Radio Frequency Energy Harvesting Project

Final Report for Science Faculty REF Fund

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1. Introduction

The ever increasing use of wireless devices, such as mobile phones, wireless computing and remote sensing has resulted in an increased demand and reliance on the use of batteries. With semiconductor and other technologies continually striving towards lower operating powers, batteries could be replaced by alternative sources, such as DC power generators employing energy harvesting techniques.

Radio frequency (RF) energy harvesting, also referred to as RF energy scavenging has been proposed and researched in the 1950s [1-2] using high power microwave sources, as more of a proof-of-concept rather than a practical energy source, due to the technologies available at the time. However, with modern advances in low power devices the situation has changed with the technique being a viable alternative to batteries in some applications. Particularly, for wireless devices located in sensitive or difficult access environments where battery operated equipment might not of been previously possible.

In the modern environment there are multiple wireless sources of different frequencies radiating power in all directions. Fig 1(a) shows some that potentially could be exploited for RF energy harvesting applications. These might be, but not limited to; TV and radio broadcasts, mobile phone base stations, mobile phones, wireless LAN and radar.

Fig 1(b) shows a block diagram of a basic energy harvesting system [3], where a transducer – typically an antenna or antenna array – harvests ambient electromagnetic energy. This harvested energy is rectified and filtered. The recovered DC then, either powers a low powered device directly, or stored in a super capacitor for higher power low duty-cycle operation.

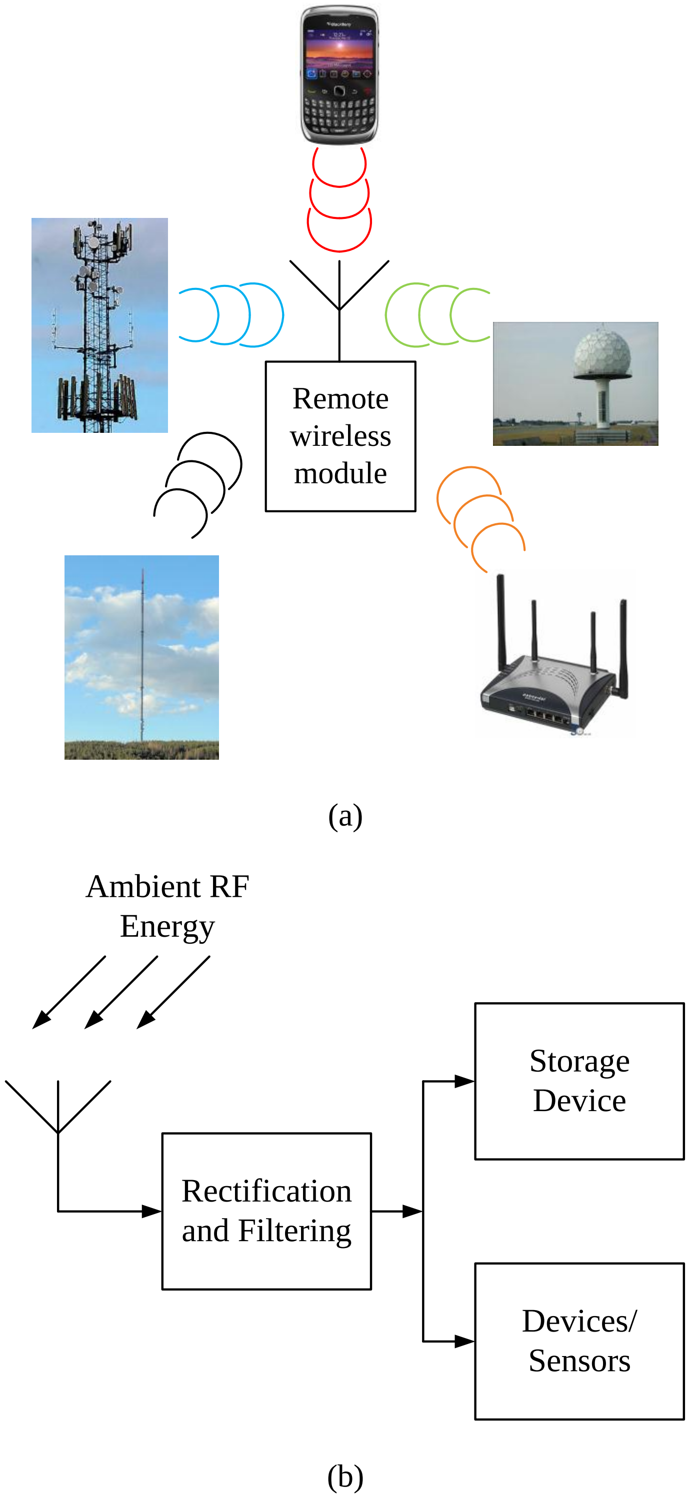


Figure 1. (a) Potential RF harvesting sources. (b) Basic RF energy harvesting block diagram.

Frequency selection is an important consideration in RF Energy Harvesting (RFEH) systems and at the same time might be environment specific. As an example for an indoor application wavelengths up into the low GHz would be a better choice, due to their ability to propagate well in these environments, rather than lower VHF/UHF transmissions. These might be more useful to outdoor or remote location harvesting applications. This project considers and indoor built environment application, where the frequency selection reflects this.

Generally in the modern built environment GSM mobile phone signals are prevalent, and propagate well both into and out of buildings, offering harvesting potential from both the GSM base stations as well as the user's handsets. With the general growth of mobile phone usage additional bands have been brought into service to cope with the demand. Three bands are used in the UK and are shown below.

UK CELLULAR FREQUENCY RANGES

GSM 900 Frequency Range:

Mobile transmit (BTx) 880 - 915 MHz
Base transmit (MTx) 925 - 960 MHz

GSM 1800 Frequency Range:

Mobile transmit (BTx) 1710 - 1785 MHz
Base transmit (MTx) 1805 - 1880 MHz

Third-Generation (3G) Frequency Range:

Base transmit (BTx) 2110 - 2170 MHz
Mobile transmit (MTx) 1920 - 1980 MHz

BTx / MTx In TDD (Time Division Duplex) 1900 - 1920 MHz

Making full use of the available bands presents its own challenges, where the options are for narrowband or broadband systems. The design of broadband antennas and their associated matching networks generally results in a compromised design resulting in lower efficiencies and hence, less energy recovered.

2. Antenna Design

From the information previously presented the antenna needs to offer.

- Narrow band, GSM 3 band operation
- Multi-polarisation
- Convenient matching impedance for maximum power transfer to the following rectifier circuitry.

Various antenna types have been previously employed in RFEH applications, from the simple dipole to more complex designs such as the bow tie or spiral antenna. Although the latter offer good performance in terms of polarisation they are generally limited to broad band designs with usable bandwidths of a few hundred MHz or so. Currently multi frequency narrow band designs are usually limited due to the need for a complex feed arrangement to each antenna element. Presented in this project is a novel design for a 3 band antenna based on close coupled resonant elements.

2.1 Close Coupled Resonator

As we all know, nearby conductors can interact with an antenna, this phenomonem is exploited in antenna designs such as the sleeve, or skeleton sleeve dipole [4] in achieving dual-band operation, a further development of these designs is the close coupled resonator (CCR) antenna. Figure 2 illustrates the general principle of operation of the CCR antenna. Each figure shows the return loss at the feed point of a dipole, over a range of frequencies. With a single dipole element as in Fig 2(a) at its half-wave resonant frequency a good return loss presented. Next, if another conductor is brought close to the dipole, we will start to see a secondary resonance appear at the resonant frequency of this new conductor as in Fig. 2(b). As we bring this additional conductor closer we reach a point where the return loss is at maximum and the antenna is now presenting a good math at both frequencies F_1 and F_2 as shown in Fig. 2(c). Depending on the structure this process can be repeated with several more conductors yielding a multi-band design. From the UK cellular band plan, for our 3 band GSM design the band centres are, 0.92, 1.8 and 2GHz.

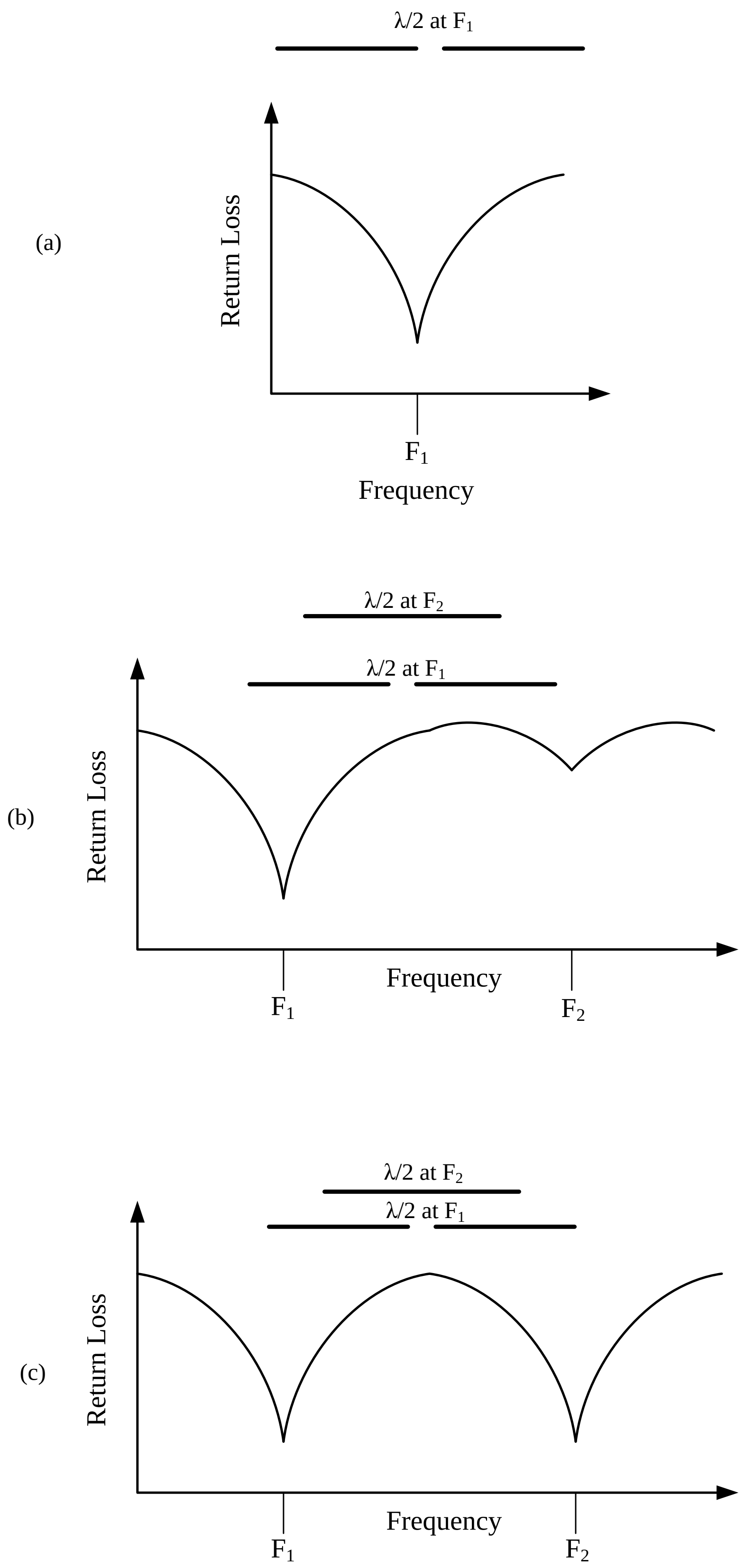


Figure 2. (a) Return loss plot of a dipole over a wide frequency range. At (b) a nearby conductor is just close enough to interact with the dipole. At (c) the second conductor is at optimum spacing. The combination is matched at both frequencies.

Figure 3 shows a CCR antenna design for energy harvesting applications. The design supports 3 band operation in both horizontal and vertical polarisations. This is achieved by including two sets of resonant elements placed at 90^o to one another. Both of which are separated by the thickness of the PCB substrate material, which in this case is 1.6mm FR4.

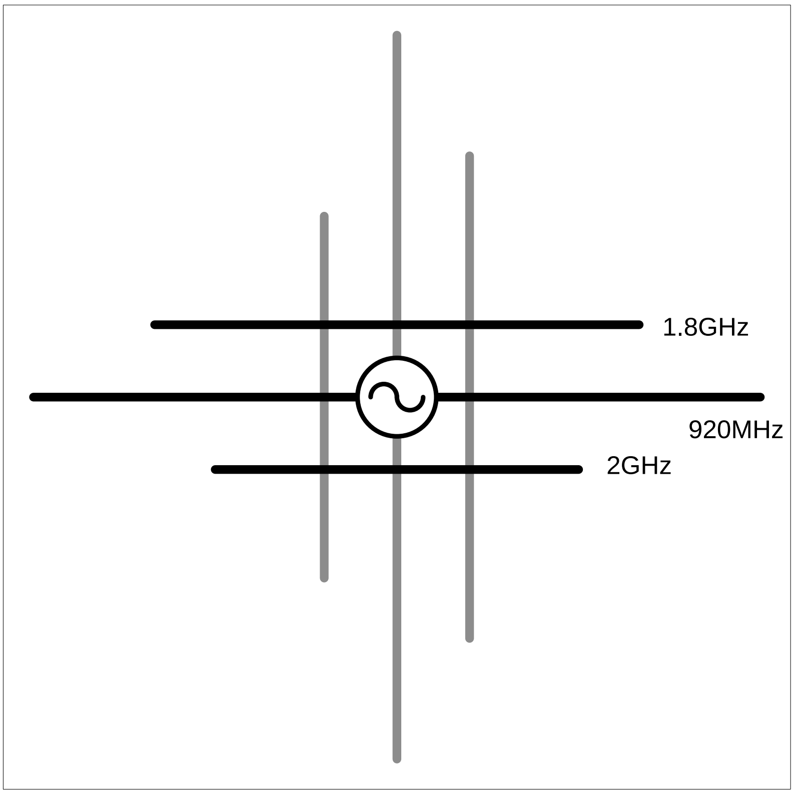
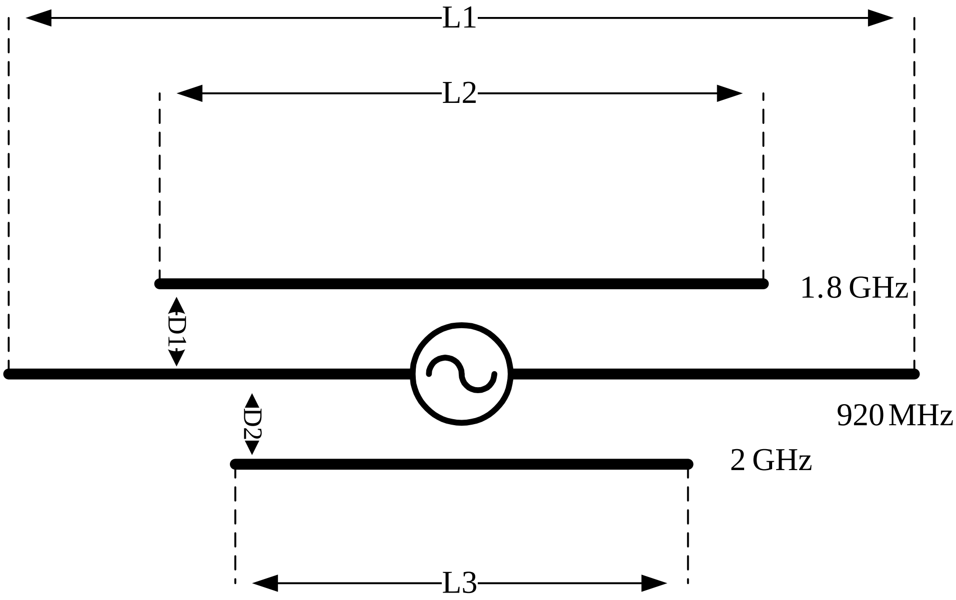


Figure 3. Three band GSM energy harvesting antenna. Both horizontal and vertical elements are placed on opposite sides of the supporting substrate.



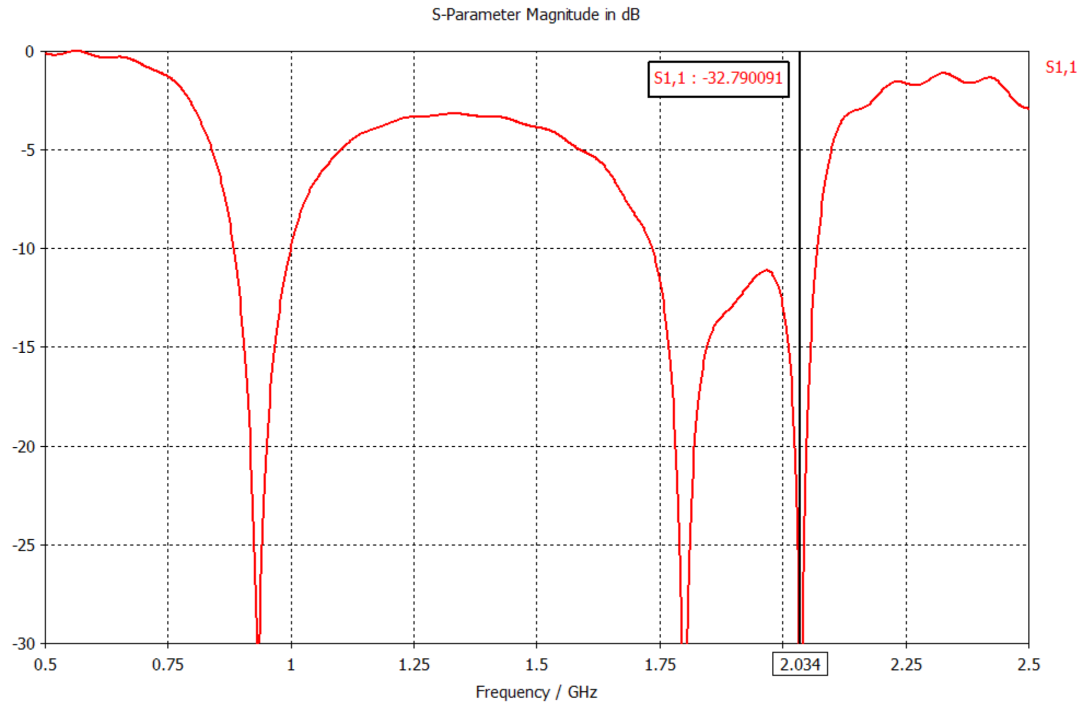
L1	124mm
L2	52mm
L3	46mm
D1	4.5mm
D2	2.5mm

Element widths = 2mm

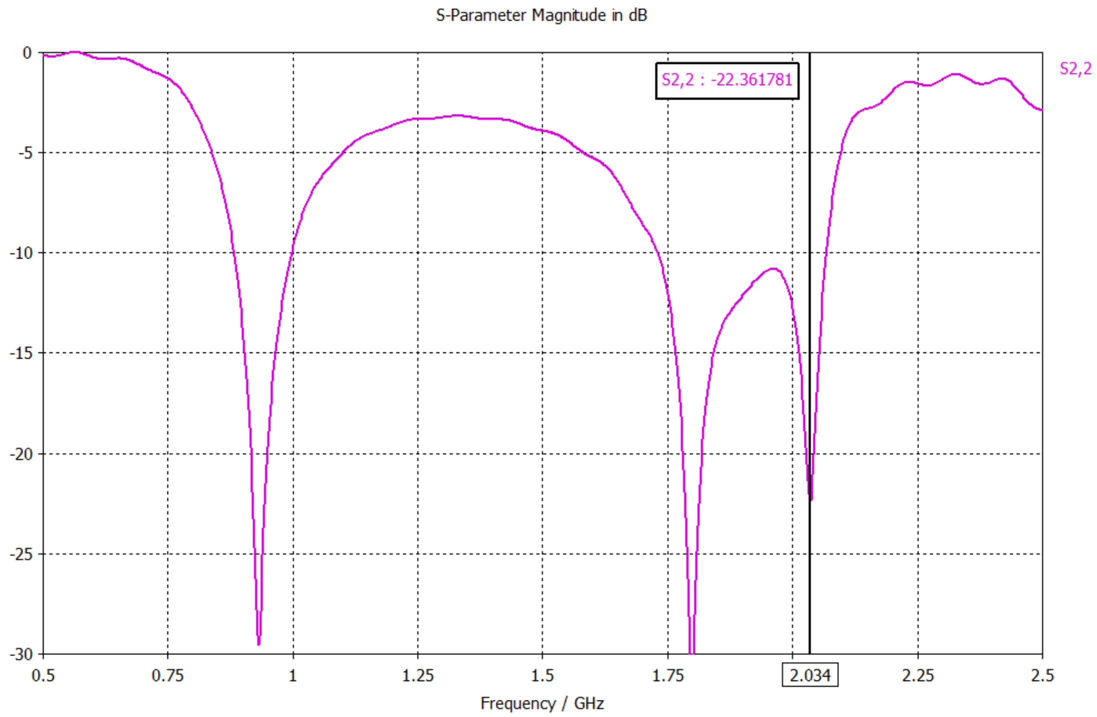
Figure 4. Dimensions for one half of the experimental three band, GSM energy harvesting antenna. The elements and their dimensions are repeated in the vertical plane for the dual polarised design.

2.1.1 CCR Simulation

From the dimensions previously presented Fig. 5 shows the CST simulation results for the three band CCR antenna in terms of return loss. The results show the three clear resonances with a return loss of 20dB or better for all three bands in both polarisations.



(a)



(b)

Figure 5. Return loss simulations for (a) vertical and (b) horizontal polarisations.

3. Input Matching and Detector Introduction

Succeeding the antenna, the impedance matching network performs impedance transformation to assure maximum power delivery. Fig. 6 illustrates the role of the impedance transformer where V_{in} and Z^{in} are the induced voltage and the input impedance of the impedance transformer respectively, and the Y_{IC} and V_{IC} are the input admittance and input voltage of the rectifier.

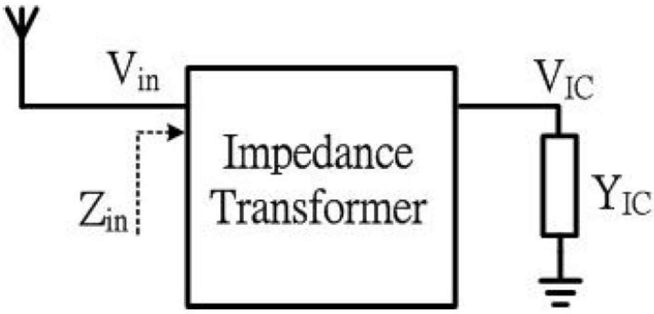


Figure 6. Impedance transformer.

Assume the impedance transformer is composed of reactive components and lossless. When the impedances are appropriately matched, then $V_{IC} = \left(\frac{\sqrt{Re}\{Y_{in}\}}{Re\{Y_{IC}\}}/2\right)V_{IN}$. It turns out the impedance transformer can also work as a voltage booster. When L-type matching network is used, the relationship of the input and output conductance can be derived as Re $\{Y_{in}\} = (1+ Q^2$ Re $\{Y_{ic}\}$, where Q is the quality factor of the matching network at resonate frequency. For a lossless L-match network consisted of L and C, $Q=\omega_0 C/$ Re$\{Y_{ic}\}$, where ω_0 is the resonate frequency. As a result, $V_{ic} = (\sqrt{1+Q^2}/2)$ V_{IN} . We observe that a high Q is required in order to achieve a high voltage gain. However, Q is practically determined by the compromises among several design parameters such as characteristics of the antenna, the input impedance of the rectifier, and the system bandwidth.

The zero bias Schottky diode detector has been previously used in RFEH [5 - 7] and other applications where no primary (DC) power is available. When combined with a simple antenna to form a receiver, it lacks the sensitivity of the superhetrodyne receiver, but offers the advantages of very low cost and zero power consumption. The single diode detector is shown in Figure 7.

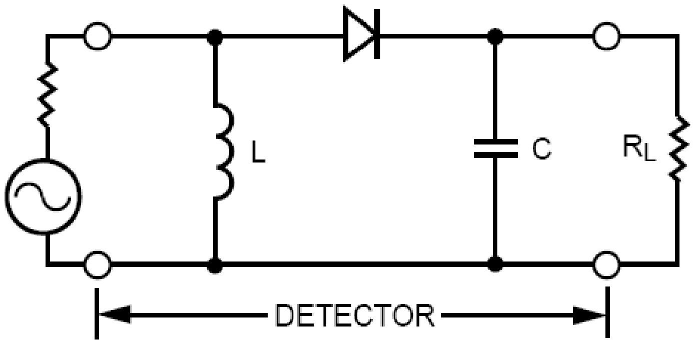


Figure 7. Diode detector.

RL is the load resistance. L, the shunt inductance, provides a current return path for the diode, and is chosen to be large (compared to the diode's impedance) at the input or RF frequency. C, the bypass capacitance, is chosen to be sufficiently large that its capacitive reactance is small compared to the diode's impedance but small enough to avoid having its reactance load the circuit [8].

Such detector circuits display a characteristic transfer curve of output voltage vs. input power as shown in Figure 8. Pin is the RF input power applied to the detector circuit and Vo is the output voltage appearing across RL. As can be seen from Figure 8, the transfer curve follows a square law (output voltage proportional to the square of input voltage) at low levels of input.

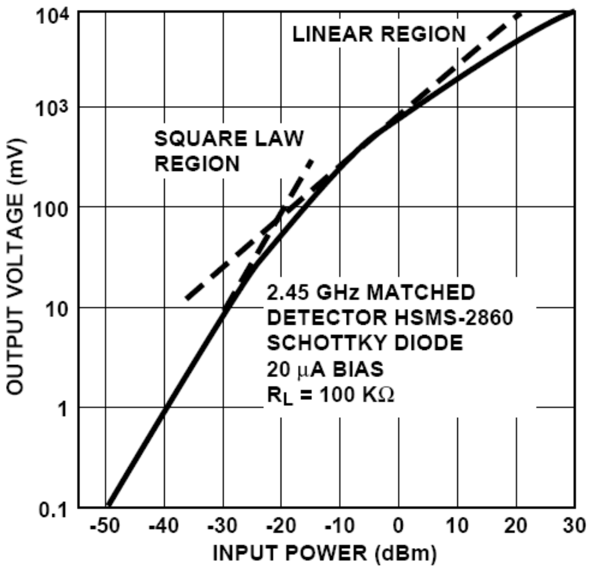


Figure 8. Detector transfer curve.

4. Super Capacitor Introduction

The environment provides infinite ambient energy (piezoelectric, thermal, vibration, photovoltaic) but at very low power which falls short of the peak power needed to transmit data across wireless networks such as Zigbee, WLAN or GSM/GPRS. A battery or super capacitor is required as a power buffer to store enough energy to provide the power bursts needed to acquire and transmit data. These energy-storage devices are charged at low power and deliver the burst power when needed.

Super capacitor cells are low voltage, typically rated between 2.3V and 2.8V. The most efficient and cost-effective strategy is to limit the super capacitor charge voltage to less than the cell-rated voltage and store enough energy for its intended application.

A simple approach to sizing the super capacitor is to calculate the energy required to support the peak power of the application = P.t and set this = 1/2.C.(V^2initial - V^2final). However, this does not allow for any losses in the super capacitor equivalent series resistance (ESR). The voltage seen by the load = Vinitial - ESR.I_{LOAD}, where Vinitial is the super capacitor voltage just before the peak power burst. Since the load voltage drops, the load current increases to achieve the load power. Referring to Figure 9, the super capacitor discharge characteristics can be modelled as:

$V_{LOAD} = V_{SCAP} - I_{LOAD}.ESR$

$P_{LOAD} = V_{LOAD}.I_{LOAD}$

$= (V_{SCAP} - I_{LOAD}.ESR).I_{LOAD}$

$= V_{SCAP}.I_{LOAD} - I_{LOAD}^2.ESR$

which gives an equation for ILOAD:

$I_{LOAD}^2.ESR - V_{SCAP}.I_{LOAD} + P = 0$

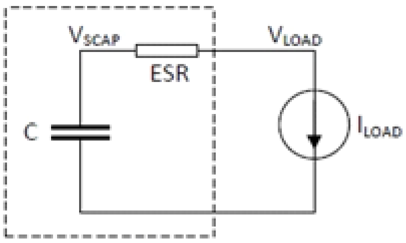


Figure 9. Ideal Super Capacitor model with series ESR.

A discharged super capacitor looks like a short circuit to an energy source. Fortunately, many energy-harvesting sources, such as solar cells or micro-generators, can drive into a short circuit and directly charge a super capacitor from 0V. Circuit designs used to interface energy sources such as RFEH, Piezo-electric or thermo-electric must be able to drive into a short circuit to charge a super capacitor.

In contrast to a battery, a super capacitor does not need to be charged at a constant voltage but will charge most efficiently by drawing the maximum current the source can supply..

In some applications, super capacitors are an alternative to batteries while in others they are best used to support them. In situations where a super capacitor may not be able to store sufficient energy, a battery is required. If the peak power needed exceeds the amount the battery can supply, e.g. for GSM calls, or for low-power transmission in cold temperatures, then the battery can charge the super capacitor at low power and the super capacitor can deliver the high power bursts. This arrangement also means the battery is never cycled deeply, extending battery life. Super capacitors store energy by physical-charge storage, not chemically as in batteries, so super capacitors have an effectively infinite cycle life.

The leakage current characteristic of super capacitors means that when a super capacitor is charged from a battery to supply peak power bursts, then there is a critical interval between bursts where if the bursts arrive more often, it is more energy efficient to leave the super capacitor always on charge. But if the bursts arrive less often, then it is more energy efficient to charge the super capacitor only prior to the peak-power event. This interval will depend on several factors, including the charge absorbed by the super capacitor before reaching equilibrium leakage current, the self discharge characteristic of the super capacitor, and the charge drawn from the super capacitor to supply the peak-power event. This is only possible if it is know beforehand when the peak-power event will occur, and is not possible if it is in response to an unpredictable event, such as battery fail or an external stimulus.

Conclusions

This paper has detailed the design of a 3 GSM band antenna for RFEH applications, along with an introduction to the other system requirements, such as input matching, RF rectification and energy storage in the form of super capacitors. Through computer simulations the antenna design is proven to be operational on its required bands and polarisations. For a fully functional design further work needs to be carried out on the RF detection/DC rectification and energy storage of the system. This initial work led to an MSc project exploring the proposed antenna use for harvesting. Additionally, Dr Batchelor attended the IDTechEX 2012 Energy Harvesting Conference in Berlin, and this experience has directly input to an upcoming EPSRC proposal on passive sensing with a co-investigator in the Functional Materials Group of SPS.

References

[1] Brown, W. Mims, J. Heenan, N. "An experimental microwave-powered helicopter" Raytheon Company, Burlington, MA, USA; 1965 IEEE International Record, vol. 13, part 5, pp.225-235.

[2] R. M. Dickinson, "Evaluation of a microwave high-power reception-conversion array for wireless power transmission," Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, Tech. Memo 33-741, Sept. 1975.

[3] D. BOUCHOUICHA, F. DUPONT, M. LATRACH, L.VENTURA "Ambient RF Energy Harvesting" STMicroelectronics, 16 Rue Pierre et Marie Curie 37071 Tours France, 4 Rue Merlet de la Boulaye, BP 30926, 49009 Angers, France, International Conference on Renewable Energies and Power Quality (ICREPQ'10) Granada (Spain), 23th to 25th March, 2010

[4] Breed G,: "The Coupled-Resonator Principle", *The ARRL Antenna Compendium, Vol 5*, p109 ISBN 0872595625

[5] Nishimoto, H.; Kawahara, Y.; Asami, T.; , "Prototype implementation of ambient RF energy harvesting wireless sensor networks," *Sensors, 2010 IEEE* , vol., no., pp.1282-1287, 1-4 Nov. 2010

[6] Nintanavongsa, P.; Muncuk, U.; Lewis, D.R.; Chowdhury, K.R.; , "Design Optimization and Implementation for RF Energy Harvesting Circuits," *Emerging and Selected Topics in Circuits and Systems, IEEE Journal on* , vol.2, no.1, pp.24-33, March 2012

[7] Arrawatia, M.; Baghini, M.S.; Kumar, G.; , "RF energy harvesting system from cell towers in 900MHz band," *Communications (NCC), 2011 National Conference on* , vol., no., pp.1-5, 28-30 Jan. 2011

[8] Agilent Technologies Application Note 923, *Schottky Barrier Diode Video Detectors*.