Optimal Transmission Frequency for Ultra-Low Power Short-Range Medical Telemetry

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Motivation

- Develop wireless medical telemetry to allow unobtrusive health monitoring
  - Patients can be conveniently monitored whilst moving around
  - Enables people's vital signs to be monitored at home
- It is desirable that wireless medical sensors are autonomous and unobtrusive
  - Energy scavenging
  - Long battery lifetimes
  - Small physical size
- Difficult combination since a small physical size results in:
  - Low battery capacity
  - Small volume/area from which to capture energy
  - Poor antenna efficiency or high transmission frequency

Requirements

- Device should consume no more than around 1μW
  - Lifetime of years for small coin cell
  - Energy scavenging becomes realistic
- Some biometric signals such as ECG require data rates in the kb/s
- Current 'off the shelf' transceivers and those presented in the academic literature would achieve data rates of a few tens of bits per second if operated at a sufficiently low duty cycle
- We aim to increase this to a few kb/s

Approach

- Need to lower the power consumption of the RF transceiver by about 100 compared to conventional designs
- Make power the main design criterion
- Trade power with:
  - Performance
  - Range
  - Spectral efficiency
- Examine the fundamental trade-offs
  - Trade-off between antenna efficiency and power dissipation in the RF electronics
  - Often mentioned but little work had previously been done to quantify this

Optimal Transmission Frequency

- Antenna dimensions will be constrained for wearable, embedded or implanted devices
- Small antenna dimensions require high frequencies to be efficient
- However, power dissipation in RF electronics will increase with frequency
- We have analysed the optimal frequency in terms of maximum power transfer from the transmitting antenna to receiver
- Having identified a suitable transmitter topology the power dissipation as a function of frequency has been evaluated and taken into account to find a modified optimal frequency

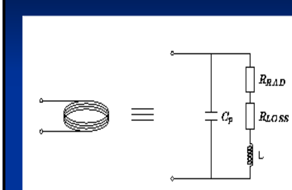
Near-Field versus Far-Field

- Two main regions surround a transmitting antenna
  - Near-field contains stored energy (i.e. reactive power)
  - Electromagnetic waves radiate in the far-field
- A receiver at a distance, r, from the transmitting antenna will lie in the near field if the carrier frequency, f, is $< c/2\pi r$
- To determine the optimal transmission frequency we must evaluate the power transfer in both the near- and far-fields
- The mathematical relationships differ substantially depending on the field region

The Loop/Coil Antenna

- The analysis has been performed for the loop antenna
- The loop antenna has been identified as the most suited to medical telemetry
  - Suitable for mobile applications due to being fairly omni-directional
  - Electrically larger than monopole in given volume
  - Used in near-field wireless power delivery systems such as passive RFID and medical implants
    - Useful to have this facility to provide initial energy to power scavenging system or to re-charge the battery
  - Particularly useful in low power short range transmitters such as that presented in [1]

Lumped Loop Antenna Model

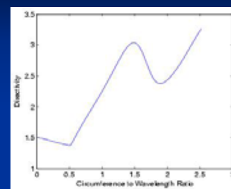


- $R_{RAD} \equiv$ radiation resistance
  - The radiated power is : $P_{RAD} = I^2 R_{RAD}$
- L is the antenna inductance
- $R_{LOSS} \equiv$ series ohmic resistance
- C_p is the parasitic inter turn capacitance

Far-Field Analysis

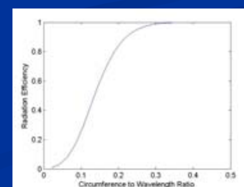
- Model power transfer using well known Friis equation
  - $P_R / P_T = p\eta_T D_T \cdot \eta_R D_R \cdot (\lambda/4\pi r)^2$
- η is the radiation efficiency of the antenna
  - $\eta = R_{RAD}/(R_{RAD}+R_{LOSS})$
  - $P_{RAD} = \eta P_T$
- D is the antenna directivity, defined as the ratio of radiation intensity in a given direction to the average radiation intensity
  - $D = U(\varphi, \theta)/U_0$
- These antenna parameters have been modelled in MATLAB for varying antenna dimensions and frequency

MATLAB Implementation

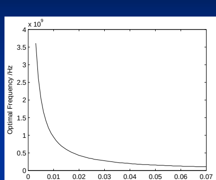


The electrical size of the antenna should be less than 0.5 wavelengths to ensure non-directional nature is maintained

The radiation resistance dominates the total input resistance of the loop antenna if its circumference is larger than about 0.35 wavelengths

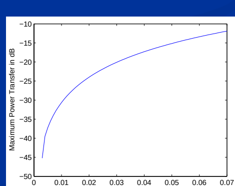


Optimal Far Field Frequency



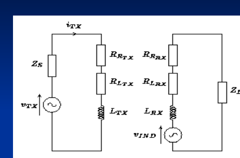
The optimal far-field frequency for a given constraint on antenna dimensions can be evaluated using this analysis

The power transfer for the optimal frequency increases with increasing antenna size



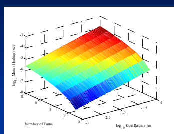
Near Field Power Transfer

- For this application area the transmission distance will be large compared to the coil radius
- Voltage induced at the transmitter coil due to the receiver will be negligible
- For an optimally driven, impedance matched and poorly coupled system, we have derived a near-field power transfer equation
- This allows direct comparison with the Friis equation
- Provides intuitive insight into how to maximise the power transfer



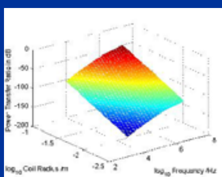
$$\frac{P_{RX}}{P_{TX}} = p\,\frac{\mu_0^2 \pi^2 N_{TX}^2 N_{RX}^2 a_{TX}^4 a_{RX}^4 \omega^2}{16 R_{TX} R_{RX} r^6}$$

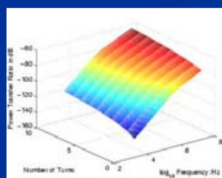
Near-Field Results



Mutual inductance small for this application

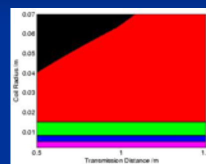
Numerator of near-field power transfer equation dominates

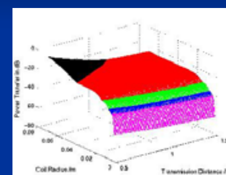




Optimal Transmission Frequency

- Designer has the choice between different frequency bands
- Using the analysis presented, a comparison can be made between different bands



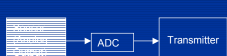


NF- 40MHz, FF - 433MHz - 900MHz - 1.8GHz - 2.4GHz

- Wire radius – 1/20th the coil radius until it reaches a maximum of 2mm

What is possible?

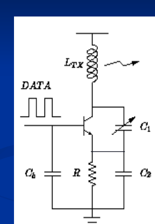
- Current 'off the shelf' devices consume over 1,000 times 1μW for required data rate
- BUT take a simple telemetry link:



  - MAX6613 temperature sensor: continuous power consumption = 20μW
  - An ADC presented in IEEE Journal of Solid State Circuits dissipated 40μW whilst achieving a bandwidth of 16kHz with 77dB dynamic range
  - A simple Colpitt's oscillator transmitter presented in [1] consumed 300 μW for a transmission distance of 3 feet at a data rate of 1Mb/s
- 100 samples per second at 10bits/sample requires a 1kbps data link
- Above components would dissipate less than 500nW in order to achieve this!

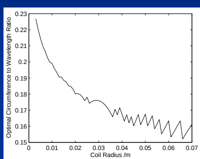
Low Power Transmitter Topology

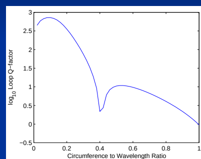
- Conventional transceiver topologies consume too much power for this application
- Candidate solution:
  SIMPLE OSCILLATOR TRANSMITTER
  REGENERATIVE RECEIVERS
- Power amplifier / LNA not required for short range communication
- Loop antenna is also the frequency defining inductor in the oscillator
- Remove power hungry PLL



Antenna Q-Factor

- Important result of this work is that the optimal electrical size of the loop antenna corresponds to a high antenna Q factor





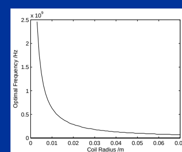
- This means efficient far-field transmission, low bandwidth and minimal power needed for oscillation can all be achieved

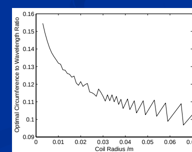
Transmitter Losses

- Assuming the antenna dominates the losses, the bandwidth of the transmitted signal is given by:

$$\Delta_{osc} = \frac{1}{V_{TANK}^2}\cdot\frac{kT}{C}\cdot\frac{\omega_0}{Q}$$

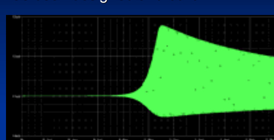
- Set receiver bandwidth set to capture the transmitted signal power
- This can be taken into account in the optimal frequency analysis



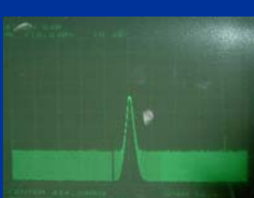


Prototype Design

- A 434MHz surface mount prototype has been designed and built
- After simulation and optimisation the power consumption for operation at 1kb/s is predicted to be less than 100nW



Power consumption of optimised colpitts oscillator transmitter operating continuously (above)



Frequency spectrum of transmitter captured using an HP8560A spectrum analyser (left)

Challenges and Future Work

- Improve operation of simple transceiver topologies
  - Alternative methods of frequency control
  - Optimise designs
- Consider system level design
  - Switch off devices completely when not used
  - TDMA allows a certain amount of frequency drift
- Continue experimental work to verify theory
- Build 2.4GHz prototype (antenna size about 6mm diameter)
- Continue theoretical work on optimal frequency

References

[1] Zaie et al, *A Low Power Miniature Transmitter Using a Low-Loss Silicon Platform for Biotelemetry*, IEEE EMBS, Proc. 19th Annual International Conference, vol 5, 1997, pp. 2221 - 2224

[2] D. C. Yates, A. S. Holmes and A. J. Burdett, '*Optimal Transmission Frequency for Ultra Low Power Short Range Radio Links*', Accepted for Publication in IEEE Trans. Circuits and Systems Part I: Circuit Theory