A Hybrid Heuristic Design Technique for Real-time Matching Optimization for Wearable Near-field Ambient RF Energy Harvesters

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***Abstract*—In this paper, a novel real-time active matching circuit design process based on preliminary measurements and a hybridization of a genetic algorithm and a data mining method is discussed. As a result, our proposed matching circuit can potentially have higher dc output power at 92.0 % and 69.6 % of potential load combinations with a maximum matching performance improvement of 21.4 % and 37.6 % compared to conventional matching methods using a dc-dc converter and a fixed passive matching circuit, respectively. After the reduction of matching circuit variable choices utilizing the clustering method, it is possible to achieve a satisfactory matching in practically very short times in the order of 1 ms.**

***Index Terms*—Energy harvesting, Flexible electronics, Printed circuits, Wearable sensors, Internet of Things, Impedance matching, Genetic algorithms, Data mining, Clustering methods**

I. INTRODUCTION

Over the last couple of decades, research towards the development of flexible and wearable electronics has been very active. Such flexible and conformal electronics could play a vital role in the implementation of Internet of Things (IoT), as well as of wireless, smart, autonomous and self-sustainable operation of sensors and devices with ultra-low cost [1]. One of the biggest issues to realize the autonomous operation of these devices is the power supply. In order to solve this problem, ambient energy harvesting technology has attracted the interest of the research community as there are numerous types of potential energy sources for ambient energy harvesting such as solar, heat and vibration. Among them, RF waves are considered as one of the strongest candidates because of their almost ubiquitous availability although their typical low energy density could be a limiting factor for the supply of sufficient power for the electronics. To overcome this low power density issue, there have been reports of ambient energy harvesting from the near-field of consumer mobile communication devices, such as a two-way talk radio, for wearable sensing applications and wearable electronics [2], [3]. The major challenge in the realization of efficient harvesters of this type is the significant variation of Transmitter (Tx) and Receiver (Rx) network topology due to human movements and of the resulting change in the input power levels of the harvester, along with the variations of harvester's load resistance during their actual operation. In the literature, some techniques, such as resistor emulation and resistance compression network, to overcome these input power and load resistance variations have already been reported [4]–[6]. However, even with these techniques, it is difficult to compensate the potential Tx-Rx network impedance variation, which can significantly degrade the performance of the wearable harvester especially when there is a high coupling between Tx and Rx. In order to overcome this mismatching problem, in this paper, a novel real-time active matching circuit design process based on measurements as well as on the hybridization of a genetic algorithm and a data mining method is discussed along with some preliminary results.

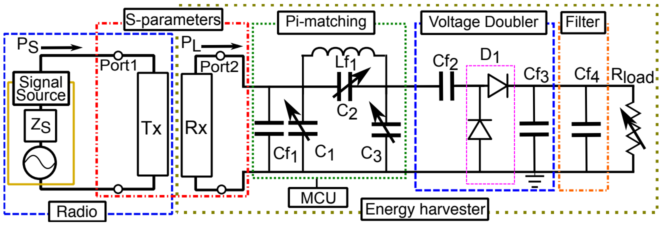

Fig. 1. Generalized near-field wearable energy harvester system with real-time active matching circuit model.

II. REAL-TIME ACTIVE MATCHING RF HARVESTER

A typical near-field wearable energy harvesting system with a real-time active matching circuit can be generally modeled as shown in Fig. 1. For this research, a Motorola RDU4100 handheld radio (2 W mode), that operates at the fixed frequency of 464.5 MHz is expected to be the RF energy source to be harvested. From the measurement with a power sensor (NRP-Z211 from Rohde & Schwarz), the actual transmitted power from the hand held radio is 2.2 W. The values of each circuit component are summarized in Table I. In our harvester, a voltage doubler topology using a two-diode package chip is used in order to achieve a high output voltage with a miniaturized feature size to solve the issues of both "cold start" and limited available footprint. The variable capacitor can change its capacitance in the range of 6.4 to 13.3 pF by 0.22 pF steps, thus leading to 32 potential values.

The basic design of the matching circuit is a Pi-network that is composed of two shunt variable capacitors and one series variable capacitor which is parallel connected to a fixed inductor (Lf_1), yielding 32^3 different impedance value combinations. In order to prevent the self-resonance of this

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TABLE I
Parameters of RF-dc conversion ckt components

Names	Part numbers	Values	Power
Cf_1	S 0603	10.0 pF	-
Cf_2 Cf_3	S 0603	1.0 pF	-
Cf_4	E 1111	390 pF	-
Lf_1	L 0603	6.8 nH	-
R_{load}	-	100 to 5000 Ω	-
D_1	HSMS282C	-	-
C_1 C_2 C_3	MAX1474	6.4 to 13.3 pF 0.22 pF step	660 µW (Active) 33 µW (Normal)
MCU	MSP430F2274	-	<1.2 mW (Active) <3 µW (LPM)

parallel LC network at 464.5 MHz, Lf_1 was chosen to be 6.8 nH [7]. The fixed-value parallel capacitor Cf_1 is used to shift the minimum capacitance value of C_1. The value of the other fixed parallel capacitors are chosen from the list of Johanson Technology's lumped components to maximize the output dc power at the load in ADS simulation. The basic operation of the active matching circuit is a simple "brute force" method [8]. The micro-controller unit (MCU) tries a list of preassigned capacitor values combinations to decide the best capacitor combination featuring the highest load dc power ("selection" state), keeps this combination for a while ("execution" state), and finds the best combination again after a certain amount of time. The genetic algorithm and the clustering are used to identify the optimum list of capacitor value combinations over time-varying conditions. In terms of the power consumption, both the MCU and the variable capacitors need to be in active mode during the "selection" state and consume about 3.15 mW of power. During the "execution state", the variable capacitors are in normal mode and the MCU is in low power mode (LPM), consuming about 100 µW of power.

III. Characterization of effect of human movement for Tx-Rx network

The transducer gain G_T in equation (1), which is the ratio of the power delivered to the load P_L and the power from the signal source P_S, is one of the most commonly used expressions to evaluate the quality of power transfer. Since the reflection coefficient Γ_L in equation (1) is a function of load impedance Z_L, there is an optimal load impedance value that gives the maximum RF power transfer to the load [2]. Therefore, in order to characterize the effect of the human body movement on the Tx-Rx network, the S-parameters of the Tx-Rx network were periodically measured using a vector network analyzer, ZVA8 from Rohde & Schwarz, which was controlled by using LabVIEW. As a proof-of-concept and without loss of generality, a coil shape flexible receiver fabricated on a liquid polymer crystal (LCP) substrate utilizing inkjet printing technology was wrapped around a spindle-shaped plastic bottle filled with water with a separation distance of about 7 cm and a model of the two-way talk radio with a whip antenna (RAN4033A) was randomly tilted within the range of movement of human wrist as depicted in Fig. 2(a). The S-parameters were sampled every 0.25 s for about 25 s to obtain 100 sample data, to represent the full range of possible configurations of the handheld two-way talk radio. For each sample, the optimal load impedance was computed and the results are depicted in Fig. 2(b). As can be seen in the figure, the impedance variation in this Tx-Rx configuration is ± 20 % around the average value of the real part.

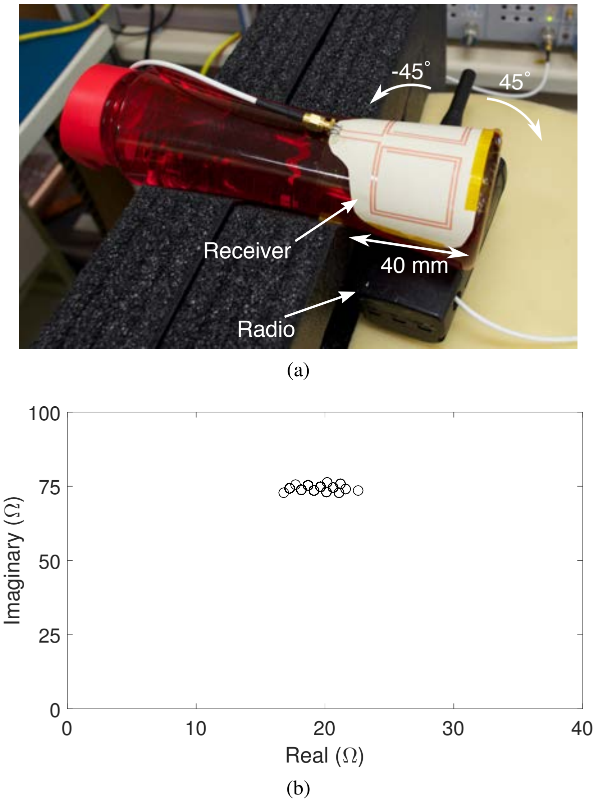
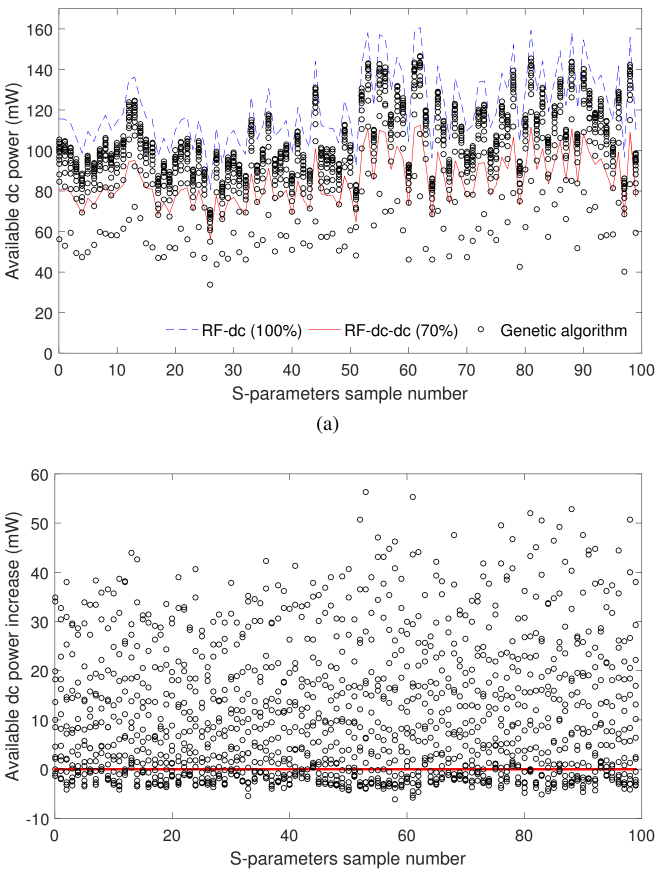


Fig. 2. (a) Tx-Rx network characterization measurement with an on-bottle setup. (b) Optimal load impedance value for each of the 100 sampled S-parameters with an on-bottle setup.

$$G_T = \frac{P_L}{P_S} = \frac{|S_{21}|^2(1-|\Gamma_L|^2)}{|1-S_{22}\Gamma_L|^2} \qquad Z_L = Z_0\frac{1+\Gamma_L}{1-\Gamma_L} \tag{1}$$

IV. Matching circuit design using GA and clustering

From the previous S-parameter measurements, it is determined that the impedance variation in the Tx-Rx network because of human movement is limited. However, there are still the effects of the load resistance variation and input power level variation, which cannot be optimally compensated using a passive matching circuit [2]. One of the commonly used techniques to compensate these effects is to stabilize the load impedance value by using a dc-dc converter. However, by using this technique, we would typically be able to achieve only below 70 % of RF-dc-dc conversion efficiency [9], which can be significantly improved by using the real-time active matching circuit. Since the RF-dc conversion circuit includes active circuit components, the analytically computed maximum transducer gain value does not always guarantee the highest power transfer to the dc load. In order to properly assess the quality of the harvesting circuit, the measured S-parameters are integrated in the circuit simulation utilizing Keysight ADS2015, and the actual available dc power is used as a measure for quality assessment. The final goal of this matching circuit design is to find out a reasonable number of capacitor value combinations which can match as many as possible Tx-Rx network conditions and uncertainties as well as the load resistance value variations out of the potential 32^3 discrete capacitor value combinations. The first stage involves the identification of the best capacitance value combination for each S-parameter sample with different load resistance values. For the proof-of-concept harvester presented in this paper, the load resistance variation included 14 different resistance values from 100 to $5000\,\Omega$ (from 100 to $2000\,\Omega$, $200\,\Omega$ step and from 2000 to $5000\,\Omega$, $1000\,\Omega$ step) are used, which implies there are 1400 sample-resistance value combinations to be optimized. For this stage, the genetic algorithm solver in the optimization function in ADS was utilized. Genetic algorithms (GA) are widely used heuristic search methods, and by introducing this solver, the simulation time and required memory are reduced drastically (more than 5 times) compared to trying all 32^3 possible capacitance value combinations. This GA process utilizing the 100 measured S-parameter samples reported above requires about $4\,\mathrm{h}$ to optimize all the sample-load resistance combinations. Because of the limited amount of available memory on the computer, the number of iteration for each optimization was restricted to 30, but the practical cases that the solutions does not converge within 30 iterations were quite rare. In Fig. 3(a), the comparison between an ideal RF-dc conversion, which is equivalent to the P_L when the transducer gain is the highest, a typical RF-dc-dc conversion efficiency of $70\,\%$ and our genetic algorithm simulation results are depicted. For simplicity and fair comparison, the delivered load power benefits from the genetic algorithm were reduced by the matching circuit power consumption in the active mode. As can be easily observed, the proposed real-time matching circuit can deliver a higher amount of power at 1289 out of 1400 data points ($92.0\,\%$), for a maximum additional power delivered to the load of $34.1\,\mathrm{mW}$. Similarly, in Fig. 3(b), the comparison between the case of the active matching circuit and the case of one fixed capacitor combination, which is optimized to give the highest output power among all the sample-load resistance combinations is plotted. At 975 out of 1400 data points ($69.6\,\%$), the additional power delivered to the load was positive for the proposed active matching circuit with a maximum value of $56.3\,\mathrm{mW}$. In Fig. 4, the distribution of the available dc power increase for both the RF-dc-dc converter case and the fixed matching circuit case are shown with their arithmetic mean values. The highest number of counts can be seen at the bin of 10 to $15\,\mathrm{mW}$ for the case of RF-dc-dc, which is implying that the degradation of matching and power dissipation associated with the use of dc-dc conversion circuit can be improved. Similarly, in the case of fixed matching, the highest number of counts can be seen at the bin of -10 to $0\,\mathrm{mW}$. This is mainly because of the power consumption of the micro-controller and the active matching circuit. On average, about $14.9\,\mathrm{mW}$ and $10.2\,\mathrm{mW}$ available dc power increases can be achieved, respectively. These results imply that the there is a high potential of a significant increase in available dc power using the proposed active matching circuit.



(a)

(b)

Fig. 3. (a) Available dc power with ideal RF-dc conversion, typical RF-dc-dc conversion and GA optimized capacitor combinations. (b) Delivered dc power increase with GA optimized capacitor combinations compared to one fixed capacitor combination.

However, we still have 1400 choices of capacitor value combinations as the candidates of the final list of capacitance combinations, which is not a practical number of combinations that can be tried one-by-one during the “brute force” real-time matching operation, especially with a low computational power micro-controller unit. In order to choose a much smaller but almost equally efficient subset of value combinations out of these 1400 cases, we employed the k-means clustering method, which is commonly used for the data mining from big data, utilizing MATLAB. At the beginning of the data mining, we have set automatically generated 1000 replicates as starting points in order to increase the accuracy of the clustering [10]. For the proof-of-concept of clustering data mining method,

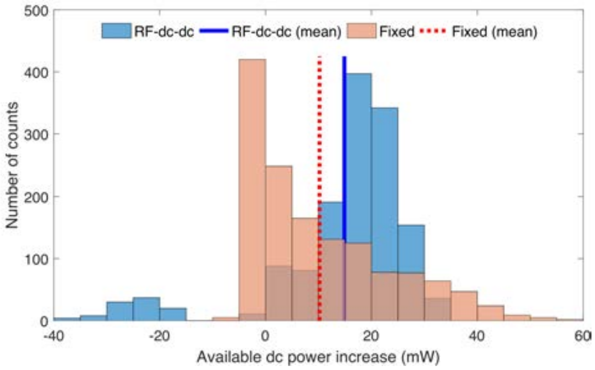


Fig. 4. Distribution of available dc power increase for RF-dc-dc converter case and fixed matching circuit case, and their arithmetic mean values.

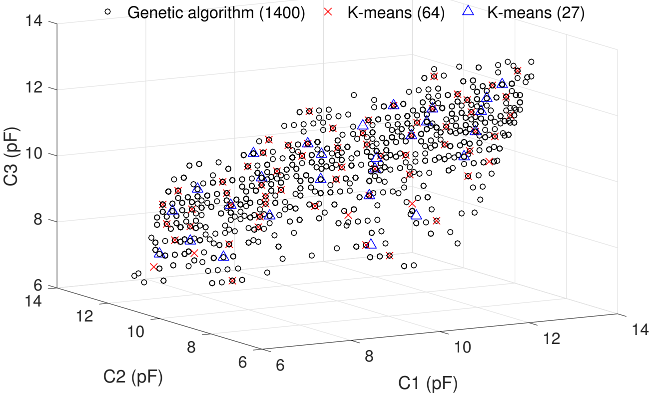


Fig. 5. Capacitor value combinations with and without clustering.

64 and 27 representative data points, that are equivalent to using 4 and 3 different capacitor values for each variable capacitor, are chosen as the the cluster sizes. In Fig. 5, all potential candidates from the genetic algorithm, and 64 and 27 clusters cases are plotted, and in Table II, the figure of merit for all three cases listing the percentage of practical configurations "coverage" of the proposed active matching features better than conventional approaches as well as the maximum additional power delivered to the load using this approach. As can be easily concluded from the table, the degradation of performance in terms of coverage and maximum power gain are less than 3 % and 13.8 mW, respectively, even with the drastic decrease of the number of combinations enabled by the k-means clustering approach. In the actual operation, MSP430F2774 chip is capable of 200 ksps analog-to-digital conversion (ADC), which implies that the required time for matching is less than 1 ms for both 64 and 27 cluster cases. This is expected to be sufficiently fast enough to real-time match and compensate the effects of load resistance variations and human movement.

TABLE II
FIGURE OF MERIT OF GA AND CLUSTERING

	dc-dc matching		Fixed passive matching	
	Coverage	Max power increase	Coverage	Max power increase
GA (1400)	92.0 %	34.1 mW	69.6 %	56.3 mW
K-means (64)	92.7 %	33.9 mW	68.4 %	45.8 mW
K-means (27)	89.4 %	30.4 mW	67.4 %	42.5 mW

V. CONCLUSION

In this paper, a novel real-time active matching circuit design process based on preliminary measurements of Tx-Rx network's S-parameters and the hybridization of a genetic algorithm and a data mining method was discussed. As a result, our proposed matching circuit can potentially deliver a higher dc power at 92.0 % and 69.6 % of sample-load resistance combinations with the maximum additional power delivered to the load of 34.1 mW and 56.34 mW, which are equivalent to 21.4 % and 37.6 % higher power compared to conventional matching methods using a dc-dc converter and a fixed passive matching circuit, respectively. After the drastic reduction of potential capacitance value combinations for the matching circuit utilizing the k-means clustering method, it is possible to achieve the matching in practically short matching time in the order of 1 ms without significant degradation of the matching circuit performances.

VI. ACKNOWLEDGMENT

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