Some thoughts on Narrow-band Ultra-low-power Radio and Energy Harvesting

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Narrow-band ultra-low-power radio

Intensive research on UWB for short range, high data rate applications, e.g. video & audio over WBAN, data transfer computer ↔ peripherals

UWB claims many advantages, including:

robustness
interoperability
high bit-rate capability
low power (potentially at least)

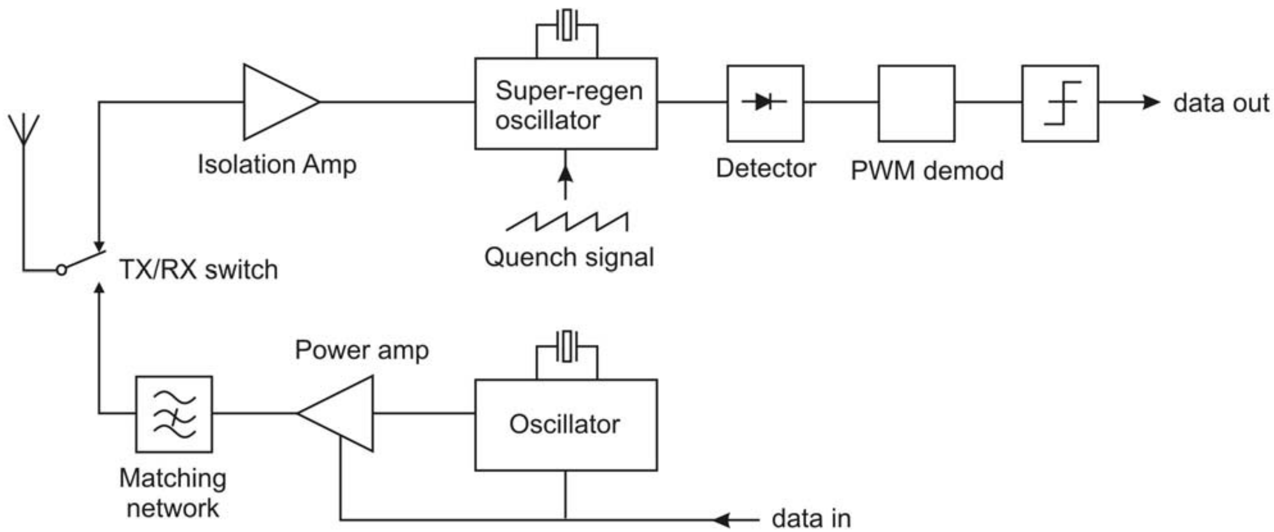
Q: Is there a place for narrow-band ultra-low power radio in WBAN / WSN?

Possible reasons for a 'Yes':

- lower ultimate operating power?
  - depends on detailed scenario: range, data rate, channel
- more tractable antenna problem
  - smaller antenna at given centre frequency
  - easier to achieve desired radiation pattern over bandwidth

ULPR transceivers

Typical low-power, narrow-band transceiver from literature (e.g. UC Berkeley):



SR design leads to very simple circuit, with potential for very low power

RX sensitivity not the best, but adequate for some scenarios

Significant amount of redundancy – can we simplify even further?

ULPR transceivers - simplifications

- At very short range (ca 1 m), radiated power becomes very small, and circuit losses dominate power consumption of transmitter circuit

$\Rightarrow$ should be able to improve efficiency by eliminating power amplifier

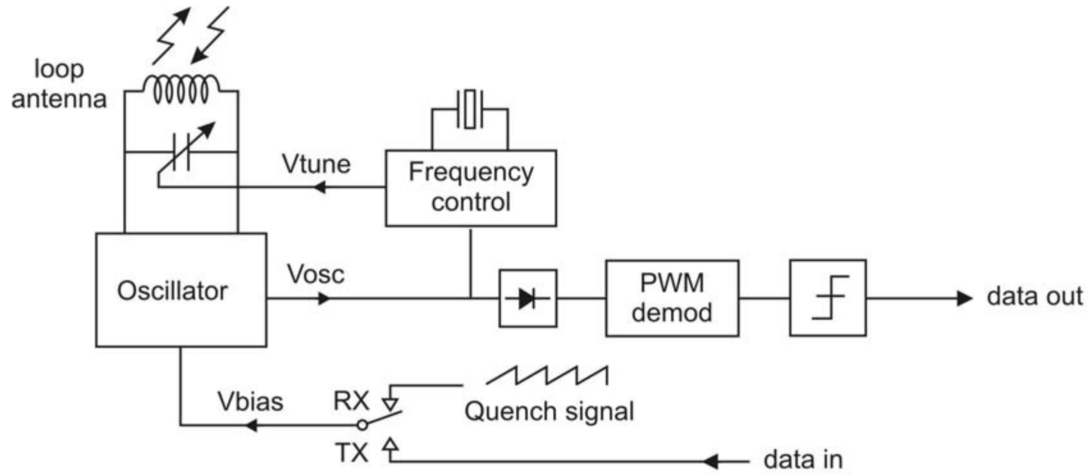
- With PA eliminated, (loop) antenna can be incorporated into oscillator as part of resonant circuit to make true “oscillator transmitter”

- Frequency reference – e.g. SAW/BAW/FBAR – probably still required in most applications, but may be able to operate on low duty cycle (cf “lock & roll” radio) depending on linewidth requirements

- Maybe even re-use the same oscillator/antenna configuration for transmitter and SR receiver … not done, and maybe a step too far, but attractive if feasible

ULPR transceiver proposal

Based on the arguments on previous page:



Open questions:

Can same oscillator/antenna really be used as basis of TX and RX?
- Sensitivity? Re-radiation? Antenna loading?

What frequency control scenarios are possible?
- Continuous? Periodic? None?

Is OOK modulation by power cycling really viable?
- Start-up time & chirp? Robustness/interoperability?

ULPR work at Imperial - antenna sizing

Analysis of power transfer (near and far field) between loop antennas as function of antenna size, frequency and range

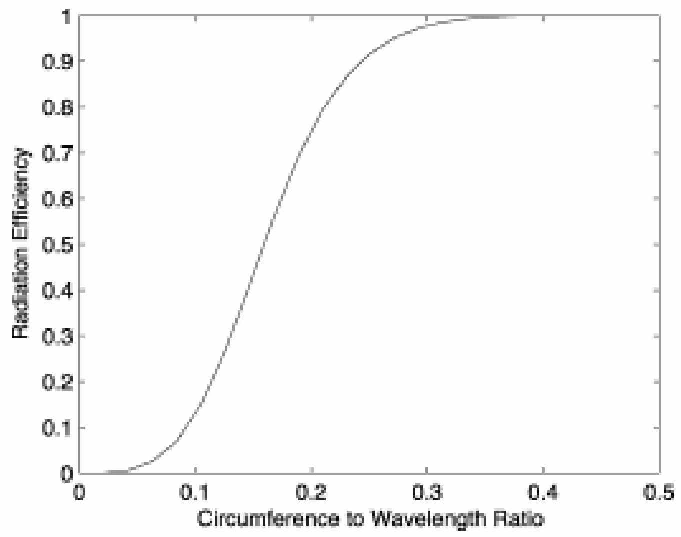


Fig. 18. Radiation efficiency versus electrical size for a loop antenna of radius 5 mm and a conductor radius equal to one twentieth of the loop radius.

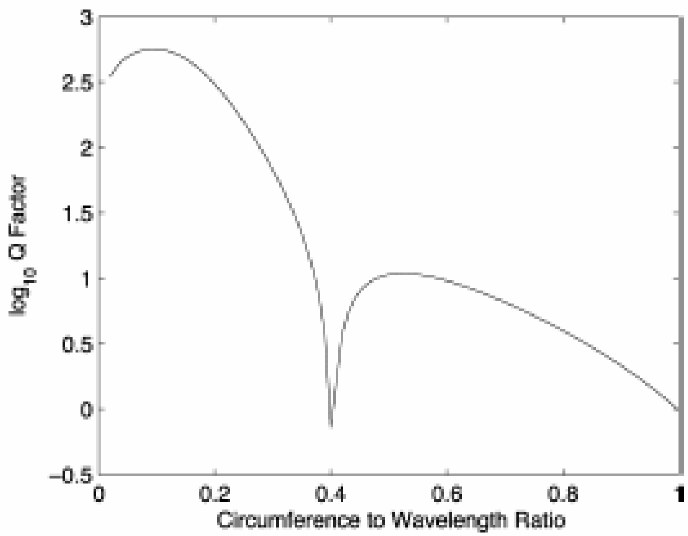


Fig. 20. Q-factor of a single-turn loop antenna against electrical size.

The electrical size can be chosen such that the single-turn loop antenna will exhibit both a high Q factor (for oscillator linewidth) and efficient radiation

Found that, for given antenna size constraint, optimal frequency in terms of power transfer corresponds to electrical size of $2\pi a/\lambda \sim 0.2$

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ULPR work at Imperial [2] – TX optimisation

Analysis of Colpitts/cross-coupled oscillator transmitters to determine bias current required for successful data transfer under different conditions (antenna size constraint, operating frequency, circuit design)

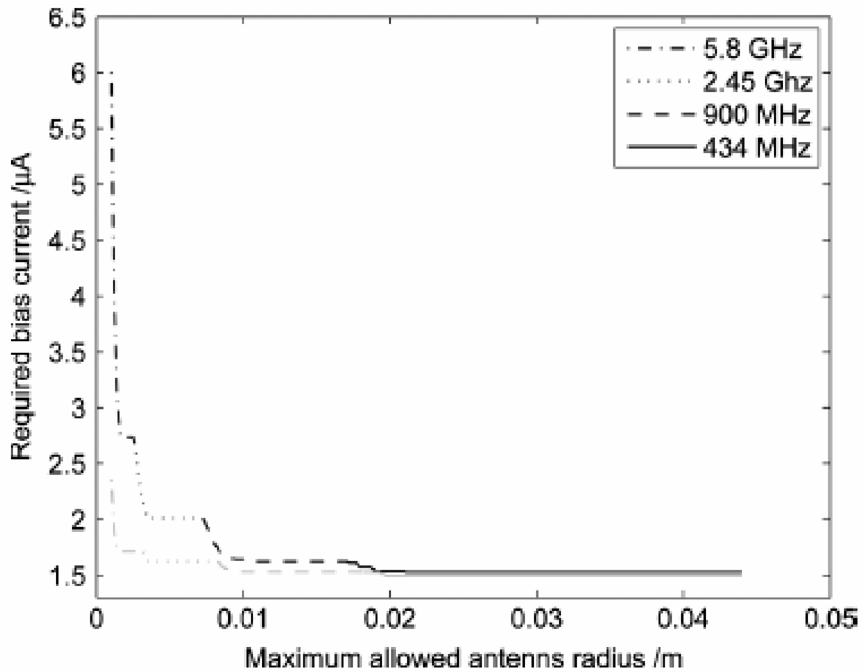


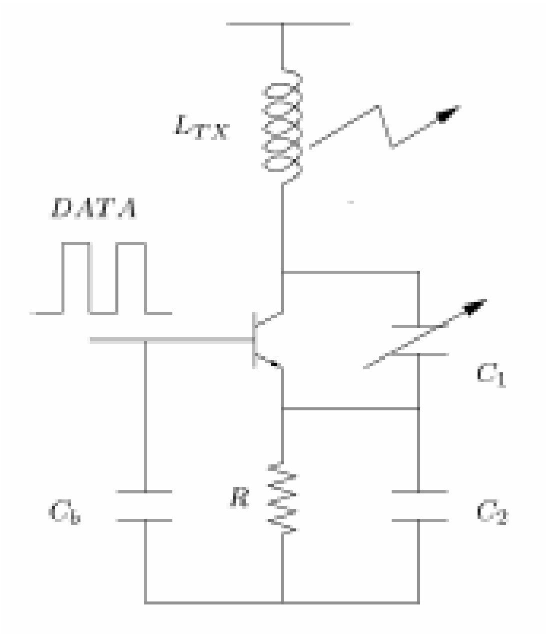
Fig. 7. Minimum Colpitts oscillator bias current required for successful demodulation against maximum allowed antenna radius for NF = 20 dB, r = 1 m. Grey line: data rate = 10 kb/s. Black line: data rate = 1 Mb/s.

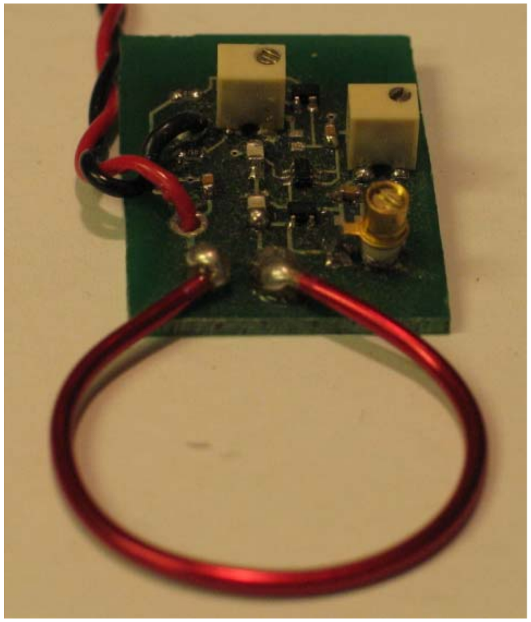
Graph shows – for Colpitts oscillator TX - preferred operating frequency from ISM bands, and minimum bias current for data transfer over 1 m range, as function of maximum allowed antenna size

Analysis is optimistic in assumptions about channel, but nevertheless results suggest that a transmitter with a mm-scale antenna should be able to achieve 1 Mbps over 1m with a TX power consumption below 10 μW

See: "Preferred transmission frequency for size-constrained ultralow-power short-range CMOS oscillator transmitters", D.C. Yates, A.S. Holmes, IEEE Trans. Circ. & Syst., 56(6), 2009, pp. 1173-1181

ULPR work at Imperial [3] – TX prototyping





Antenna size: 3cm diameter (circ. to wavelength ratio of 0.14 at 434 MHz)

434 MHz oscillation starts up with sub- 20 uA bias current (detected using spectrum analyser fed by similar loop antenna)

Self-powered wireless duct sensor

Figure 2. Prototype turbine installed in the experimental section of an 18" × 18" wind tunnel.

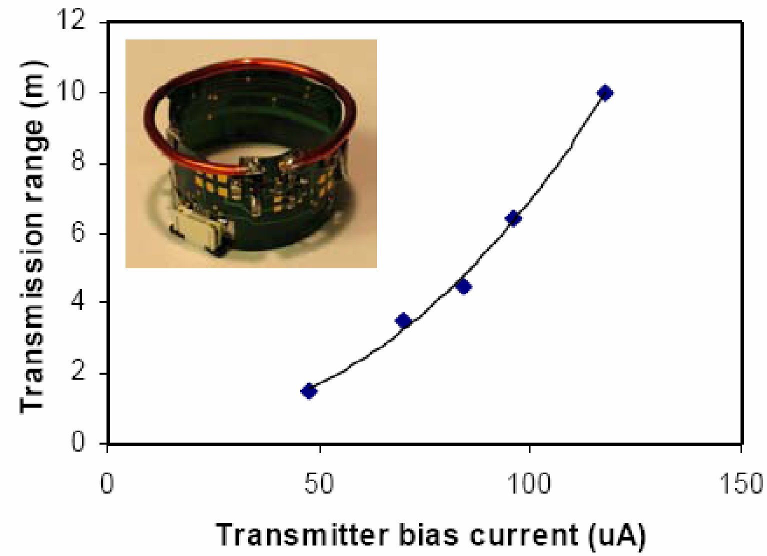


Figure 4. Measured variation of transmission range with bias current for Colpitts oscillator transmitter. The receiver is an RF Solutions AM-HRR3-433.

Battery-less sensor comprising: 2 cm-dia shrouded turbine + power conditioning electronics, microcontroller, temperature sensor and osc transmitter

2 kb/s data transfer to commercial SR receiver module demonstrated

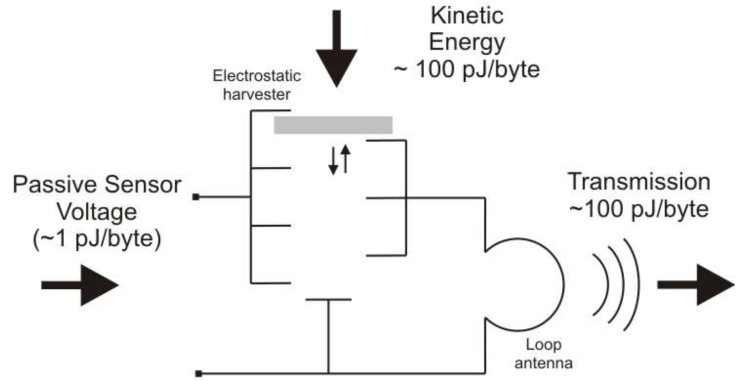
See: "Self-powered wireless sensor for duct monitoring", A.S. Holmes, D.A. Howey, A. Bansal, D.C. Yates, to be presented at PowerMEMS 2010

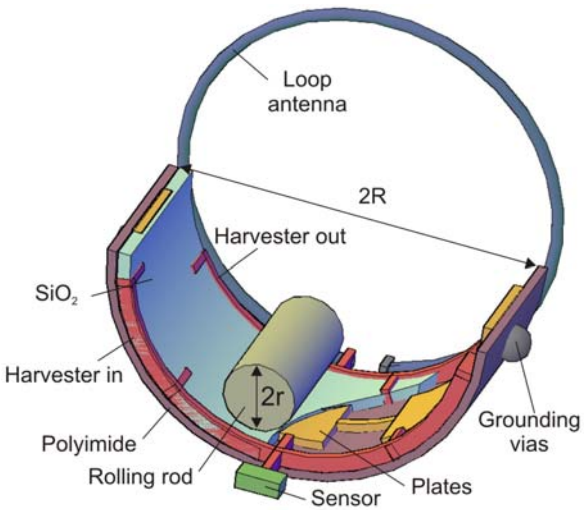
Kick-and-resonate transmitter

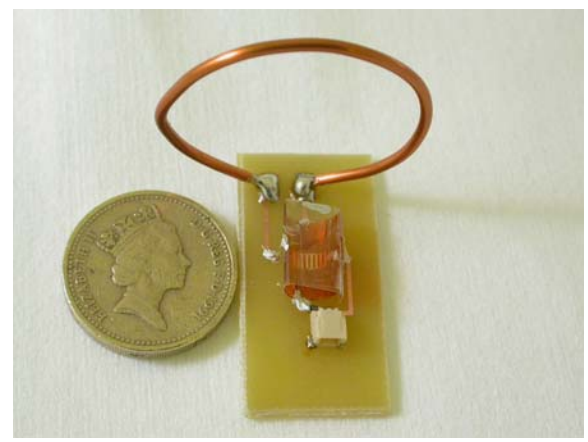
Limit of simplification?

Sensor output provides priming voltage for motion-driven electrostatic generator

Generator discharged through resonant loop antenna sized for high Q and efficient radiation

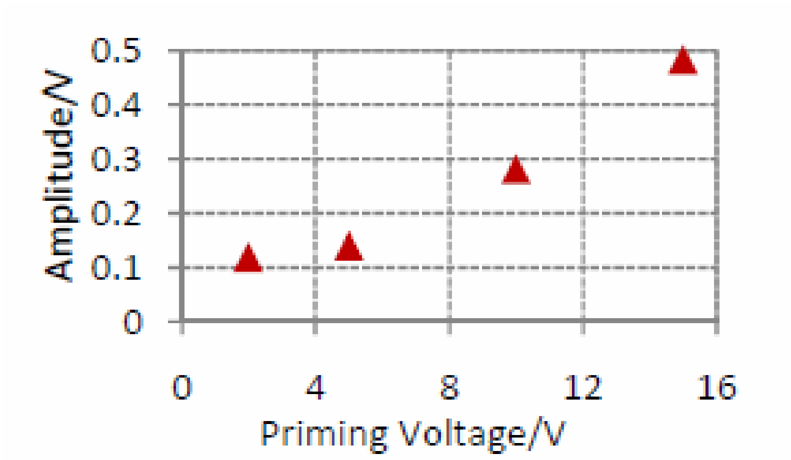


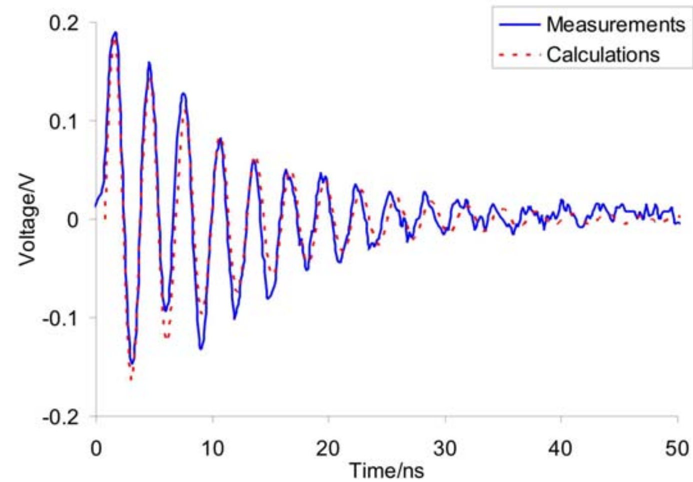




See: "MEMS energy harvester for wireless biosensor", C. He, M.E. Kiziroglou, D.C. Yates, E.M. Yeatman, Proc. MEMS 2010, pp. 172-175

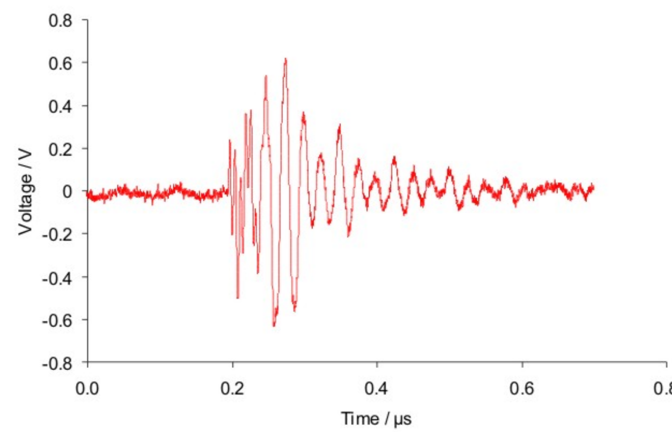
Kick-and-resonate transmitter demo





Capacitively tapped measurement of the discharge of the harvested power through the loop antenna showing oscillation at 330 MHz.

- Successful transmission and detection achieved over 1m
- Increased frequency will allow smaller antenna
- Need to improve fidelity of detection system and reduce working priming voltage range

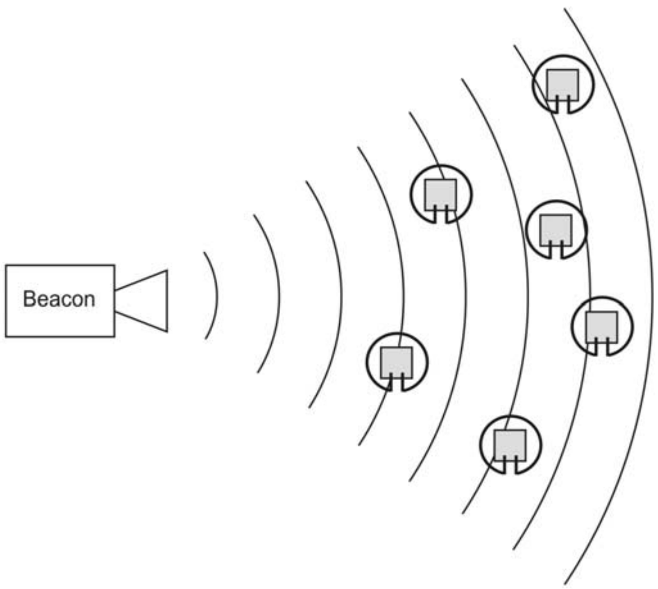


Detection of oscillation primed by 1 V, at a distance of 1 m.

Energy harvesting – downscaling

At micro-scale (and probably even sub-mm-scale) there is little prospect of energy harvesting from "already present" ambient energy sources. This is not being defeatest; it is just being realistic.

Wireless energy distribution from an installed source or "beacon" is an attractive solution. This was in NAWIS… nevertheless we should not dismiss it!



Beacon delivers power – either by flooding local environment or via directed beams; motes accumulate energy and re-radiate to communicate peer-to-peer or with higher level node

Energy exchange between motes also a possibility

For small motes, mm-Wave or THz look attractive. Should we be looking for additional partners for this?

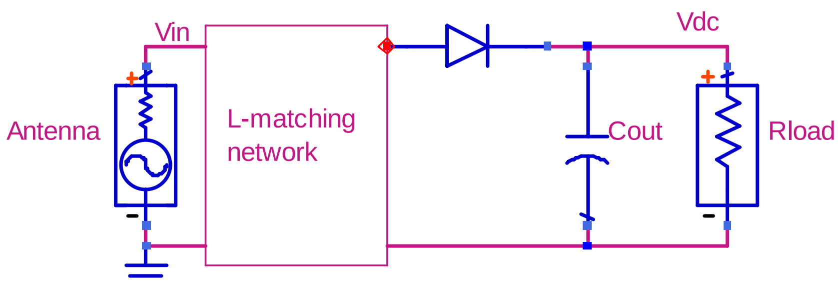
Could also look at optical power delivery for some scenarios

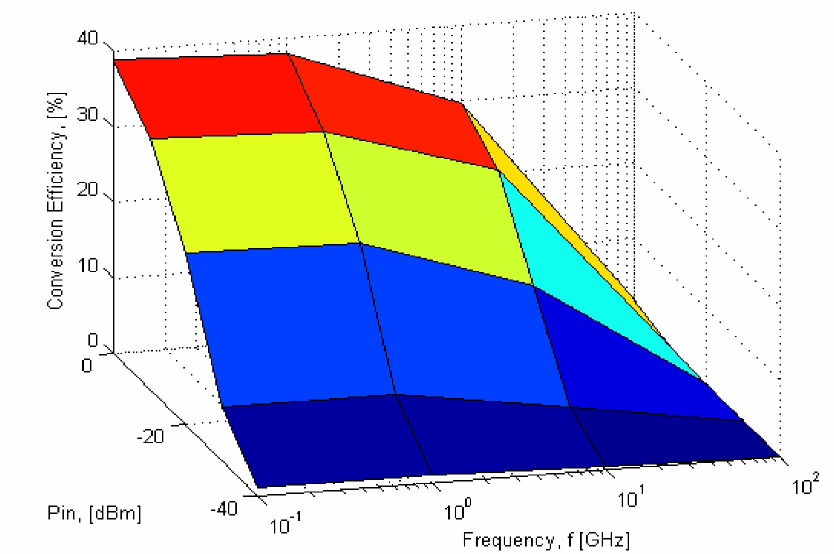
EM power delivery – initial work at Imperial

Simulation (Agilent ADS) of energy harvesting rectennas over 0.1 - 100 GHz

Comparison of different zero-bias Schottky diode detectors: HSMS-2850, SMS-7630, and MZBD-916

Comparison of different topologies: series, shunt, voltage doubler





Conversion efficiency vs input power and frequency for matched series rectenna with MZBD-9161 diode

MZVD-9161 achieves 7% conversion efficiency at 60 GHz with 0dBm power input – this is useful

See: "Analysis of scalable rectenna configurations for harvesting high frequency ambient radiation", M. Pinuela, P.D. Mitcheson, S. Lucyszyn, to be presented at PowerMEMS 2010

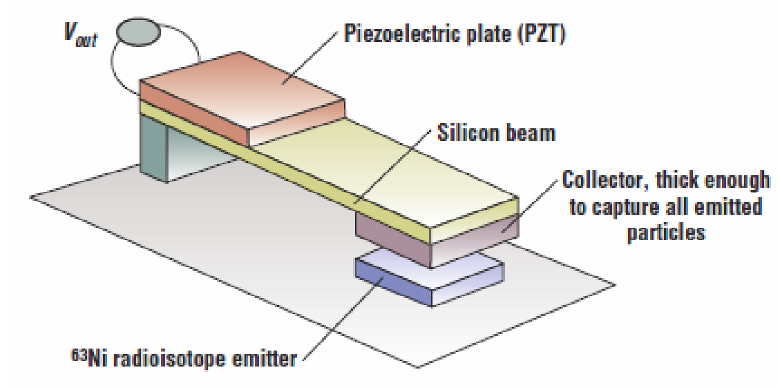
Energy harvesting - priming

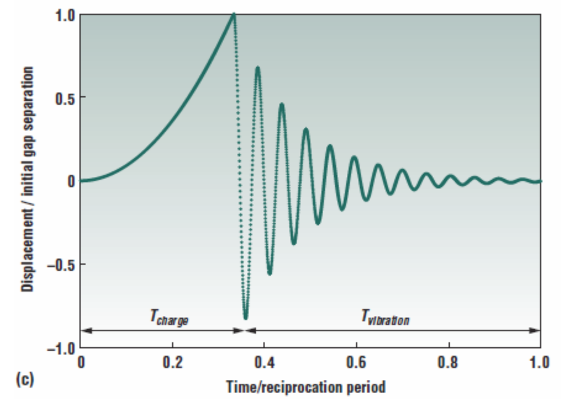
Harvester and power conditioning electronics must be able to start "from cold"

Need to be able to generate ~ 0.5 V for priming, and this is increasingly difficult as devices size shrinks

Possible solutions: electret; micro-battery; radioactive battery

Radioactive approach is particularly interesting because of very long lifetime e.g. work at Cornell Univ:





From: A. Lal et al, Pervasive Computing 4, pp. 53-60 (2005)

Can/should we try to build collaboration here? We bring piezo and power conversion/conditioning expertise

Energy harvesting - transduction

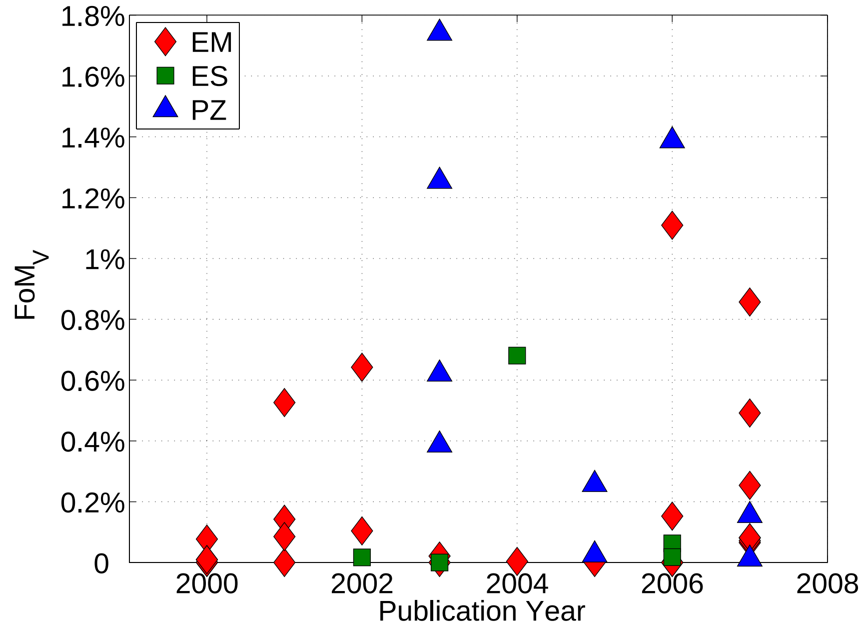
With downscaling it becomes increasingly difficult to realise an effective (strong) electromechanical damper for transduction

This is one of the main reasons for the poor performance of most energy harvesters to date

Piezo devices most promising and can be further enhanced through research on:

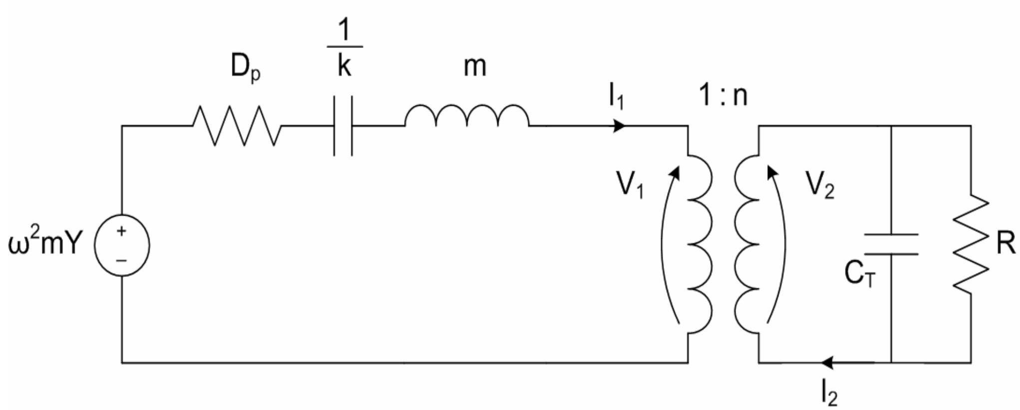
Materials – e.g. piezo nanostructures (Univ Houston and others)

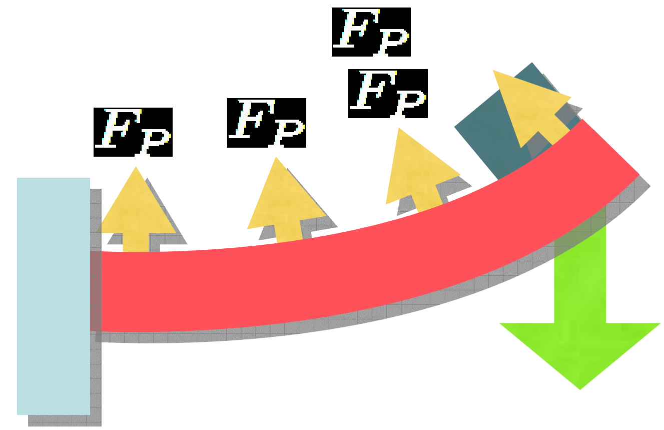
Pre-biasing and related methods…



$$FoM_V = \frac{\text{Useful Power Output}}{\frac{1}{16}\rho_{Au} Vol^{4/3} Y_0 \omega^3}$$

Piezoelectric pre-biasing



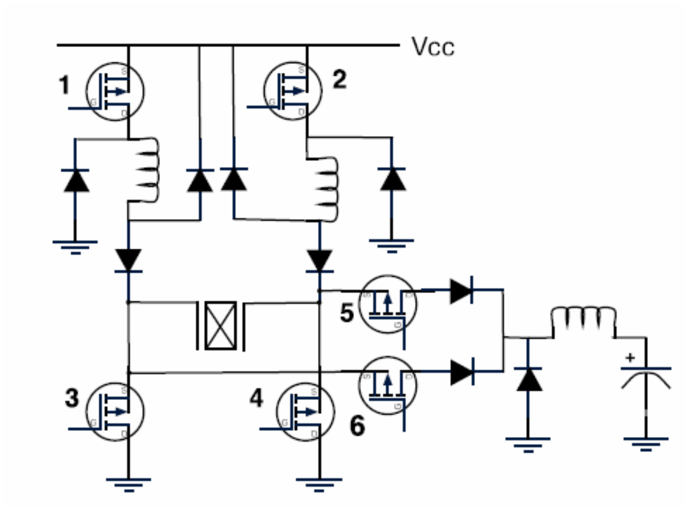


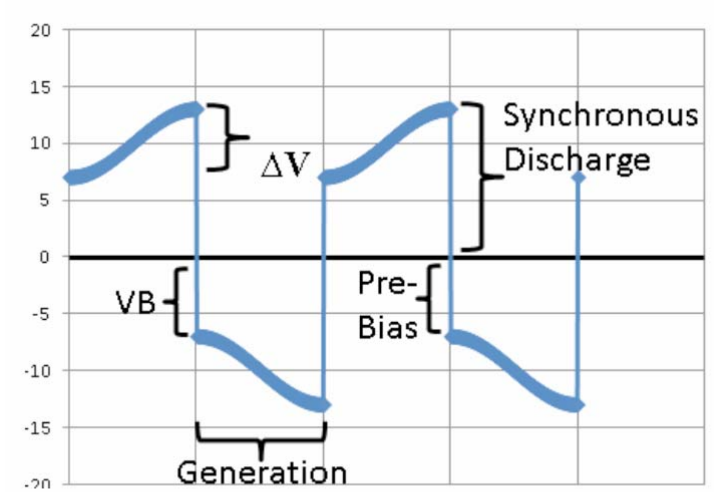
Putting a bias charge on the piezoelectric layer (pre-charging C_T) makes it impose a higher mechanical load on the beam, allowing more energy to be extracted when the beam moves

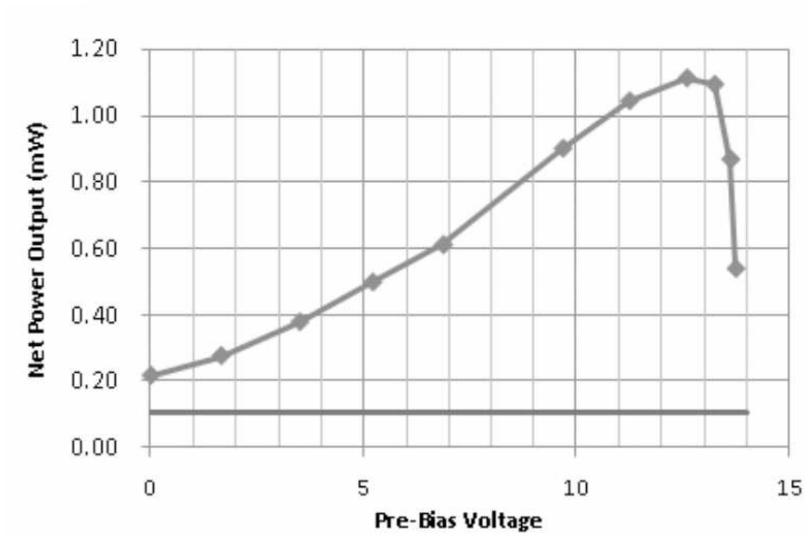
Pre-charging and discharge must be carefully synchronised with beam motion

Technique demonstrated giving power output increase of 20 times over resistive load

Piezoelectric pre-biasing [2]







Upper graph: idealised voltage waveforms to achieve increased damping

Lower graph: measured results showing up to ~11× increase in net o/p power over simple resistive load

See: "Increased power output from piezoelectric energy harvesters by pre-biasing", Dicken J., Mitcheson P.D., Stoianov I., et al, Proc. PowerMEMS 2009, pp. 75-78

Summary

Interesting areas for us, mainly building on existing activities (at various stages of development):

- Pushing power limits of narrow-band, short-range ultra-low power radio – mainly through simplified architectures with antenna/RX/TX co-design
- mm-Wave / THz power delivery – new area for us, but we have been building links with other groups at Imperial and across UK
- Vibration energy harvesting – improving conversion efficiency of piezo devices; priming technologies (would need to be in collaboration others)