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Possibilities and Challenges of Radio Frequency Energy Harvesting in Dar es Salaam, Tanzania

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ABSTRACT

This paper presents investigation on the possibilities and challenges of harvesting ambient Radio Frequency Energy (RFE) at Dar es Salaam region in Tanzania. The Radio Frequency (RF) signals were measured using a Rohde and Schwarz FSC 3 spectrum analyzer observing available frequencies with their respective power. Among several RF signals received, the most powerful signals observed were; 800 MHz, 950 MHz, 2100 MHz and 2400 MHz, having average signal strengths of about -30.29 dBm, -35.94 dBm, -42.90 dBm and -30.42 dBm respectively. The power possessed within these frequencies were suitable to be harvested due to their signal strengths, an overall power average of -34.89dBm was obtained and a multi narrowband harvester was designed and simulated using real-time values on Keysight's Advanced Design System (ADS) 2019. The simulation results confirm a promising possibility of harvesting RF energy to power ultra-low-power devices in the Internet of Things (IoT) and beyond.

Key words: *DC-DC Boost, Energy Harvesting, Impedance matching, RF-DC conversion Schottky Diode, Super Capacitor array, Voltage multipliers.*

INTRODUCTION

The gradual demands in ultra-low-power devices are of great interest nowadays, from the inception of the Internet of Things (IoT) (Jose *et al.*, 2015; Ejaz *et al.*, 2017), devices have become smarter, smaller and more energy-efficient (Cansiz *et al.*, 2019). Radio Frequency (RF) energy harvesting, being a major source for providing reliable and sustainable energy is expected to keep Ultra-Low Powered (ULP) devices powered throughout its lifetime. To achieve such promising longevity, there is a need to investigate the possibilities of harvesting the available frequencies so as to enable proper functionality of battery-less systems with zero maintenance (Saini and Baghini, 2019). The RF spectral power density obtained from the spectrum analyser were analysed and simulated in real-time to demonstrate a predictive output based on the feasibility study.

RF energy harvesting sometimes termed as wireless power transfer was initially proposed by Nikola Tesla in the early 20th Century, as one of the most reliable and maintenance-free system (Marincic, 1982; Valenta and Durgin, 2014). The basic structure of any RF energy harvester is comprised of a receiving antenna that accepts a specific frequency band and tunnels its energy to rectifiers that convert the signal to DC. More energy can be converted to achieve more output voltages and currents through using extremely sensitive rectifiers as described by Shariati *et al*. (2015). The energy harvested is thereafter stored in either a battery or supercapacitor awaiting to be used (Olgun *et al.*, 2010).

This work, proposes a new multi narrowband one to one architecture on impedance matching, as well as a newly designed Nano dc to dc boost converter using MAX 17220, which improves output voltage and current. In addition, this work also provides a summary on the RF intensities available in Dar es Salaam region. The RF analysis and experiments were carried out at the College of Information and Computer Technology (CoICT) campus, University of Dar es Salaam, while data was collected at random places in Dar es Salaam region in Tanzania.

METHODS AND MATERIALS

Description of Study Area

Dar es Salaam region was chosen as a study case area for investigative purpose of RF energy harvesting as described in Figure 1. RF data was collected from different parts of the City using a synchronized spectrum analyser and GPS, the later was analysed with Rohde & Schwatz (R&S) Instrument view and Quantum Geographic Information System (QGIS) to provide an intuitive RF coverage intensity map.

Tools and Methods

The RF survey was conducted using the Rhode & Schwarz FSC 3 Spectrum analyser, Garmin GPS 18x for RF location tags, as in Figure 2. The block diagram describes the equipment layout and connections used for data logging, synchronization and graphical output generation.

The RF density data was collected at random locations within the University's premises; sample data attained are graphically presented in Figure 3 and Figure 4. The setup used for sample RF data collection was as shown in Figure 2. Through keeping the same setup on different locations within Dar es Salaam, a heatmap output expressing location-based radiation intensities will be shown as an output. The average sample data obtained from the RF survey at CoICT campus of the University of Dar es Salaam are expressed on Table 1. The results demonstrate a positive possibility on harvesting the received RF signals at such power levels (Khemar *et al*., 2018).

The RF to location data log time was set to a 60 second interval in a vehicle collecting RF data around the city. More than 180,000 points were collected across the city and was used for simulation purpose. Table 2 describes the location with its RF signal power in dBm.

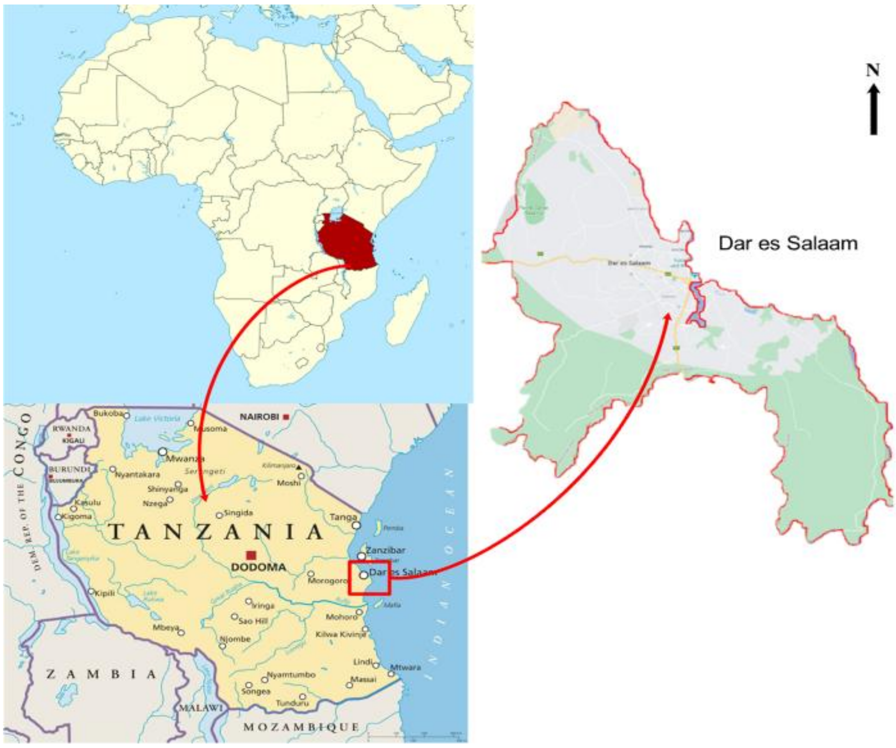

Figure 1: Dar es Salaam Region (Source: QGIS Development Team, 2020)

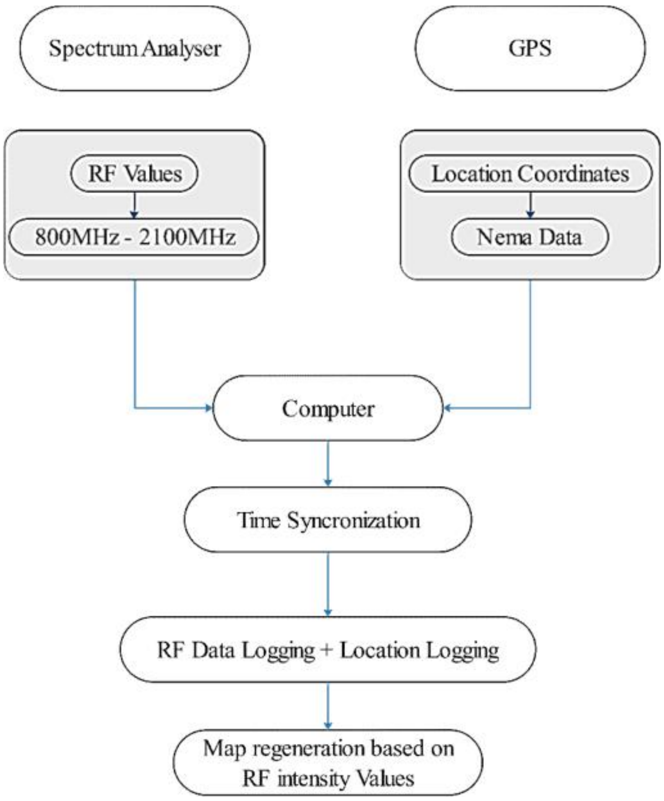

Figure 2: Experimental design setup

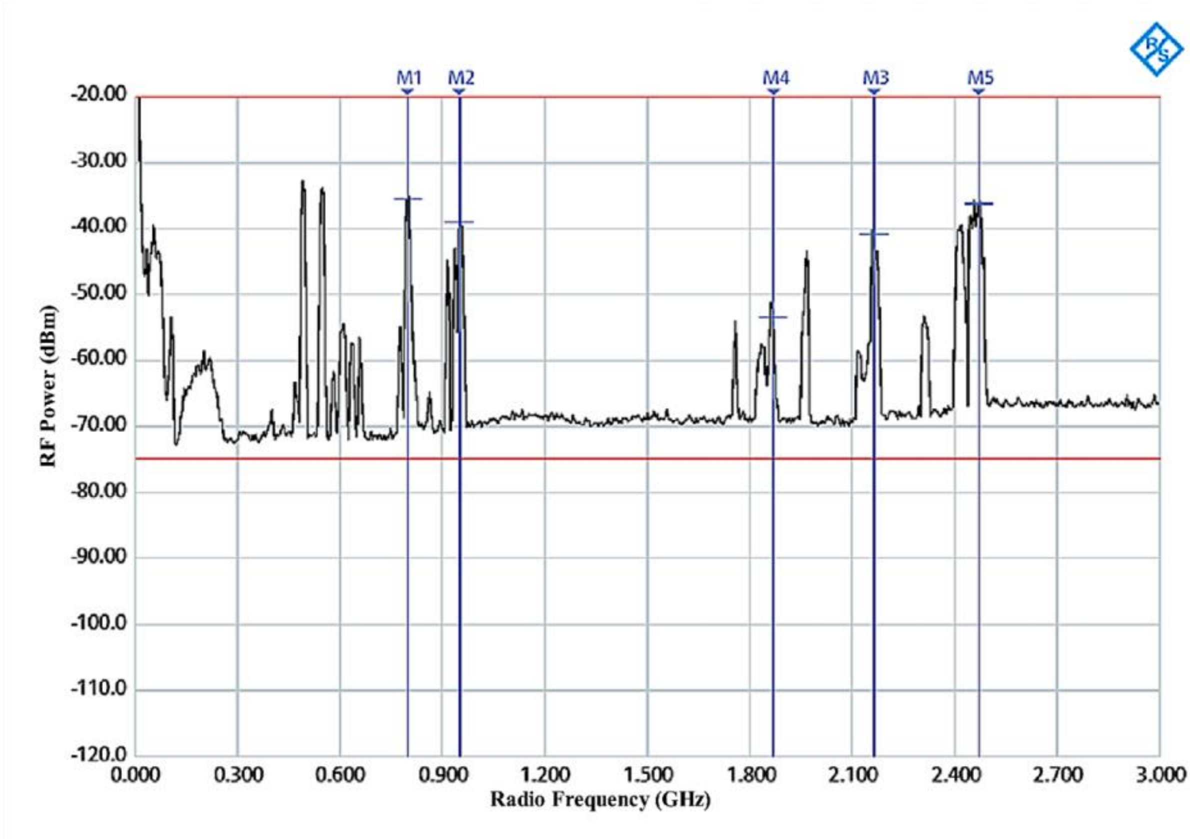

Figure 3: Maximum RF levels at UDSM – CoICT

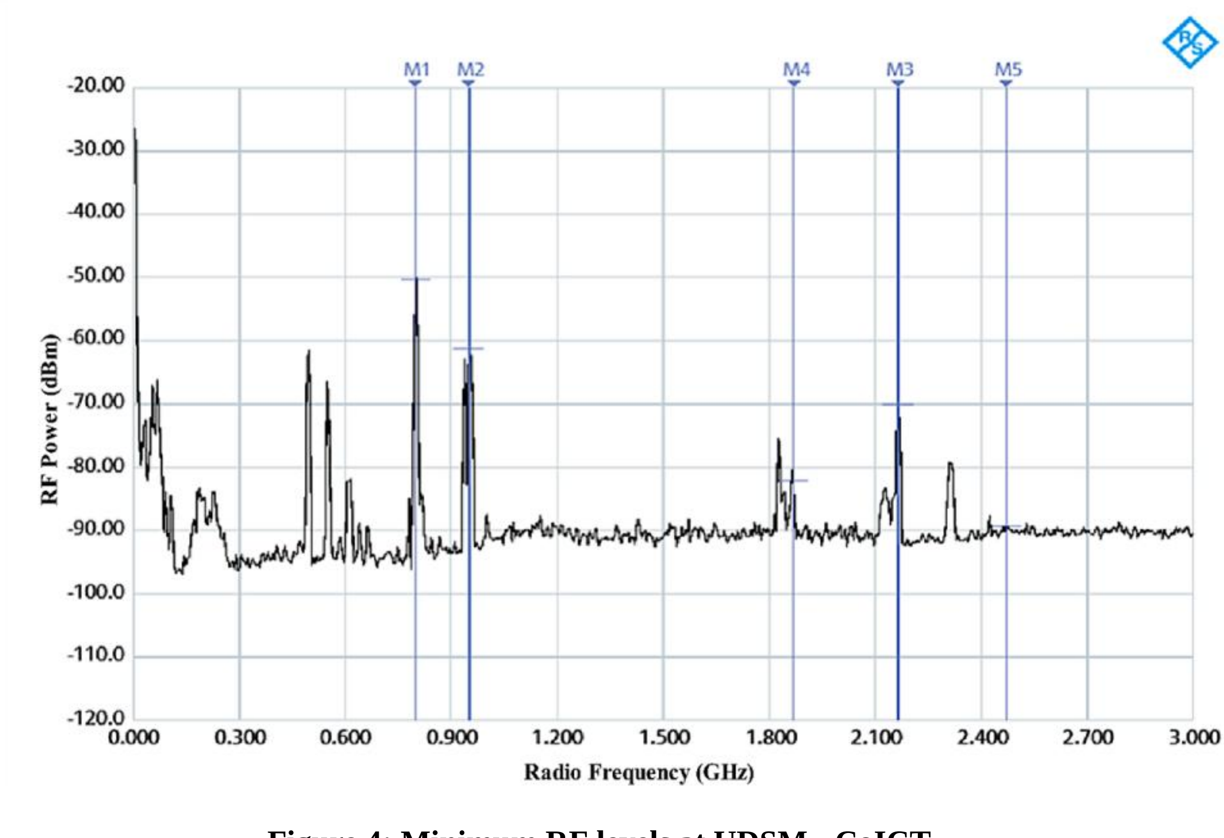

Figure 4: Minimum RF levels at UDSM - CoICT

Table 1: Average received power

Available Frequency (MHz)	Maximum Power (dBm)	Minimum Power (dBm)	Average power (dBm)
800	-55.46	-70.97	-63.60
	-53.51	-94.06	
	-48.25	-69.91	
	-50.11	-66.55	
950	-45.91	-67.31	-61.53
	-41.67	-70.04	
	-65.37	-89.88	
	-46.57	-65.53	
2100	-45.93	-67.49	-60.82
	-50.62	-62.80	
	-59.72	-69.75	
	-59.25	-71.04	
2400	-24.2	-65.30	-52.04
	-17.6	-65.96	
	-41.7	-70.37	
	-69.68	-61.57	

Table 2: A 60 second location to RF signal power data

Latitude	Longitude	800 MHz	1800 MHz	2100 MHz	2400 MHz
-6.602997	39.123123	-55	-75	-86	-108
-6.610755	39.104663	-59	-78	-71	-99
-6.619622	39.092296	-48	-74	-70	-42
-6.646222	39.086112	-56	-81	-63	-65
-6.643494	39.117718	-39	-55	-60	-83
-6.619934	39.112707	-40	-53	-51	-56
-6.618911	39.130404	-55	-60	-42	-70

System design and Simulation

System Design

The overall system design was based on the Input frequency, Impedance matching topology and Voltage multiplier. Taking into account the factors, frequencies less than 1 GHz are matched using a T-type impedance match topology while frequencies greater than 1 GHz were matched with a Pie type impedance matching, as recommended in the literature (Sun, 1994; Thakuria *et al*., 2018; Tran *et al*., 2017). The T type and Pie type impedance matching topologies were designed based on their input frequencies and input power level, which was a key parameter on circuit optimization on determining component values that will attain maximum power transfer to load. In accordance with Uzun (2019) and Clerckx *et al*. (2019), it is important to have a simple and yet efficient passive network that accommodates effectively the use of a single frequency.

For matching network designs, values were determined using matching circuit synthesis in ADS 2019. The major advantage of ADS is its unique ability to provide near practical values of any Electromagnetic (EM) design circuitry, which has been widely used in various research activities (Devi *et al.*, 2012; Nimo *et al.*, 2015; Ur-Rehman *et al.*, 2017; Uzun, 2019).

Figures 5 and 6 provide ideal design setup for value determination of resistors, capacitors and inductors (RCL) for the appropriate frequency and average power density. Based on the received signal frequency to be matched, impedance measurement values to match the load is crucial, for this case to obtain theoretical values of indictors and capacitors

$$Z_G = R_G + jX_G \quad \text{(1)}$$

$$Z_L = R_L + jX_L \quad \text{(2)}$$

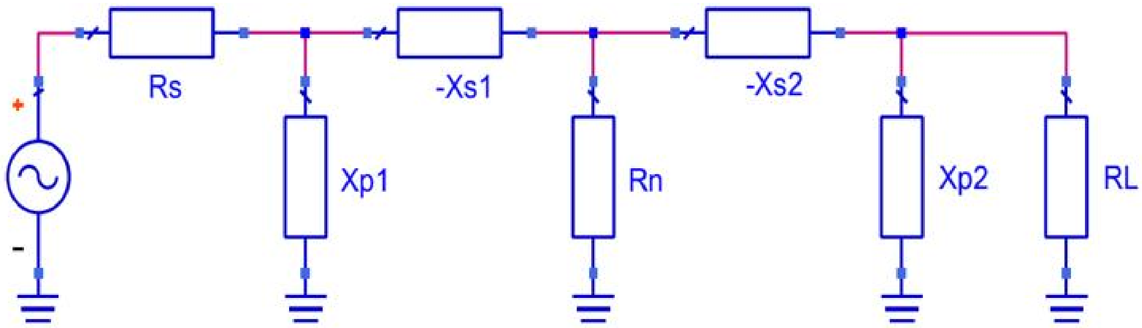

Figure 5: An ideal Pie matching network

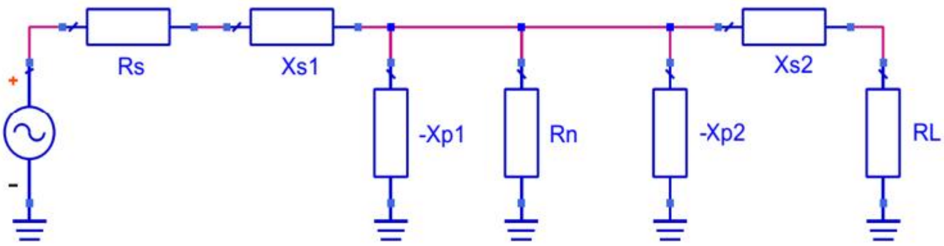

Figure 6: An Ideal T matching network

The impedances described in equations (1) and (2) can be taken as resistors R_S or R_L whose reactance is X_G or X_L at the desired matching frequency. Assuming an 800 MHz signal is received, having the antenna and load impedance respectively.

$$Z_G = 50 + j6.283\Omega \quad \text{(3)}$$

$$Z_L = 71.701 + j45.216\Omega \quad \text{(4)}$$

For this case, a Q based algebraic method was preferred as suggested by previous researchers such as, (Nimo *et al.*, 2015; Ur-Rehman *et al.*, 2017). This method can be easily described by the following series to parallel transformation approach.

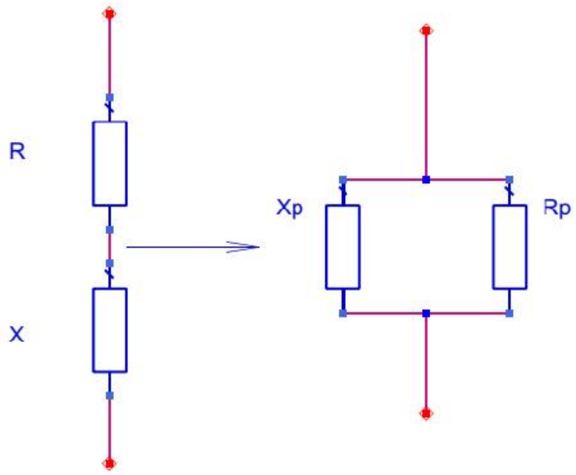

Figure 7: Series to Parallel transformation in passive value determination

The new virtual elements observed in Figure 7 can be determined using equation (5).

$$R_P = R(Q^2 + 1) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

$$X_P = X\left(\frac{Q^2+1}{Q^2}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Where $Q = \frac{X}{R}$ ………………………… (7)

$$Q_{new} = \sqrt{\frac{R_{G,P}}{R} - 1} = \sqrt{\frac{50.789}{3.269}} = 3.9416$$

……………………………………….……… (8)

$$X_{P1} = \frac{R_{G,P}}{Q_{new}} = \frac{50.789}{3.9416} = 15.199\Omega$$

……………………………………….……….. (9)

$$X_{S1} = Q_{new} x R = 3.9416 x 3.269 = 12.885\Omega$$

……………………………………..…….. (10)

This proposed method has widely been utilized in Pi and T matching networks. Assuming that, Q = 5, the receivers impedance can be modelled as a resistor having $R_{G,P} = 50.789\ \Omega$ with an inductor $L_{G,P} = 64.326nH$ and the load impedance of $R_{L,P} = 85\Omega$ with 1 pF capacitor in parallel. The virtual resistor values can be determined, Because $R_{L,P} > R_{G,P}$ it is important that X_{S2} and X_{P2} are determined first (Şengül and Yeşilyurt, 2018).

$$R = \frac{R_{L,P}}{Q^2+1} = \frac{85}{5^2+1} = 3.269 \quad \ldots\ldots\ldots.. (11)$$

$$X_{P2} = \frac{R_{L,P}}{Q} = \frac{85}{5} = 17\Omega \quad \ldots\ldots\ldots\ldots\ldots (12)$$

$$X_{S2} = QxR = 5x3.269 = 16.345\Omega \quad \ldots.. (13)$$

Calculating the Q from the receiver,

Based on the ideal impedance matching networks described in Figures 5 and 6, the approach is theoretically correct on determining lumped components values for pie networks. The same is applied to T matching networks except that, $R_G < R_L$ hence X_{S1} and X_{P1} are first identified.

After a complete design as described on Figure 8, circuit simulation and optimization were performed on each frequency independently. This utilized two common topologies with different values, the output signals received were integrated to the Villard voltage multiplier, producing an overall output of 149 mV.

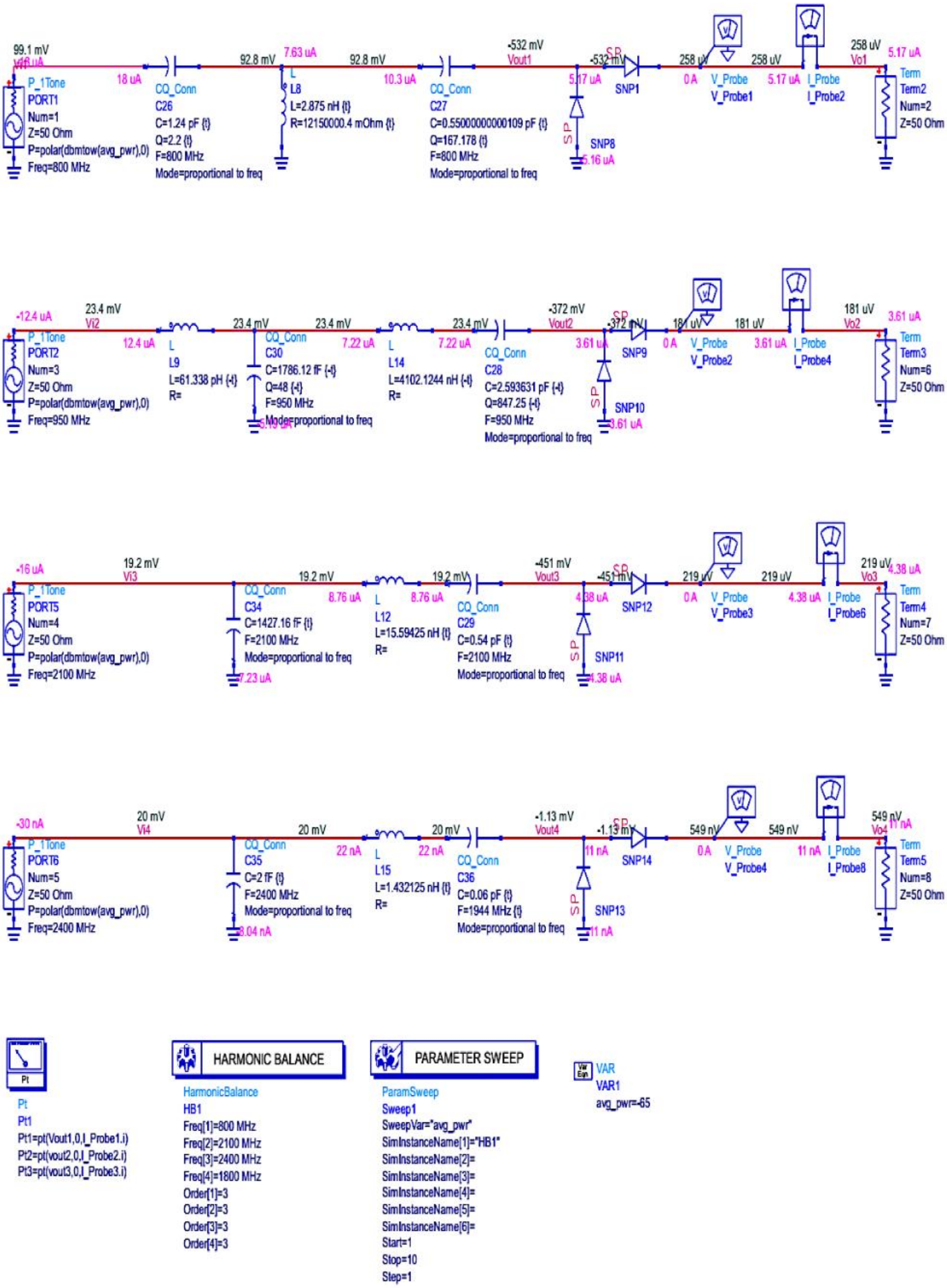

Figure 8: Overall System Design

RESULTS AND DISCUSSION

System Design and Simulation

Figure 8 provides the overall system design showing a one to one, frequency to preferred impedance topology. This investigation provides the maximum achievable power that can be harvested at similar environments using ideal components. Table 3 provides the relationship between the input frequency and output voltages and currents attained from the simulation.

Table 2: Input Frequency with respective output Voltage and Currents

Frequency (MHz)	Input Current (uA)	Output Voltage (mV)	Output Current (uA)
800	3.251	2.417	3.415
1800	3.142	3.952	3.334
2100	2.031	5.218	2.081
2400	8.405	11.325	10.208

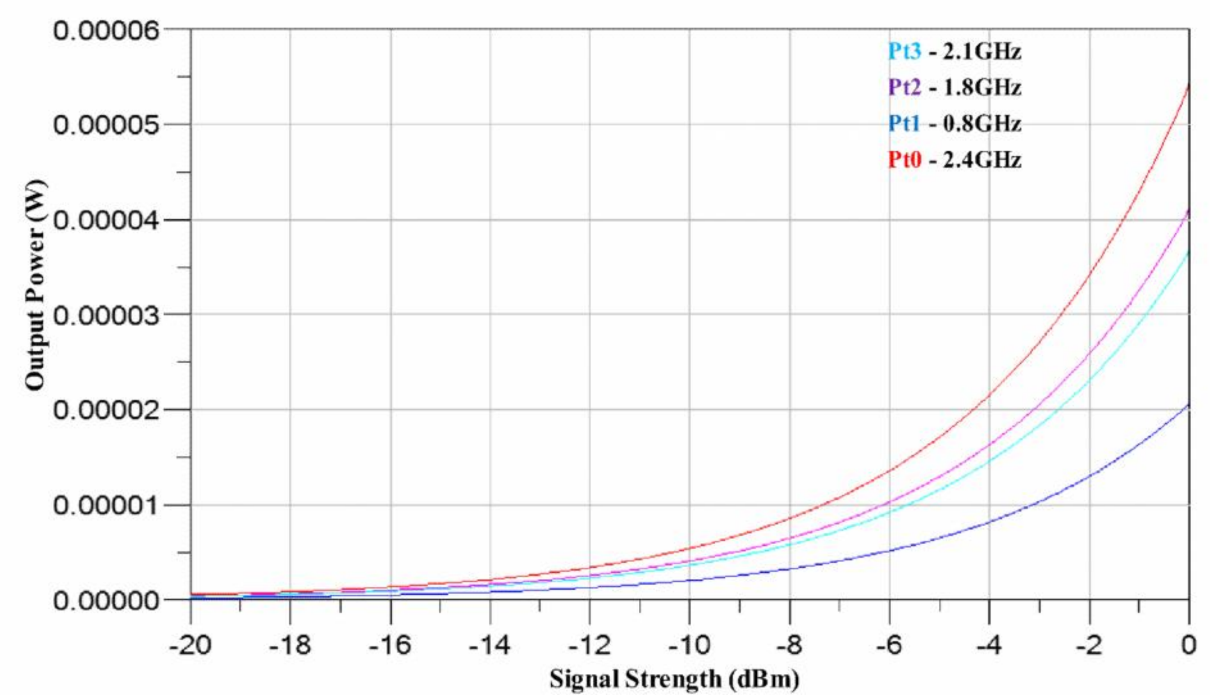

Figure 9: RF Received Signal Strength Vs Output power (W)

Through utilizing narrowband antennas for particular singular frequency reception has shown promising results over time, the capacitor charging time may vary depending on its capacity as larger capacitors will take longer charging time and vice versa. The received RF signals induce an electric and magnetic flux into the system via the designed antenna. It can be observed that there is a small amount of current input due to the nature of RF's being of a low density. For that reason, RF harvesters have limited applicability on devices as they will operate for a short period of time and have longer periods of off-state quietly recharging. As observed, the output current released from the voltage multiplier is slightly greater than the induced current, which is mainly due to the rectification process and the use of BAT 63.03 rectifiers. The output power released by the designed and simulated circuit, can easily be observed that the stronger the signal, the higher is the output power. This fading or sometimes termed free space path loss effect is normally observed when moving away from a transmitting source which is expressed by equation (14).

$$RSSI = 10\log\frac{P_{RX}}{P_{\mathrm{Re}f}} \quad \text{……………..…….. (14)}$$

RF Survey

From the Dar es Salaam RF survey data in Figure 3 that contained a 60 second location to RF signal power data, a heat map was generated using QGIS to show the RF intensities between 800 MHz to 2400 MHz in Figure 10. The results expressed included 181,000 points with location coordinates (Latitude, Longitude) and RF received signal strength intensity (RSSI) in dBm.

Challenges

The main challenges facing RF energy harvesters are low output voltages and currents. To improve such shortcomings there is a huge necessity on improving antennas to meet specific impedance matching topologies so as to assure maximum power transfer. In addition to that, further improvements of voltage multipliers are also inevitable so as to accommodate a wider range of appliances.

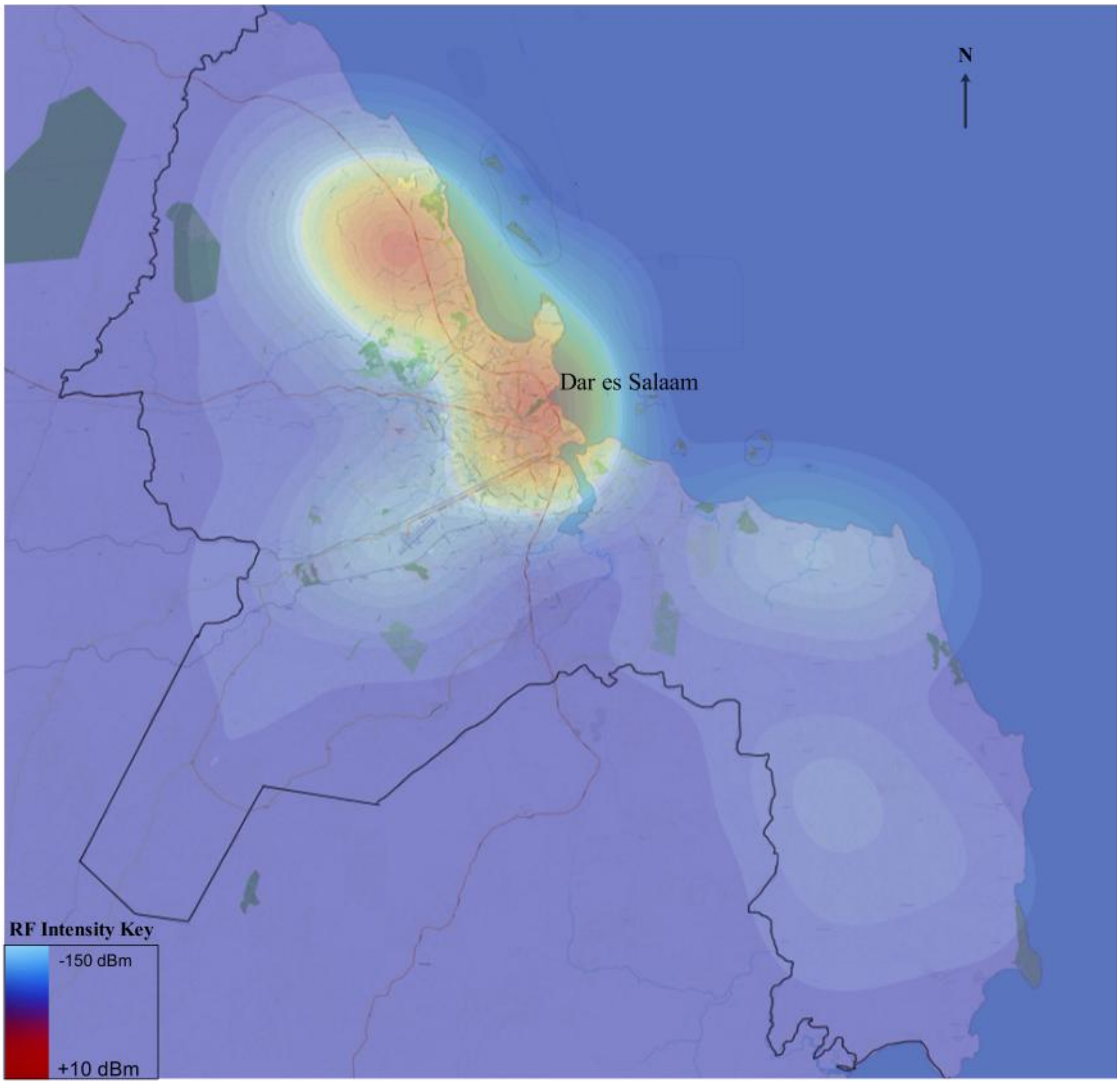

Figure 10: Dar es Salaam City RF Heatmap

CONCLUSIONS

This paper discusses the possibilities and challenges of RF energy harvesting in Dar es Salaam City, based upon the RF survey, tools used and their efficiencies. The results obtained revealed a promising future on harvesting ambient RF energy to endlessly power up low power and ultra-low power devices throughout its lifetime. To achieve better results, there is a need for more sensitive antennas need to be designed within the narrowband frequency limits. There is also a need for pursuing intensive research on extremely low power (ELP) active and passive devices such as rectifiers and inductors to operate on Pico to Nano voltage scales. The achievements on this will lead to smaller and more efficient electronic components size that will utilize less power compared to the existing ones.

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