Design Considerations of Antennas and Adaptive Impedance Matching Networks for RF Energy Harvesting

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Abstract

- This paper reviews recent developments in design of antennas and impedance matching networks for RF Energy Harvesting (RF-EH) at UHF. The antenna design is considered in conjunction with the requirements that it places on the impedance matching network (IMN), in order to match the load which is an RF to DC converter.
- It is shown that there may be advantages in using an interface impedance between the antenna and the IMN that differs from the conventional 50 Ω impedance. Various options are considered for the design of an IMN driving a rectifier load. A novel adaptive IMN architecture is proposed that can match two different load impedances, depending on the received power level. This can optimize Power Conversion Efficiency (PCE) over a range of different input powers that may be encountered in RF EH.

I. INTRODUCTION (1)

- The Internet of Things (IoT) is predicted to grow but a limiting factor is the available power sources.
- Remote powering of devices using energy harvesting is a possible alternative to batteries for devices that have sufficiently low average power consumption.
- Remotely powered devices have lower cost, are smaller, more environmentally friendly and free of maintenance [1].
- Energy may be harvested from various sources but this paper focuses on Radio Frequency Energy Harvesting (RF-EH).
- An RF-EH device receives energy from ambient RF signals using an antenna and rectifies the RF signal to power an embedded device. This has various applications including Radio Frequency Identification (RFID), Wireless Sensor Networks and Wake Up Radios [2].

I. INTRODUCTION (2)

- RFID and wireless sensor networks have differing requirements:
- When RFID receives power above a certain threshold, it activates a transponder in real time.
- Wireless sensor networks can use RF-EH to accumulate energy by charging a capacitor or a battery to power a transceiver that operates intermittently on a low duty cycle.
- This paper focuses on impedance matching networks (IMN) for energy harvesting, to match an antenna to a rectifier.
- Antennas and antenna matching for communications have been an active research topic for some time [3], [4], [5], [6] but this application of IMN faces special challenges due to the very low and variable level of input power.

I. INTRODUCTION (3)

- The source impedance of the IMN is the source impedance of the antenna, which is not necessarily 50 Ω
- The load impedance is the input to the rectifier, which is non-linear and varies with power received by the antenna.
- A consequence of this is that the IMN needs to be designed to match at a particular received power level but it will be mismatched at other power levels.
- The adaptive IMN presented here can be switched between two or more different load impedances, thereby improving Power Conversion Efficiency (PCE) compared to a fixed IMN.

II. RF ENERGY HARVESTERS

- The RF signal received by the antenna is fed to the matching network
- This matches the source impedance of the antenna to the load impedance of the RF to DC converter.

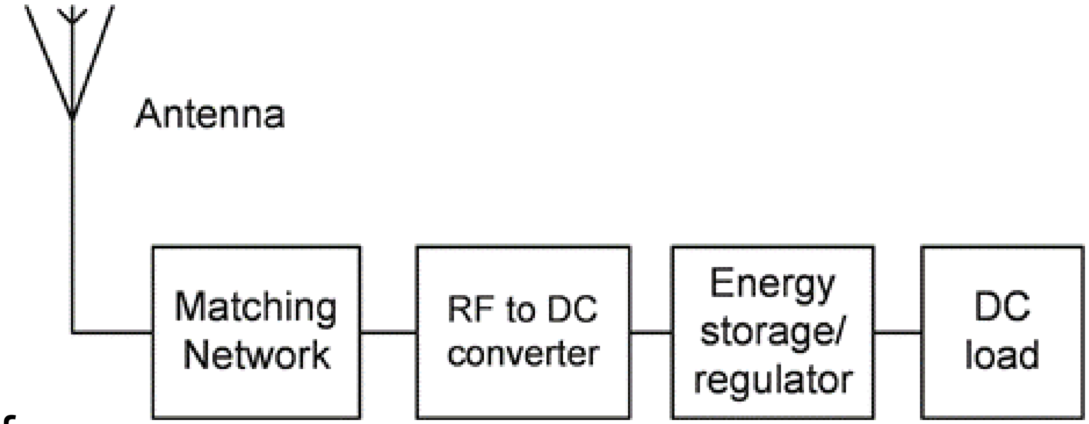

Fig. 1. A block diagram of an RF Energy Harvester

- The RF to DC converter contains one or more rectifying devices that produce a DC output.
- The output of the RF to DC converter is normally stored in a capacitor which feeds a regulator to provide a regulated voltage to the DC load.

III. ANTENNAS FOR RF ENERGY HARVESTING (1)

- Antenna design for RF-EH devices:
- Compact UHF antennas are likely to be "electrically small" at some frequencies, particularly below 1 GHz.
- "Electrically small" commonly means that the largest dimension of an antenna is no more than one tenth of a wavelength [7].
- A resonant microstrip antenna for 2.45GHz presented in [8] is described as "electrically small" although it is slightly larger at 0.14 wavelength.
- An "electrically small" antenna, e.g. $\lambda/10$ dipole has a low radiation resistance of $<2\Omega$ in series with a high capacitive reactance of approximately 1750Ω.
- To match this to a practical impedance such as 50Ω requires conjugate matching using series inductors.

III. ANTENNAS FOR RF ENERGY HARVESTING (2)

- In [7] it is shown that the high impedance transformation ratio results in high loss (21 dB) with practical inductors.
- An "electrically small" antenna also has relatively narrow standing Wave Ratio (SWR) bandwidth, e.g. 1% of the center frequency so it may be too narrow for some RF-EH applications.
- Ideally a resonant half-wavelength dipole should be used if the physical size is suitable for the application, e.g. 6.1 cm for the 2400MHz - 2483.5MHz band.
- Interface between the antenna and the IMN - impedance of 50 Ω is not necessarily optimum impedance for RF-EH.
- Half wavelength folded dipole has approximately 300Ω impedance compared to 72Ω for a straight dipole [9].
- Efficient passive voltage step-up a ratio of 2:1 but feed point of a 300Ω folded dipole needs to be connected directly to the IMN or to the input of the RF-DC converter if no IMN is used.

IV. A. IMPEDANCE MATCHING NETWORKS FOR RF ENERGY HARVESTING - Impedance of a rectifying load

- Rectifier input impedance needs to be known in order to design the IMN.
- For any RF to DC converter,input impedance varies with RF input power and load leading to mismatch and reduced power conversion efficiency (PCE).
- Analysis and measurement of the non-linear input impedance of an RF to DC converter - [11], [13].
- Multi-stage threshold-compensated rectifier using Dickson multiplier topology in 0.13μm CMOS technology is used in [14] to simulate the input impedance of the rectifier at various RF input power levels. Fixed L-section matching network is a compromise between the low and high input power conditions.
- This paper propose that PCE could be improved over a wider range of input powers using an adaptive IMN that varies its characteristics depending on input power.

IV. B. IMPEDANCE MATCHING NETWORKS FOR RF ENERGY HARVESTING - IMN topologies (1)

- Types of matching network include the Pi network [6] and the L-network. If the impedance transformation ratio is relatively high or low, the network operates with a high 'Q' factor, leading to increased circuit losses and reduced Standing Wave Ratio (SWR) bandwidth.
- Reactive components need to be switched or varied using electronic devices that are suitable for the frequencies and very low power levels that are normally found in RF-EH.
- At frequencies in the upper part of the UHF band, e.g. 2.4GHz, microstrip transmission lines provide an alternative to discrete inductors.

IV. B. IMPEDANCE MATCHING NETWORKS FOR RF ENERGY HARVESTING - IMN topologies (2)

- The IMN in Fig 2 uses an alternative topology where L1 acts as an autotransformer which drives a voltage doubler rectifier using Schottky diodes D1 and D2.

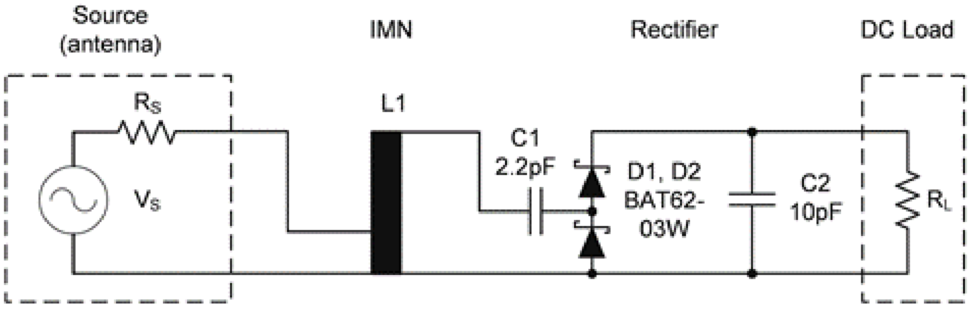

Fig. 2. An autotransformer IMN with rectifier for RF EH

- L1 is a 7.5 mm length of transmission line 2.5 mm wide that is grounded at one end and tapped at 2.5 mm from the grounded end. L1 is parallel resonant with C1 in series with the shunt capacitance of rectifier load D1 and D2 in parallel.

IV. C. IMPEDANCE MATCHING NETWORKS FOR RF ENERGY HARVESTING - Measured Characteristics of IMN for RF EH (1)

- Input impedance of the IMN in Fig. 2 was measured at, -30dBm and 0dBm.
- Fig.3 shows S_{11} from 2.3 - 2.6GHz at -30dBm. This is a small signal case where D1 and D2 are operating in the square law region.

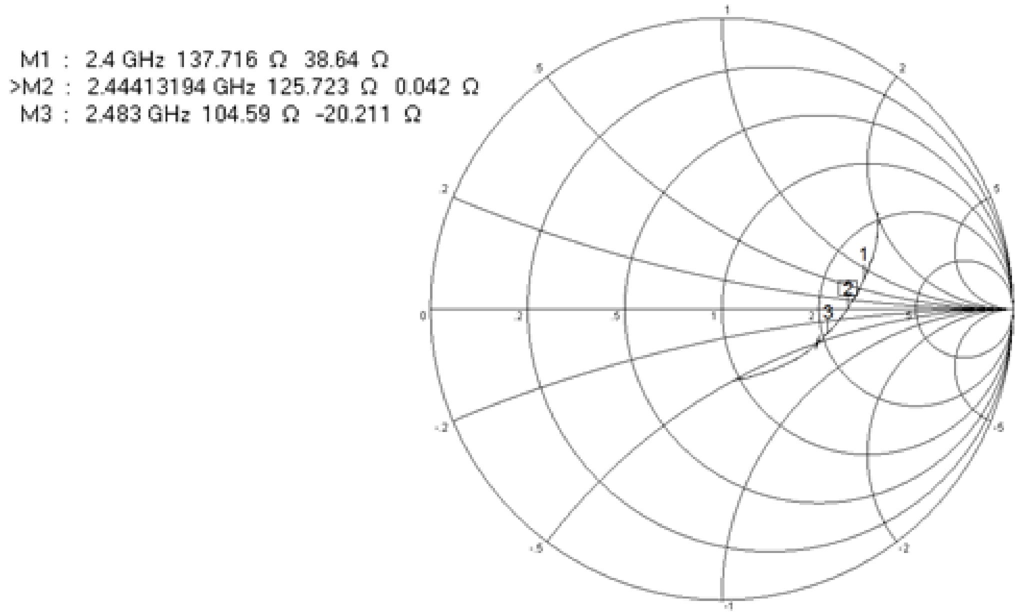

Fig. 3. Measured S_{11} of the IMN in Fig. 2 at -30dBm

- The imaginary part of S_{11} is close to zero at 2.44GHz but there is scope for further optimization of the IMN to bring the real part closer to 50Ω.

IV. C. IMPEDANCE MATCHING NETWORKS FOR RF ENERGY HARVESTING - Measured Characteristics of IMN for RF EH (2)

- Fig.4 shows S_{11} from 2.3 - 2.6GHz at 0dBm.
- This is a large signal case where D1 and D2 conduct on peaks of each half-cycle.
- The imaginary part of S_{11} is close to zero at 2.483GHz.

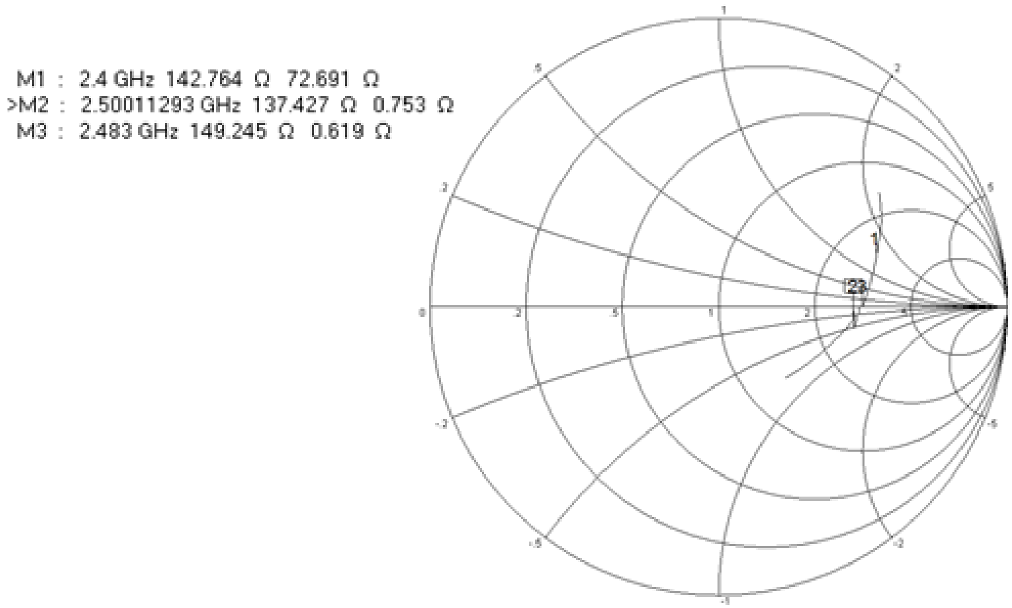

Fig. 4. Measured S11 of the IMN in Fig. 2 at 0dBm

- The resonant frequency of the IMN has increased so that it is no longer at the center of the 2.4GHz ISM band. It needs retuning to reduce mismatch loss particularly if the IMN is operating with a relatively high 'Q' factor.

IV. D. IMPEDANCE MATCHING NETWORKS FOR RF ENERGY HARVESTING -Tunable IMN for RF EH

- Fig. 5 shows an autotransformer IMN with rectifier,
- The IMN is tuned by a CMOS on-chip tuner.
- Shunt capacitors C_1 - C_n are switched by switching FETs

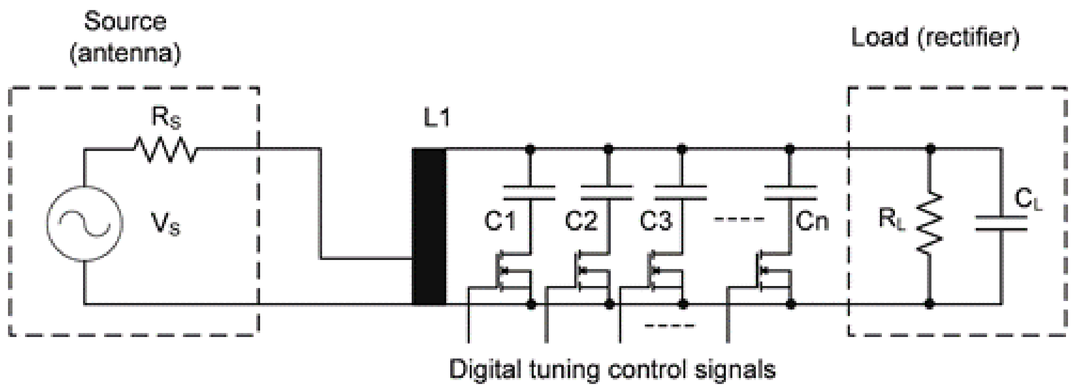

Fig. 5. A tunable IMN for RF EH with CMOS on-chip tuning

- The IMN has two preset settings. When the DC output of the rectifier exceeds a certain threshold, the gates of some or all switching FETs are driven positive, switching in a preset combination of capacitors C_1 - C_n, using combinational CMOS logic that consumes negligible DC current

V. CONCLUSIONS

- This paper reviews recent developments in design of antennas and impedance matching networks for RF-EH at UHF.
- The antenna is considered in conjunction with the requirements that it places on the IMN, rather than in isolation.
- The design of an IMN to match the non-linear load presented by the RF to DC converter is studied.
- Variations in RF input power and DC output load cause a variation of the input impedance of the RF to DC converter. This in turn leads to mismatch and reduced PCE.
- A novel adaptive IMN architecture is proposed that can improve PCE by matching two different load impedances, depending on the received power level.
- At lower available power levels, the IMN operates without the need for any DC bias voltage or current. At higher power levels, it requires a DC bias voltage but negligible DC current.

Any questions?