GLOBAL IoT SUMMIT

1st Workshop on Internet of Energy Neutral Things

June 7, 2017 Geneva, Switzerland

A Self-powered wireless bolt for smart critical fastener

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Motivation

Critical fasteners in electromechanical systems are susceptible to

- Heating and rapid cooling which causes brittleness
- Wear and tear by being overstressed
- Become loose and unable to provide the necessary tension due to movement

Particularly in ***high end applications*** periodic **maintenance and replacement** are **required**

- Avionics
- Supercars

Motivation

Monitoring critical fasteners

- Prevent failures
- Proactive/Programmed maintenance
- Improved security

How

- Monitor temperature and understand current state from recorded temperature profile
- Monitor tension (eventually)

Titanium Fasteners for avionics applications (credits: poggipollini.it)

Objective of the work

Objective

- Designing a smart bolt
- Evaluating the feasibility of powering the smart bolt using TEGs under very low temperature gradient

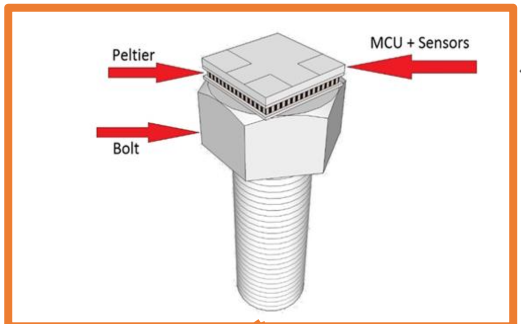
Challenges

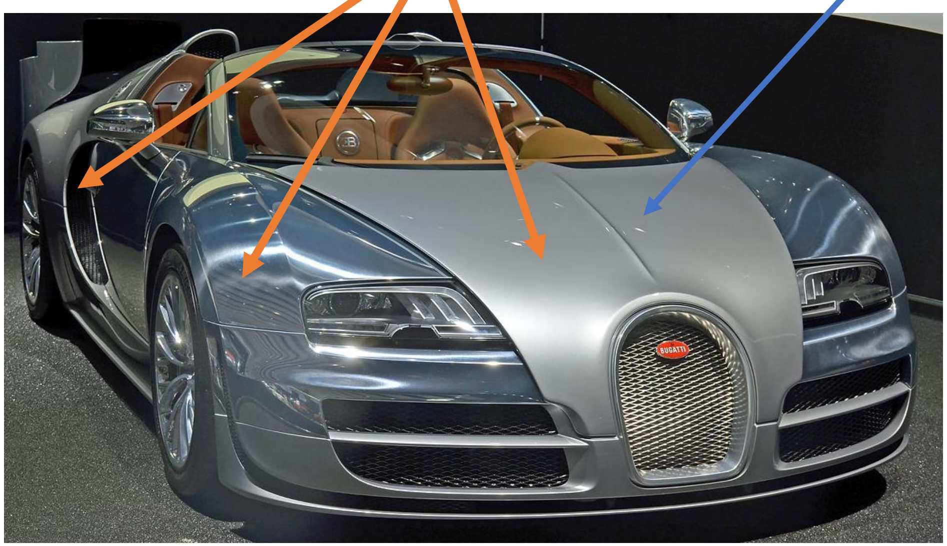
- Size (must fit the head of critical bolts → few cm^2)
- Energy autonomy (no wires, no recharge plug)
- *Price is not an issue in high-end applications*

Methodology

- Characterization
  - 3 commercial TEGs
  - 2 DC-DC converters
- Design and development of smart bolt "demo"

Self Powered wireless bolt for smart critical fastening





A set of smart bolts are deployed in critical structures

- Data are stored in local memory
- Forwarded wirelessly when energy available
    - Star network topology (single-hop)

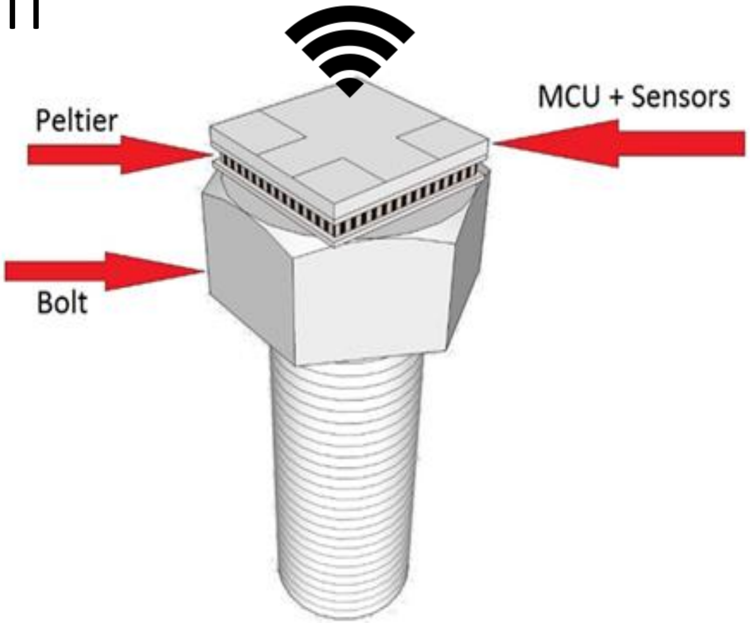
Data are collected by:

- The main control unit (supercars)
- Downloaded during maintenance (aircraft, copters)

Self Powered wireless bolt for smart critical fastening

Design

- **CC1310** low power wireless SoC from TI
  - ARM cortex M3 @48MHz
  - 8KB RAM
  - 128KB flash
  - Running TI-RTOS + application
  - Sub-GHz Radio
- **LTC3108** DC-DC boost converter
- **TEG** as power supply

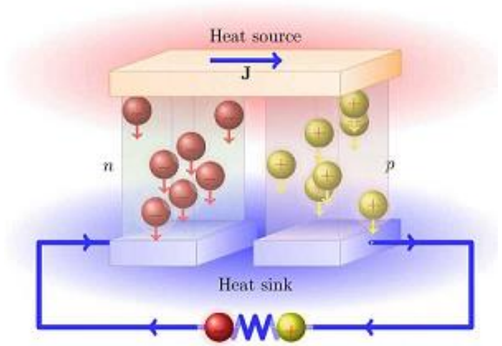


Data collector (or gateway) based on the same SoC

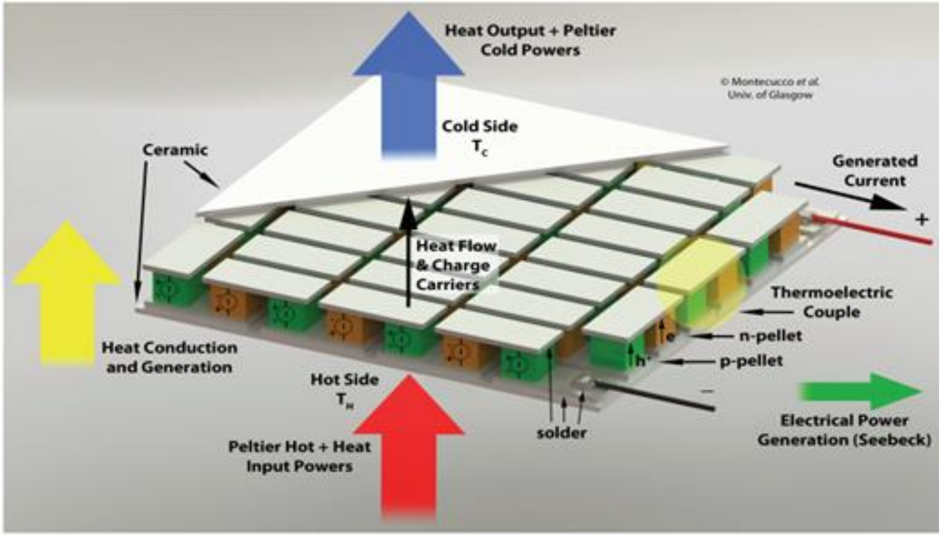
Thermoelectric Generators

Thermocouple

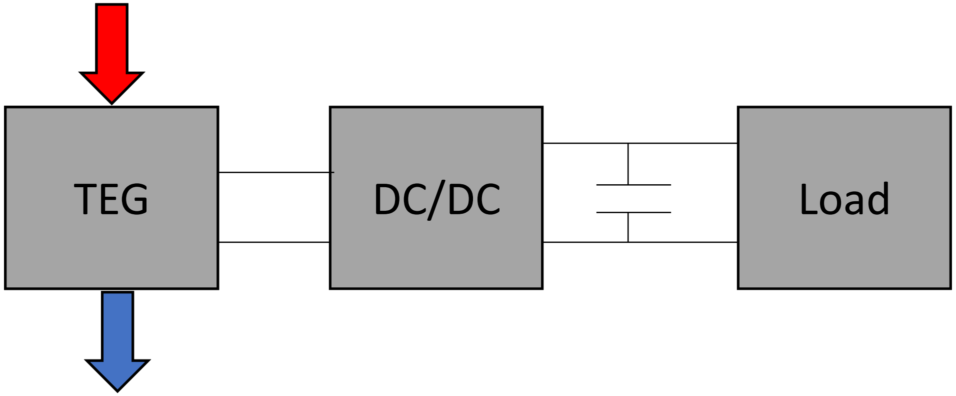
Made by conjoining two dissimilar metals (usually P and N type materials) at their free ends



TEG



Thermoelectric circuit



Experimental Setup

Characterization of

- TEGs
- DC-DC converters

Characterization Challenges

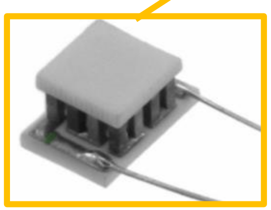
- No standardized way of characterization yet
- Complex circuitry to prevent maintain junction temperature constant
- Fluctuation of thermal gradient with current
- Fluctuation of Seebeck coefficient with temperature

Novelties in Characterization

- Simple characterization without thermal regulation circuit
    - Mitigation of Peltier effect
    - Stabilized fluctuation of Seebeck coefficient with temperature

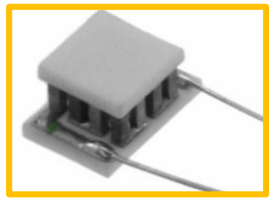
Summary of specification of the TEGs

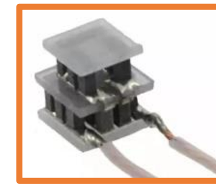
Label	TEG specification from datasheet					
	Model	***L [mm]***	***H [mm]***	***Rin [Ω]***	***ΔTmax [K]***	***A*** $[mm^2]$
TEG1	926-1216-ND	26	14	0.25	67	1507
TEG2	926-1192-ND	5	3.4	1.04	67	17
TEG3	926-1225-ND	3.9	3	-	92	15.21

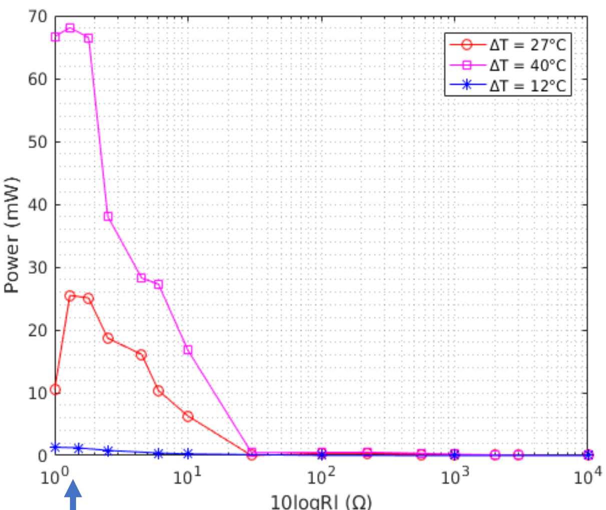


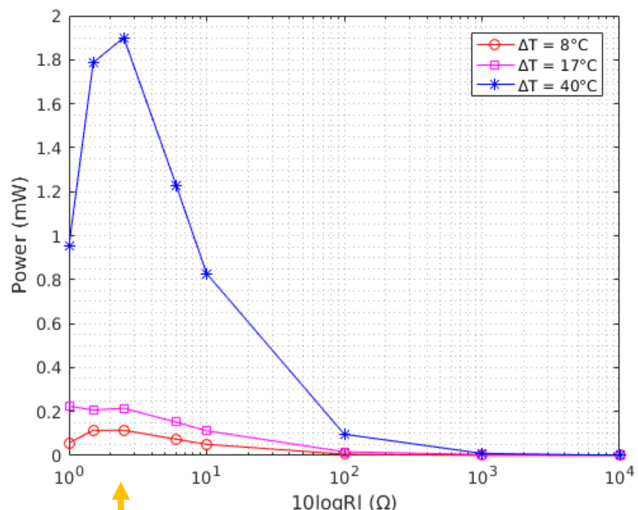
Experimental Characteristics

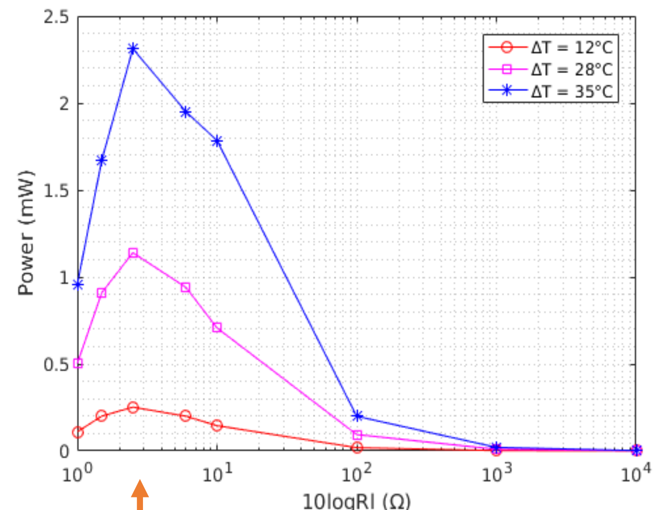
ΔT → TEG → Variable Load



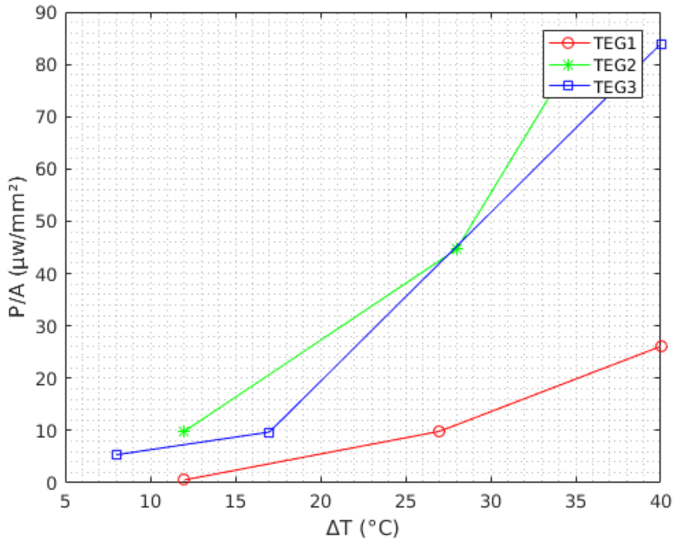




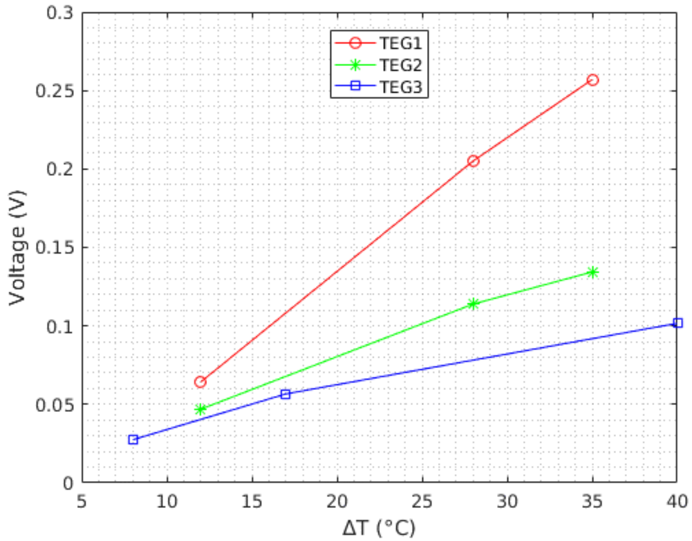




TEG Characterization Results



Power Vs ΔT



Open Circuit voltage vs ΔT

TEGs 2 and 3 have higher power density w.r.t. TEG1
Almost linear relationship between Voc and ΔT

TEG Characterization Results

Comparison of results with related works

Label	Experimental results		
	R_{in} [Ω]	$Pmax/\Delta Tmax^2$ $[\mu w/K^2]$	**PF** $[\mu w/mm^2k^2]$
TEG1	1.4	40.625	0.0271
TEG2	2.3	6.94	0.404
TEG3	2.1	6.04	0.397
TEG4 [1]	2.23	224	0.14
TEG5	250K	1	0.015
TEG6 [2]	1.9	5.31	0.0033
TEG7 [3]	1.08	0.25	0.156

Highest power density

Fluctuation of temperature with current

Label	*I = 12.5mA*	*I = 42.7mA*	*I = 101.7mA*
TEG1	1.01°	2.71°	3.6°
TEG2	0.82°	1.56°	2.95°
TEG3	0.56°	1.48°	2.78°

[1] S. Dalola, M. Ferrari, V. Ferrari, M. Guizzetti, D. Marioli and A. Taroni, "Characterization of Thermoelectric Modules for Powering Autonomous Sensors," in *IEEE Transactions on Instrumentation and Measurement*, vol. 58, no. 1, pp. 99-107, Jan. 2009

[2] L. Rizzon, M. Rossi, R. Passerone and D. Brunelli, "Energy neutral hybrid cooling system for high performance processors," International Green Computing Conference, Dallas, TX, 2014, pp. 1-6

[3] W. R. Fernandes, Z. Á. Tamus and T. Orosz, "Characterization of peltier cell for the use of waste heat of spas," 2014 55th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), Riga, 2014, pp. 43-47

DC-DC Converter Characterization

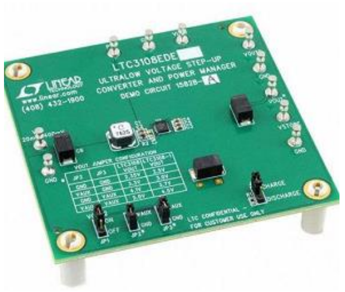
Characterization to determine

- **Efficiency**
- Charging profile

Characterization done by supplying the converters from

- TEG
- DC source

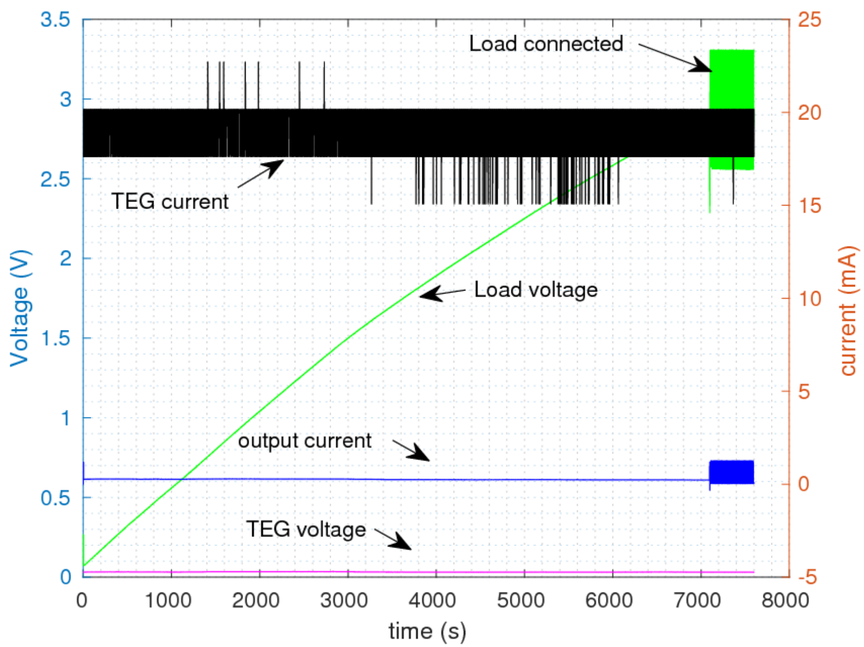
DC-DC converters



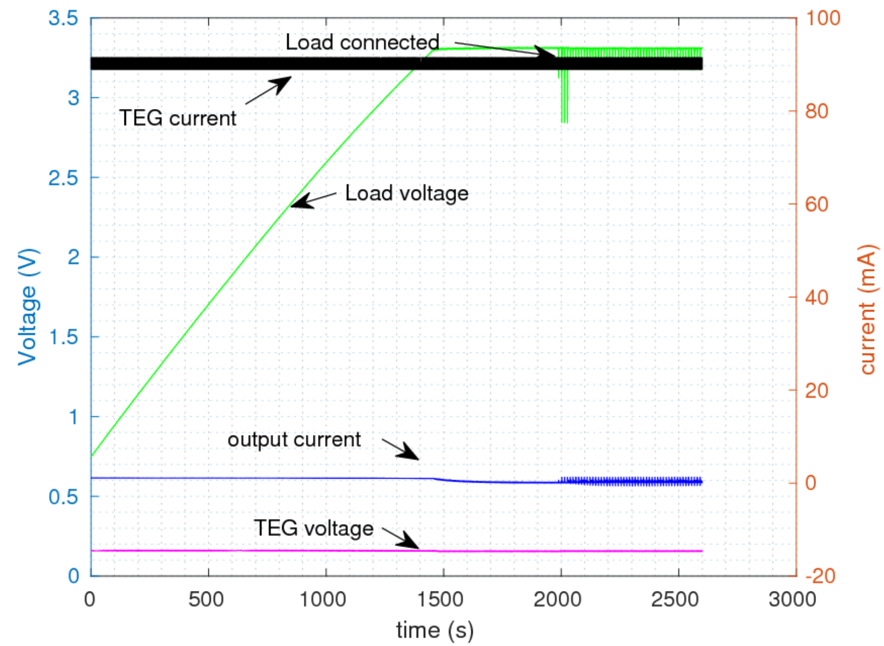
LTC3108

NEX WPG-1

Characterization Result of LTC module



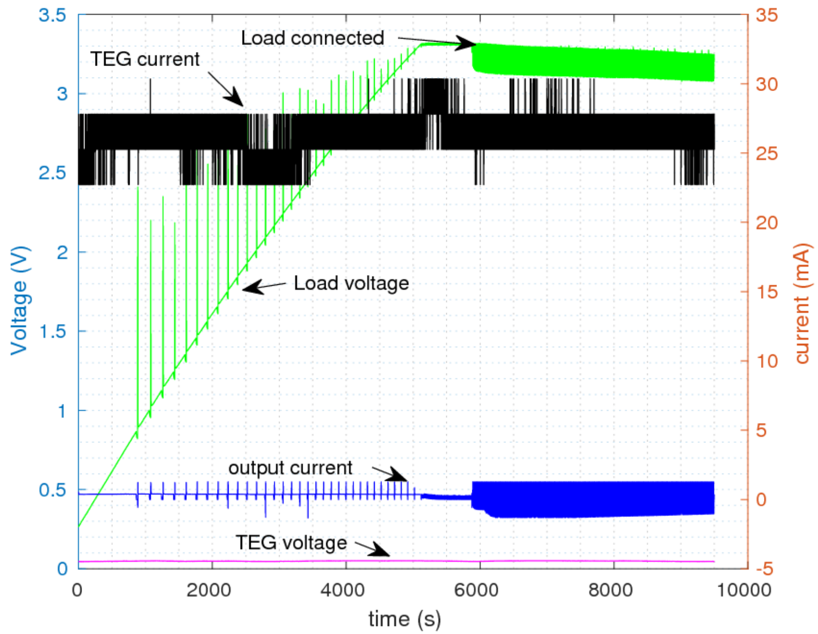
LTC3108 Supplied from TEG



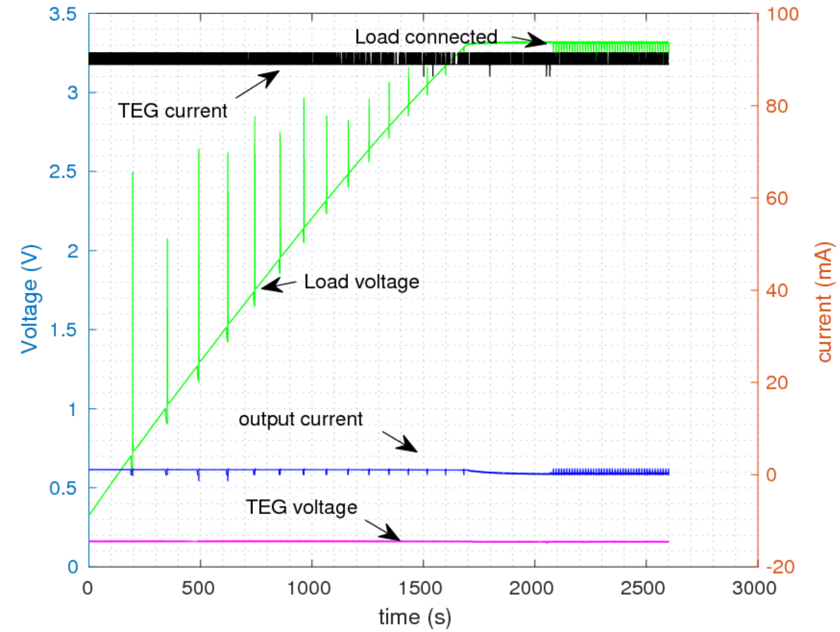
LTC3108 Supplied from d c

- DC supply: 16 minutes to reach 3V
- TEG supply: approximately 40 minutes

Characterization Result of Nextreme module



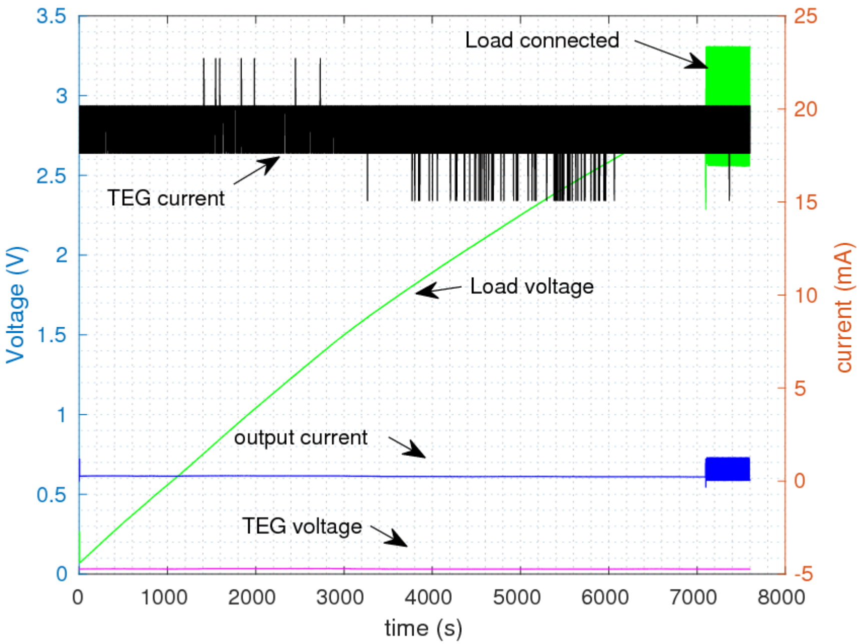
NEX WPG-1 Supplied from TEG



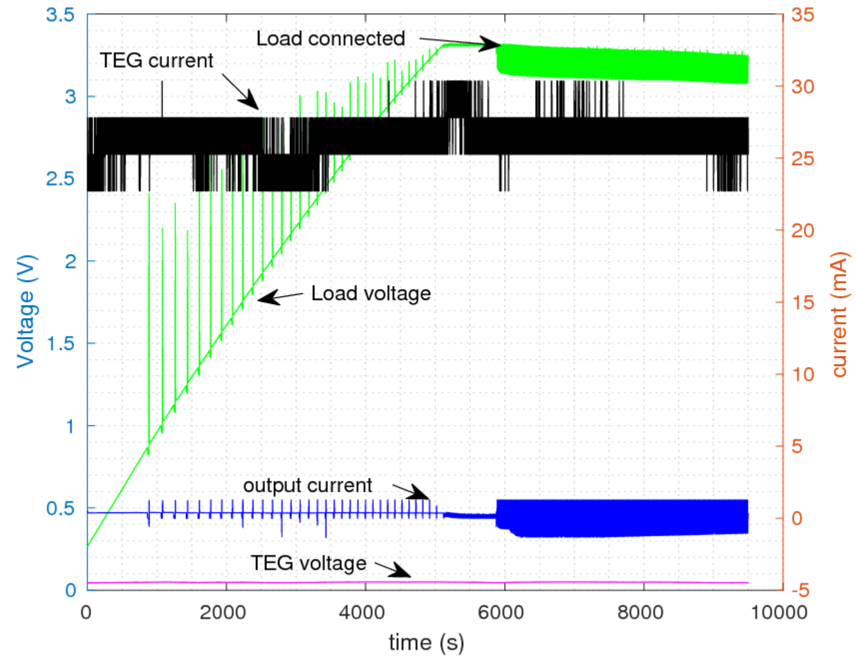
NEX WPG-1 Supplied from dc

- DC supply: 12 minutes to reach 3V
- TEG supply: approximately 25 minutes

Considerations



LTC3108 supplied from TEG



NEX WPG-1 supplied from TEG

In both cases, when supplied from TEG the output voltage remains stable after connecting the load

- *Application becomes* ***energy neutral***
- *Frequency of temperature TX controlled with internal clock*

Converter Characterization Result

Supply	LTC 3108 characterization				
	Vin [mV]	Iout [µA]	Pin [mW]	Pout [mW]	η (%)
TEG	78	250	1.69	0.83	49.1
DC	477	1000	42	3.16	13.29

Supply	Nextreme WPG-1 characterization				
	Vin [mV]	Iout [µA]	Pin [mW]	Pout [mW]	η (%)
TEG	136	380	3.4	0.95	27.1
DC	477	850	43.5	2.6	5.9

- In both cases efficiency dropped with increasing input power
- When supplied from the TEG
  - The Nextreme module took 25 minutes to charge the supercap
  - The LTC3108 module took 40 minutes but this was because the LTC module was getting less input power
  - LTC has higher efficiency but the WPG can extract more power from the same ΔT

LTC3108 selected because of higher efficiency

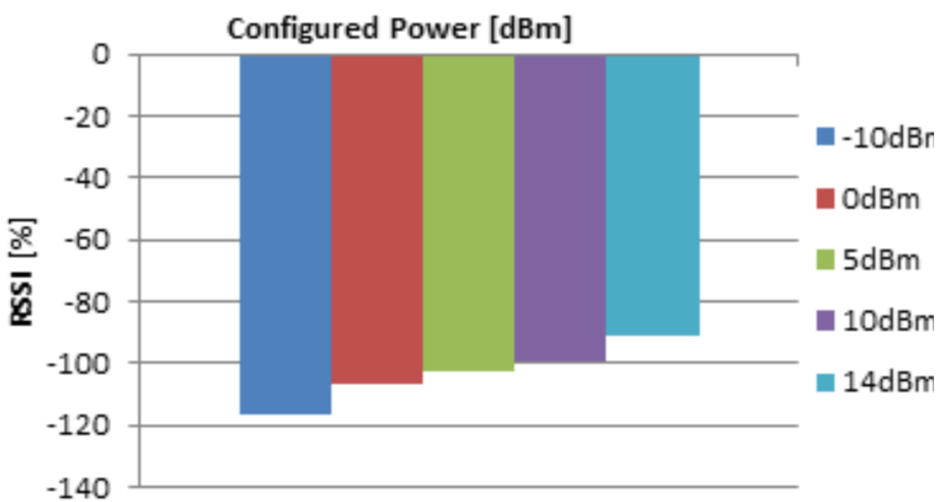
Self-Sustainable Application

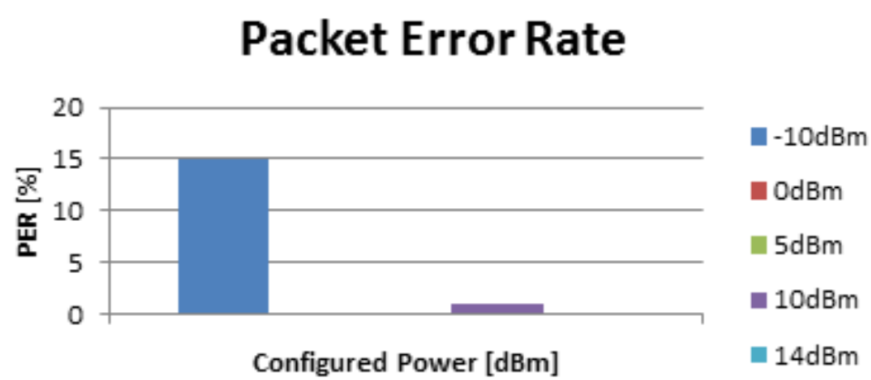
CC1310

- Low power SoC
- Sub-GHz Radio
- Custom LPWAN networks

Configured Power (dBm)	RSSI (dBm)	Numbers of Packets recieved	Numbers of Packets lost	PER (%)
14	-91	999	1	0.1
10	-99	989	11	1.1
5	-103	999	1	0.1
0	-107	998	2	0.2
-10	-117	851	149	14.9

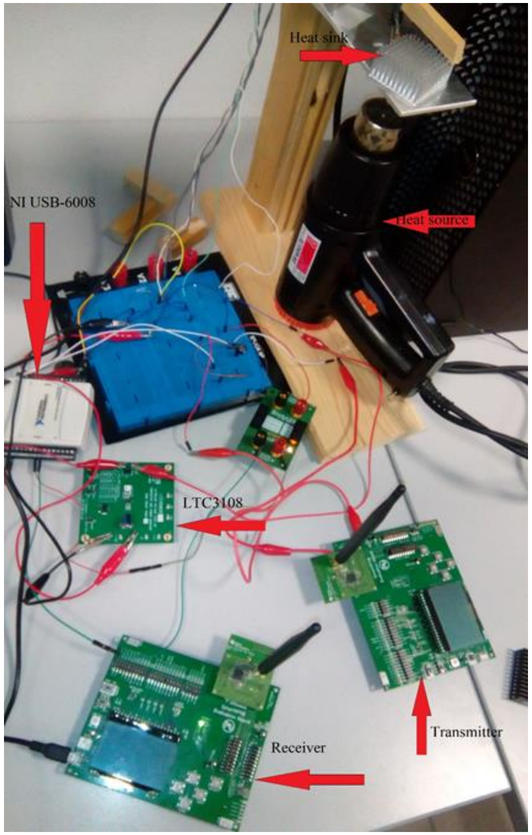
Negligible PER down to 0dBm @ 100m





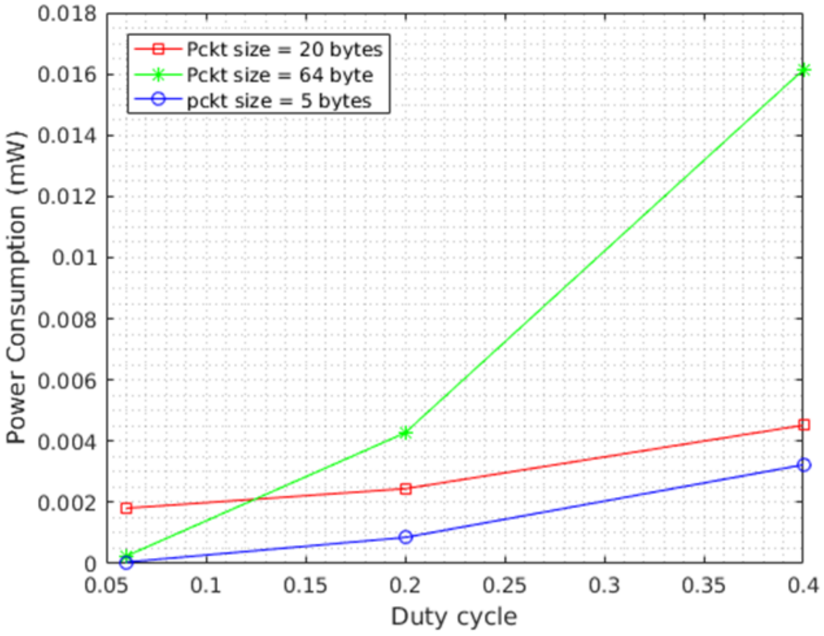
Self-Sustainable Application

- Transmitting temperature readings at **868MHz** GFSK
- System was tested by transmitting
  - 5, 20 & 64 bytes packets sizes
  - 40%, 20%, & 6.6% duty cycle by fixing the period to 500ms, 1s & 3s
  - TX power 14dBm (worst case)

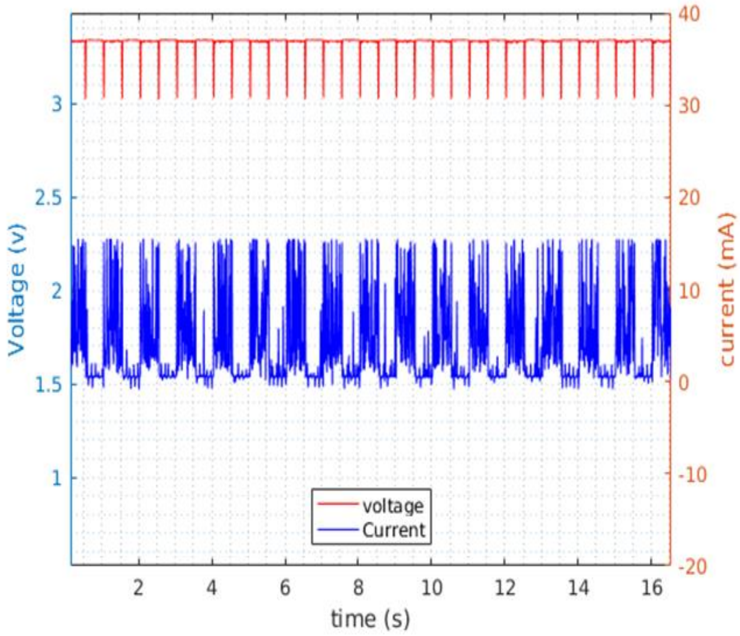


Self-Sustainable Application

TX Power vs. duty-cycle



Disaggregated consumption



CC1310's power consumption increases with packet size

- Trade-off between buffering and available energy
- Sleep mode exhibits µW consumption (when application is synchronized with clock)

Self-Sustainable Application

Label	Experimental Result					
	$\Delta T = 10$		$\Delta T = 20$		$\Delta T = 30$	
TEG1	P_{in} (mW)	1.8	P_{in} (mW)	16.4	P_{in} (mW)	44.5
	$\%d$	7.1	$\%d$	21	$\%d$	48
TEG2	P_{in} (mW)	0.18	P_{in} (mW)	0.87	P_{in} (mW)	2.0
	$\%d$	0.24	$\%d$	2.0	$\%d$	2.6
TEG3	P_{in} (mW)	0.15	P_{in} (mW)	0.45	P_{in} (mW)	1.4
	$\%d$	0.13	$\%d$	1.3	$\%d$	2.2

Computed duty-cycle

$$E_{tot} = E_{active} + E_{sleep}$$

$$P_{in}\, T = P_{tx}\, t_{tx} + P_{sleep}\, (T - t_{tx})$$

- E_{tot} is the total energy
- T is the total time which is the sum of transmission and sleep times
- t_{tx} is already determined from the experiment and is about 200ms
- Including conversion efficiency for LTC3108

Expected to stream temperature data **every 2.8s** (7.1% duty-cycle) with a ΔT as low as **10°C**

Conclusions

- This work was an investigation of designing smart safety-critical fasteners
- The powering of this system from a reliable, low cost, small size thermoelectric generators was investigated
- Accordingly the characterization of TEGs and DC-DC converters was done to determine
  - The maximum output power
  - The input resistance
  - The relationship between thermal gradient and output power
- Finally, the system was powered from one of the TEGs and its performance was tested

thank you very much for the kind attention

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