energy solutions for powering the autonomous Smart Objects. As an ECSEL Innovation Action, EnSO’s work addresses the market replication, demonstration and technological introduction activities. EnSO ecosystem involves all of the value chain - from key materials and tools to many demonstrators in different fields of application.

Ruth Houlihan, Tyndall National Institute, Spatial Dependence of a Piezo-magnetic MEMS harvester Relative to the Electromagnetic Source

A piezoelectric MEMS cantilever with an integrated magnet may be used to scavenge energy from the electromagnetic field surrounding a current carrying conductor such as a household power cord. The electromagnetic field generated by the AC current flowing the power cord exerts an alternating force on the magnet which then drives the cantilever into oscillation at the frequency of the AC source.

The power available from the wire is highly dependent on the position of the harvester magnet with respect to the wire. While this is typically assumed to be optimized when the magnet is at 45° to the y-axis of the wire (where the remanence of the magnet defines the y-axis), we show that this assumption takes into account only the vertical force exerted by the electromagnetic field on the magnet and not the magnetic torque. The inclusion of the magnetic torque into the equations changes the relation between transferred power and relative position dramatically. When accounted for, our theoretical and measurement results are shown to be in excellent agreement.

Martin Kluge, Fraunhofer IPM / Imperial College / Airbus, Dynamic Thermoelectric Energy Harvesting in Aircraft

Digitalisation offers optimised aircraft operation, enabling, for example, more efficient airspace use, maintenance and crew support. Connected aircraft and wireless network infrastructure solutions are required to turn aircraft into an internet-of-things-type device. Many efforts have been done in recent years to improve hardware and software for wireless networks and sensor/actuator nodes, such as energy-aware protocols and ultra-low power electronics. However, the power supply currently relies either on high cabling efforts or high maintenance efforts in case of batteries. A key enabling approach to overcoming these drawbacks is energy harvesting. Aircraft offer unique temperature variations during operation due to high temperature differences and gradients, when flight phases change. An extremely promising thermoelectric harvesting solution is the use of phase change materials, in order to exploit the latent heat. In addition to the temperature gradient induced heat flow between the aircraft and the outside environment, the latent heat of the phase change material, e.g., water, contributes significantly to the resulting energy budget. Several dynamic thermoelectric energy harvester designs have been realised and tested in the lab. A seven-month test flight campaign has successfully demonstrated the capability of the dynamic thermoelectric energy harvester as reliable power source.

Gerd vom Bögel, Fraunhofer IMS, Wireless Sensor System for Industrial Applications Powered by Thermoelectric Generator

The industrial environment of a manufacturing plant is a suitable field of application for a variety of measuring tasks for process monitoring on the use of thermoelectric generators (TEG) for the power supply of wireless sensor modules. This poster presents some aspects of the development of a self-sustaining system using the example of coolant monitoring and control. Subject is a continuous pressure and temperature measurement at each mold of a cooling system. The energy for operation of the sensor module is provided by a TEG using the temperature difference between the coolant tube and the "warm" environment. To attain a stable energy supply, various TEG and construction practices with controlled heat flow have been evaluated and optimized. In combination with a specific power management a robust, industry-compliant solution has been realized.

Philip Schmidt, Fraunhofer IMS, Boost & Fly - RF Powering of Wireless Sensors for Industry 4.0

Cyber-physical systems are essential elements of industry 4.0. In the production these systems include physical objects (such as machines, production modules, workpiece carriers, tools etc.) which are equipped with embedded systems. They directly acquire physical data and affect physical processes via actuators. Communications interfaces serve the integration in decentralized control systems and networks and also allow for a real-time synchronization of the physical world with the models of the digital world. Currently used production plants and machines do not provide the needed interfaces or sensors. Because of high investment costs and the long operating life of these machines, retrofittable solutions are required.

Regarding the predicted high amount of sensors and actuators, wire-bound systems reach their technical and economical limits. Wireless solutions are going to stay incomplete, if wireless power supply of these systems is not accessible. Energy sources, such as light energy, thermic or mechanical energy for the transformation into electrical boost & fly system energy (“Energy Harvesting”), are not sufficiently made available.

Fraunhofer IMS has developed a solution for the contactless electrical quick charging (“Boost”) of mobile cyber-physical systems and their energy self-sufficient operation (“Fly”). The idea is based on the thesis that cyber-physical systems (CPS) move in deterministic traces in production environments and remain on at least one position for a sufficient time to charge the energy storage ("Boost"), shown in image 1. Then the stored energy can in the following time course supply the system with electrical energy ("Fly") again.

Tracy Brennan, Boston Scientific Limited, COMPOSITION – Conditional Monitoring and Asset Tracking Sensors for Industry 4.0

COMPOSITION is an EU 'Factories of the Future' project led by Fraunhofer FIT that develops inter-operable systems for inter and intra-factory collaborative systems. Tyndall is providing guidance on WSN (wireless sensor network) retrofit opportunities and developing/selecting IoT hardware platforms for improving energy and resource efficiency in a medical device factory deployment in close partnership with Boston Scientific Limited (BSL) Clonmel Ireland. The 2 high priority use cases selected are (i) sensors for tracking high value assets (high value component reels, test fixtures) & (ii) conditional monitoring of reflow oven fans for predictive maintenance. Potential savings of 100s of thousands of Euro can be realized annually by being able to identify the location of assets at short notice to minimize downtime & material value loss. Similar savings are possible if fan wearout can be detected (using acoustic and power sensors) and predictive maintenance undertaken reducing downtime and material loss (scrappage from oven failure). To date the work has focused determining the appropriate types of sensors and wireless infrastructure on selecting commercially available and emerging platforms taking into account inter-operability, scalability, range, operating conditions and battery life and systems have already been installed in BSL. The next stage of the project involves the use of energy harvesting and power management techniques to determine to what extent the power consumption of the IoT devices can be reduced and what type of ambient energies can be used to extend battery life.

Cian O'Shea, Tyndall National Institute, RECO2ST – WSN Power Modelling and Optimisation Tool for Retrofitting Intelligent Building Energy Efficiency Systems

ReCO2ST is an EU Building Energy Efficiency project led by Aalborg University Denmark that develops a Residential Retrofit assessment platform and demonstrations for near zero energy and CO2 emissions with optimum cost, health, comfort and environmental quality. Complex systems are required to enable near zero energy and emission buildings. As buildings approach zero energy, the systems that enable this have to be highly efficient themselves otherwise they may start to contribute significantly to the overall energy consumption. Wireless sensor systems offer retrofit opportunities to enhance energy efficiency in buildings based on contextual data that utilize highly efficient power supply systems.

Bobby Bornemann, Tyndall National Institute, MOEEBIUS – Low Power Multi-radio Wireless Sensor Platform Enabling Optimisation of Radios, Sensors and Energy Harvesting

Overview of a power management solution developed to extend battery life of a NOD (multi-radio multi sensor Wireless sensing node).

Oskar Olszewski, Tyndall National Institute / MCCI, MEMS Piezoelectric Vibrational Energy Harvester – Characterisation for MISCHIEF Platform Gen II

Tyndall has a research trajectory in MEMs scale AlN Piezo transducers. There are numerous and quite disparate techniques for maximising power extraction from AC piezoelectric sources – AC MPPT. This work involves experimental characterisation and modelling of a high frequency (stiff) AlN on Silicon prototype transducer to create and validate dynamic electro-mechanical models for use in AC front end design in Mischief II. The key question is around the magnitude of the reverse piezo effect and how much adverse electrical damping will be created by the HF resonant bias flip, versus the gained increased rectifier conduction angle.

Tim Daly, Tyndall National Institute / MCCI, MISCHIEF - Design Techniques for Ultra Low Quiescent Power Controller

A novel configurable, high efficiency, power management IC with best in class quiescent current and efficiency below 50uW. It uses a quasi resonant buck boost topology to deliver an extremely wide input voltage range compatible with many energy harvesting sources. The MISCHIEF platform is modular enabling fast cycle time silicon development to meet a given application need.

Paul Roseingrave, Tyndall National Institute, EnABLES – EU Research Infrastructure Program 'Powering the Internet of Things'

EnABLES is a European Union funded infrastructure access programme led by Tyndall comprising 11 leading research centres in Europe focusing on powering the Internet of Things (IoT) by extending battery life an ultimately eliminating battery replacement where possible.

To support feasibility studies and characterisations it provides free of charge access to laboratories and expertise in research institutes at Tyndall, CEA, Fraunhofer and IMEC along with virtual access to vibration databased from Universities in Perugia & Southampton. Knowledge hubs of excellence (Universities at Bologna, Turin and Karlsruhe) complete the consortium also undertaking JRAs (join research activities) between partners to provide future system optimised technology platforms. EnABLES is built upon the technology pillars of Energy Harvesting, Storage, Micropower Management and system integration.

Swatchith Lal, Tyndall National Institute, Micro-thermoelectric Cooler for the Thermal Management of Photonic Devices

Thermal management of microelectronics and optoelectronics devices using thermoelectric (TE) coolers is an efficient way for active temperature control, where miniaturization of the devices led to generate a high heat flux, which is difficult to manage[1, 2]. In this regard, bismuth telluride (Bi-Te) based materials have been extensively studied due to their relatively high thermoelectric efficiency near room temperature regime for the fabrication of thermoelectric devices. The use of electrodeposition in synthesis of thermoelectric materials and device is highly recommended due to its suitability in terms of cost effectiveness, up-scalability and ease of controlling material properties such as composition, crystallinity and morphology. Moreover, because of its compatibility with microelectronic processing techniques, electrodeposition can be used to fabricate micro-scale thermoelectric cooler directly on the wafer for thermal management of photonics and electronic devices.

In the present work, we studied comprehensively the influence of electrolytic bath content, deposition potential and surfactant on the composition and microstructure of thin films and in turn on the thermoelectric properties. The impact of annealing temperature-time profile on the films composition, structure and the Seebeck coefficient/electrical conductivity is thoroughly investigated. We also demonstrate and discuss the fabrication procedure of cross-plane configuration, flip-chip bonded micro-thermoelectric cooler (μ-TEC). The device is fabricated from low-cost microfabrication technique using electrodeposition for TE material deposition, forming 210 pairs. We also discuss the electrodeposition of gold (Au) and indium (In) as a barrier layer and bonding material respectively. And the impact on internal resistance of the device by bonding materials and the challenges faced with the flip-chip bonding of the device are discussed.

DEMOS

Shane Hollmer, Adesto, Non-volatile Serial Memory for Energy Harvesting Power Applications

The demonstrated family of non-volatile memory (32-256Kb) leverages Adesto's CBRAM technology, a data storage mechanism that is based on changing cell resistance through an electrochemical process. This memory (Moneta) can be used for both code and data storage and is designed to provide ultra-low power EEPROM alternatives in discrete and embedded IoT applications that can operate off an energy harvested source.

The board demonstrates the capability of Moneta to work at low levels of power provided by an energy harvested source. The primary components of the board are a LED display, microcontroller* and a non-volatile memory. A typical routine loop of write, standby, and read is powered by solar panels, three for an industry EEPROM and one for Moneta. As light is reduced to the solar panel, the EEPROM cannot maintain the operating loop and the loop counter stops far earlier than the Moneta parts showing the ability of CBRAM to operate with far less energy.

Mehmet Ozturk, North Carolina State University, Wearable Flexible Thermoelectric Generator Using Liquid Metal Interconnects and Bulk BiTe Legs

This demonstration will include working flexible thermoelectric energy harvesters that convert heat to electricity. The work is carried out under The Advanced Self-Powered Systems of Integrated Sensors and Technologies (ASSIST) Center at NCSU working on wearables that monitor individual health and environment. The goal is to create self-powered wearables that rely entirely on the energy harvested from the human body in the form of heat or motion. In this demo, we will present thermoelectric generators that produce electricity when placed on the body. The wearable generator will be connected to a built-in voltmeter to demonstrate how the output voltage is changing with motion (i.e. convection) and variations in ambient temperature.

Dushan Vuckovic, FORCE Technology (DELTA), Implementing Energy Harvesting Solutions Using Commercial Off-the-shelf Components

This demo focuses on evaluating and demonstrating energy harvesting powered wireless sensor nodes. The first part of the demo consists of a modular platform that allows rapid prototyping and evaluating of energy harvesting power sources through the use of different modules for power management, radio communication and the main system controller board. Power management modules interface with various energy harvesting sources such as thermoelectric generators or photovoltaics. These modules convert the power output from the harvesters and perform power management as well as energy storage. The RF module connector allows easy exchange of radio modules thus increasing flexibility for evaluating different communication protocols and standards. The main board houses the MCU with power management features implemented onboard that help reduce power consumption of the entire system. Breadboard compatibility ensures rapid prototyping.

The second part of the demo shows three Bluetooth low energy temperature sensors based on the power management block developed and shown in the first part of the demo.

Peter Spies, Fraunhofer IIS, Micro-Energy Management for Broadband Energy Harvesting Systems

BlueTEG is a wireless sensor platform with thermo-electrical power supply. It has a Bluetooth LE radio module and different standard sensors like temperature, humidity and acceleration. With a transmission rate of once per second, only 2K thermal gradient are sufficient to realize a fully self-powered operation. It includes a special power management module to enable the operation with very small thermal gradients. It has no battery, just a small capacitor for energy storage. Typical applications are condition monitoring sensors for machines, plants or buildings. Energy metering, thermal control of machines and wearables are further use-cases.

Gerd vom Bögel, Fraunhofer IMS, TEG Powered Wireless Sensor System for Process Monitoring and Control

The industrial environment of a manufacturing plant is a suitable field of application for a variety of measuring tasks for process monitoring on the use of thermoelectric generators (TEG) for the power supply of wireless sensor modules. This demonstrator shows a realized self-sustaining system for coolant monitoring and control. Subject is a continuous pressure and temperature measurement at each mold of a cooling system. The energy for operation of the sensor module is provided by a TEG using the temperature difference between the coolant tube and the "warm" environment. In combination with a specific power management a robust, industry-compliant solution has been obtained.

Philip Schmidt, Fraunhofer IMS, RF Powered Wireless Sensors for Industry 4.0

Wireless solutions for Industry 4.0 sensors are going to stay incomplete, if wireless power supply of these systems is not accessible. Energy sources, such as light energy, thermic or mechanical energy for the transformation into electrical boost & fly system energy ("Energy Harvesting"), are not sufficiently made available.

Fraunhofer IMS presents a solution for the contactless electrical quick charging ("Boost") of mobile cyber-physical systems and their energy self-sufficient operation ("Fly"). The idea is based on the thesis that cyber-physical systems (CPS) move in deterministic traces in production environments and remain on at least one position for a sufficient time to charge the energy storage ("Boost"). Then the stored energy can in the following time course supply the system with electrical energy ("Fly") again.

Bobby Bornemann, Tyndall National Institute, MOEEBIUS – Energy Harvesting Powered Multi-radio WSN Mote for Building Energy Optimisation

Indoor solar micro-power management circuit to extend battery life of the MOEEBIUS multi-radio WSN node (NOD) that measures temperature, light, humidity, occupancy, CO2 and VOCs.

James McCarthy, Tyndall National Institute, COMPOSITION – Conditional Monitoring Case Studies for Energy Harvesting Opportunities in Industry 4.0

Use of acoustic sensors and power consumption sensors to study behaviour of fans in a factory reflow oven. Onset of bearings in fans starting to wear can be detected via increases in acoustic emission at various frequencies and power consumption thereby providing the opportunity to do predictive maintenance and minimize losses related to machine downtime (10s of thousands of Euro per incident).

Oskar Olszewski, Tyndall National Institute, Evaluation of Vibrational Piezo-MEMS Harvester That Scavenges Energy From a Magnetic Field Surrounding an AC Current-Carrying Wire

The Internet of Things (IoT) requires development of energy-autonomous nodes and energy harvesting is a key technology addressing such a demand. Multiple energy sources are available within the environment e.g. light, vibrations, electromagnetic waves, temperature gradients, and these can be converted into electrical power using various transduction methods, e.g. photovoltaic, thermoelectric, electromagnetic, electrostatic, and piezoelectric. Due to numerous advantageous the vibrational piezoelectric harvesters have received much attention in recent years, e.g. vibrations are ubiquitous in many applications and advances in MEMS piezoelectric films offer wafer-scale and high-volume fabrication.

In this demo, we demonstrate a CMOS/MEMS-based vibrational piezoelectric energy harvester technology being researched in Tyndall. The device operation principle, fabrication process and major performance characteristics are discussed. One of key challenges of vibrational harvesters is that the devices typically resonate with a high Q-factor or, in other words, have a very narrow bandwidth. Away from the resonance frequency the power generation drops significantly. This is a major problem because the frequency of the vibration source may vary over time and, as a result, no usable power may be generated. The frequency can also vary significantly between different vibration sources so this would require devices with different resonant frequency to be developed for individual applications. A number of solutions to broaden the bandwidth of vibrational harvesters have been proposed. An alternative approach is to select an application that provides a stable source of excitation frequency. One such source is the AC magnetic field surrounding an AC current-carrying wire such as the power mains of electrical equipment. A proof-of-concept of harvester under operation that scavenges energy from a wire carrying an ac current are demonstrated in this demo.

Denis Pasero, Ilika, Autonomous Wireless End Nodes Powered by Solid State Batteries and Energy Harvesting

Trends to miniaturise IoT end nodes, whilst at the same time extending their functionalities, is placing increasingly stringent requirements on the energy storage component. Combining an energy dense solid state battery with a source of harvested energy (solar, thermal, vibration…) enables small size, long life operation. Ilika will present its family of IoT demonstrator, including a Smart Home temperature sensor; an Agritech temperature, moisture and light level sensor; and an Industrial IoT sensor that can operate to 150°C.

Peter Haigh, Tyndall National Institute, COMPOSITION –Asset Tracking Case Studies for Energy Harvesting Opportunities in Industry 4.0

High value assets need to be tracked in factories to enable their location to be determined at short notice to optimise production flow (e.g. sub-assembly testing, component replenishment). UWB (ultra wide band) & BLE (Bluetooth low energy) technology based platforms were selected and integrated for the project for stage 1 and demonstrated at EnerHarv. The next stage will involve developing energy harvesting micropower management solution to be developed to extend battery life.

Cian O'Shea, Tyndall National Institute, ROWBUST WSN Deployment Assistance Tool

This demonstration will present a first beta version of the tool which shows the trade-offs involved with sizing photo voltaic cells and super capacitors. It also shows difference between COTS (commercial off the shelf) and Tyndall power management circuits. This application has the ability to simulate the power availability in the super capacitor over a given time period to monitor how long the device will last with the chosen parameters.   This will enable the user to determine whether a certain set of chosen components can power commercially available Wireless Sensors.

Roberto La Rosa, ST Micro, Powering Battery-Free Systems with PV Cell

This demo shows a Battery-Free sensor node whose energy is supplied by a Photovoltaic cell able to feed a system with several sensors, a microcontroller and a Bluetooth Low Energy radio system to wirelessly send the acquired data to any BLE receivers. In this specific case the receiver is implemented with an Android Smartphone and an App able to perform the monitoring by collecting data and performing statistics.

The key device is the Ultra Low power Management with a quiescent current as low as 75nA, which is able to smartly manage the harvested energy, provided by the photovoltaic cell, and to deliver a regulated voltage to supply the internal circuitry of the system on chip as soon as the amount of energy is big enough to guarantee the active phase of the system.

With such a low current consumption (75 nA) in the charging phase, a photovoltaic cell with a current capability of just 1µA can easily charge the storage capacitor Cstorage. This allows energy harvesting by using small photovoltaic cells, essential for th miniaturization of IoT devices, in environments with poor ambient light.

Pierre Mars, CAP-XX, Solar Cell Energy Harvester with Supercapacitor

CAP-XX is demonstrating the use of a low ESR single cell supercapacitor as an energy storage device to enable data capture and transmission at much higher power than delivered by a small energy harvester, in this demonstration, a small solar cell. A solar cell with area ~17cm2 designed for indoor LED / CCFL lighting produces ~0.8mW which drives an efficient e-peas PMIC, AEM10941. This charges the HA102, 240mF supercapacitor to 2.65V which powers a Sensor Puck, reporting temp, light level, RH% over blue tooth once per second to a phone app. The reporting power is ~50mW. A supercapacitor, with very low leakage current, low ESR and “unlimited” cycle life is ideal in this and other applications where average output power is ≤ average input power, but peak output power is >> available input power. The thin prismatic form-factor of the CAP-XX HA102 supercapacitor used here is ideal for sensors where a flat unobtrusive design is desired, or for wearables where bulky sensors are not practical. To ensure average output power is limited to average input power, a FET disconnects the load from the supercapacitor when supercapacitor voltage < 2.3V and re-connects the load when the supercapacitor has charged to 2.6V. The demonstration shows solar cell current, output current on an oscilloscope showing transmit peaks, and supercapacitor voltage.

Katherine Kim, Ulsan National Institute of Science and Technology (UNIST), Differential Power Processing Converter Design for Photovoltaic Wearable Applications

Wearable applications can be powered by photovoltaic (PV) cells, but they have a high probability of experiencing uneven lighting or partial shading, which greatly decreases output power harvest. Previously, this has been a limiting factor for PV-powered wearables. To overcome this problem, the concept of differential power processing (DPP) converters is implemented in a PV-powered bag to effectively capture energy from PV cells receiving different light intensities. This demo shows the feasibility of this technology to effectively capture ambient sunlight and use it to power hand-held devices even under uneven lighting conditions.

David Newell, NUI Galway, A High Efficiency Switched Supercapacitor Energy Management Circuit for Energy Harvesting Powered Wireless Sensor

The aim of this work is to showcase the potential increase in efficiency of energy management circuitry that can be achieved. This increase in efficiency is achieved by designing an optimised energy management circuit that delivers pulses of energy similar to the requirements of the wireless sensor. The circuit includes a low power maximum power point control circuit that is powered from within the circuit. The demonstrator circuit will show the energy management circuit harvesting energy from a DSSC and using it to power a temperature and humidity wireless sensor. The sensor data will be displayed on a laptop and live measurements of the overall system efficiency will be demonstrated. Some additional information pages will be supplied showing the circuit operation and some key waveforms.