The effect of Resonator Configurations on the optimized sensitivity in the Wireless Resistive Analog Passive (WRAP) sensors

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***Abstract*—Body signal monitoring during normal daily activities requires wireless wearable devices. Furthermore, fully passive body-worn wireless sensors can provide significant advantages by eliminating the need for batteries. With this goal, we have previously proposed a novel Wireless Resistive Analog Passive (WRAP) sensor concept that captures body signals via modulation of carrier signals sent from the primary Planar Spiral Coil (PSC) using the inductive loading principal. Additionally, we reported the optimization methods for the PSC design to maximize the inductive link sensitivity for the wireless signal transmission. A higher efficiency and sensitivity can be achieved when both the primary and secondary circuits are in resonance with the carrier frequency (at 13.56 MHz ISM band in this work). There are four configurations for these resonator arrangement in the primary and secondary circuits according to the series or parallel arrangement of the tuning capacitors, namely: series in primary/secondary (called SS), parallel in primary/secondary (PP), series/parallel in primary/secondary (SP), and vice versa (PS). A Genetic Algorithm (GA) based method is employed to maximize the sensitivity by optimizing the components for each arrangement. It is shown that the PP structure, with the sensitivity of 6.3 m℧, has the highest sensitivity. Moreover, the susceptibility of PP structure vs primary and secondary self-inductance variations is minimum among the other configurations.**

***Keywords*—Genetic algorithm, Inductive coupling, Optimization, Planar spiral coil, Wearables, Wireless sensors**

I. Introduction

Early diagnosis of some diseases and prompt alert for risk factors can be clinically practical by a long term continuous monitoring setup with an unobtrusive wearable system. Patient comfort, reliability, and cost are main factors for a practical long-term wearable system. Bluetooth, WiFi, and RFID have been frequently reported as the employed wireless technologies in the medical field for wearables [1]-[4]. Both the transmitter and the receiver circuits in the Bluetooth and WiFi technologies are activated by the power sources. It not only makes them cumbersome, large, and heavy, but also adds the electrical circuit complexity and cost. RFID, an alternative solution for the wireless communication between the sensors and the interrogators, is fully passive and has the advantage of battery-less. However, RFID requires custom Application Specific Integrated Circuit (ASIC) for body signal capture which can be prohibitively expensive. Furthermore, it is slow (typically 2 sps only) as wireless power from the scanner (primary) must exceed the "turn-on power" to activate the chip on the RFID tag (secondary). Moreover, designing a tag antenna to match with the microchip is also a challenging process in the RFID technique [5].

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We have previously proposed an inexpensive, light weight Wireless Resistive Analog Passive (WRAP) sensor [6] that utilizes a pair of Printed Spiral Coil (PSC) and can collect several physiological signals with low-cost (non-ASIC) components. This chip-less WRAP sensor can sample at rate up to 1 ksps and consumes significantly lower power [7]. The WRAP sensor concept is shown in Fig. 1. According to this figure, a passive circuit including a resistive transducer and a resonator, as the secondary side, inductively connects to the primary side. The primary side, as the scanner or reader, is driven by a signal source with the ISM band frequency, e.g. 13.56 MHz. The primary and secondary PSCs are in the resonance with the resonators which mainly consist of tuning capacitors. The physical characteristics of a PSC are shown in Fig. 2. Several methods have been previously reported [6], [8] to optimize the PSC design including the number of turns, space between tracks, width of the tracks, and the size of PSC to maximize the sensitivity, which is defined as follow in this context:

$$Sensitivity = \left|\frac{d(V_{Out}/V_{Osc})}{dR_{Sensor}}\right| \quad (1)$$

The coil characteristics have been optimized based on the circuit schematic in Fig. 3. In this figure, R_{in} and C_{in} are the signal generator internal resistor and the matching impedance, respectively. C_1 and C_2 are the primary and secondary resonators' tuning capacitors. In the schematic shown in Fig. 3, the tuning capacitors along with the coils' intrinsic *RLC* configure the parallel resonators in primary and secondary circuits and it is called "Parallel-Parallel" (PP) configuration in this study. This report evaluates the effect of the different possible resonator configurations including "Parallel-Series (PS)", "Series-Series (SS)", and "Series-Parallel (SP)" (Fig. 4) on the maximum sensitivity. Moreover, the coil intrinsic *RLC* are subject to change either by application based coil size modification or coil fabrication tolerance. Any coil physical

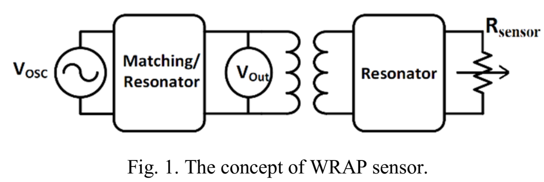

Fig. 1. The concept of WRAP sensor.

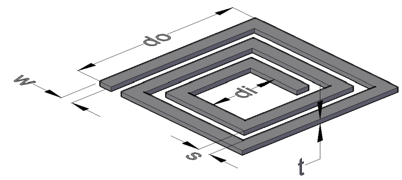

Fig. 2. The coil physical characteristics.

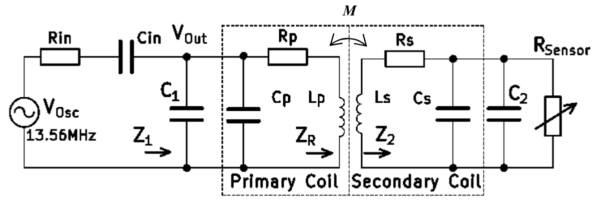

Fig. 3. The circuit schematic shows Parallel-Parallel (PP) that is used for the coil optimization ([6], [8]).

change affects the coil electrical equivalent components that consequently alters the sensitivity. The sensitivity variation in response of the coil physical changes is also evaluated for different resonator configurations. The best configuration should have the highest sensitivity and lowest susceptibility which in this context, is the sensitivity of sensitivity to the coil characteristics or circuit components

II. METHOD

In this report, the primary and secondary PSC's relative position is considered constant and as a result the coupling factor (k), which is defined in (2), remains unchanged.

$$k = \frac{M}{\sqrt{L_P L_S}} \tag{2}$$

Here, M is the mutual inductance between the primary and secondary PSCs and L_P (L_S) is the primary (secondary) coil's self-inductance (Fig. 3). For the different configurations of primary and secondary resonators, the sensitivity can be maximized by optimum circuit components including coils and the capacitors. Experimentally, the coil equivalent resistors (R_P and R_S) are in the range of 1 – 2 Ω, and it can be shown that their variations do not significantly change the sensitivity and the same for intrinsic capacitors, C_P and C_S. Then, by taking these intrinsic components (R_P, C_P, R_S, and C_S) as the constant values and independent of coil self-inductance, the variables in the sensitivity optimization problem are reduced to L_P, L_S, C_1, C_2, and C_{in}. According to Fig. 3 and Fig. 4, the following equations can be concluded ($R_{Sen} = R_{Sensor}$):

$$\frac{V_{Out}(R_{Sen})}{V_{Osc}} = \frac{Z_1(R_{Sen})}{Z_1(R_{Sen})+Z_{in}} \tag{3}$$

$$Z_{in} = R_{in} + \frac{1}{j\omega C_{in}} \tag{4}$$

(For SS and SP, $C_{in} = C_1$)

$$Z_1(R_{Sen}) = 1/\left(j\omega(C_1 + C_P) + \frac{1}{R_P + j\omega L_P + Z_R(R_{Sen})}\right) \tag{5}$$

(For SS and SP, C_1 =0 in (5))

Z_R is the reflected impedance from the secondary to the primary side and is calculated from (6).

$$Z_R(R_{Sen}) = \frac{[M\times\omega]^2}{Z_2(R_{Sen})} = \frac{[k\times\omega]^2 L_P L_S}{Z_2(R_{Sen})} \text{ (Using (2))} \tag{6}$$

For SP and PP structure, Z_2 is defined by:

$$Z_2(R_{Sen}) = R_S + j\omega L_S + \frac{1}{1/R_{Sen} + j\omega(C_S + C_2)} \tag{7}$$

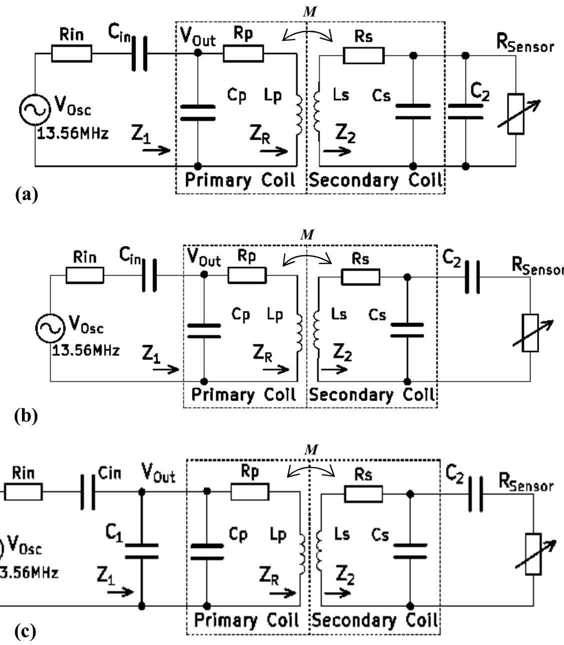

Fig. 4. Different possible resonators structures: (a) Series-Parallel (SP), (b) Series-Series (SS), (c) Parallel-Series (PS)

For SS and PS structure, Z_2 is defined by:

$$Z_2(R_{Sen}) = R_S + j\omega L_S + \frac{1}{\frac{j\omega C_2}{(1+j\omega C_2 R_{Sen})} + j\omega C_S} \tag{8}$$

Equations (3) – (8) create the different objective functions for various resonator configurations which consequently lead to the different maximum sensitivities. For this multivariate objective function optimization, Genetic Algorithm (GA) that is an appropriate optimization approach for the complicated and highly nonlinear objective functions has been employed for the optimization method. The five variables (L_S, L_P, C_1, C_2, C_{in}) have been optimized for each resonator configuration to maximize the sensitivity as the objective function, as defined by (1) and (3) – (8).

The settings and the lower/upper boundaries for the non-constraint GA problem are listed in Table I and Table II. According to Table II, the lower and the upper boundaries for the primary and secondary self-inductances are defined as 1 to 5 μH and 1 to 2 μH, respectively, with the steps of 10 nH. In this study, the secondary coil size (d_O in Fig. 2) has been considered as 20 mm [6] so that, the specified boundary 1 to 2 μH, experimentally is a practical range. The primary coil, which is a part of the reader (viz. scanner) circuit, has less constraints in comparing with the secondary coil, that attaches to the body and its small size which is a requirement considering patient comfort. With the more size flexibility, if the primary maximum size is confined on 60 mm, then 1 to 5 μH is an appropriate self-inductance range. It is worth mentioning that although increasing the self-inductance range with the fixed size constraint, increases the sensitivity, two practical counter-acting effects will appear. Firstly, the coil quality factor (Q) decreases due to the more number of turns and thinner coil track's width (Fig. 2), and secondly, the optimum tuning capacitor values (C_1 and C_2) decrease and consequently the whole circuit is more sensitive to the stray capacitors. Therefore, the mentioned ranges for the primary

Table I. GA option settings

Population Initialization	Population size	1000
Stopping Criteria	Max Stall Generation	50
	Max Stall Time	Inf.
	Maximum generation	200
Fitness scaling		Rank
Selection Function		Stochastic uniform
Mutation	Function	Adaptive Feasible
Crossover	Fraction	0.3
	Function	Scattered
Elite	Elite count	50 (5% of population)

Table II. The Lower and Upper bounds GA

Bound	L_P (µH)	L_S (µH)	C_1 (pF)	C_2 (pF)	C_{in} (pF)
Lower	1	1	1	1	1
Upper	5	2	500	500	500

and secondary self-inductances are the optimum practical ranges. It is notable that although the coils' self-inductance ranges are empirically well-defined for comparing the resonator configurations, the equal self-inductance ranges by itself is enough to find the best arrangement.

For the parallel format, either in the primary or the secondary, the coil's intrinsic capacitors (C_P or C_S) are considered as a part of C_1 and C_2 in the optimization algorithm and results. That means the optimized C_1 or C_2 are the sum of C_1 and C_P or C_2 and C_S (Fig. 3 and Fig. 4). According to the previous results [6], the optimum tuning capacitors (C_1 and C_2) are large in comparison with C_P and C_S in primary and secondary parallel configurations, that their values do not have significant effect on the results. For the series structures, in the primary or secondary, C_P and C_S do not have the determinative effects on the results, however they are considered as 2 pF, based on experimental values. Moreover, R_P, R_S, and the coupling factor (k) for all configurations are considered as 1 Ω, 2 Ω, and 0.08, respectively, according to the experiments [6]. R_{in} is defined by the signal generator output resistor as 50 Ω.

III. Results

Fig. 5 shows the maximized sensitivity for each L_P and L_S pair by a set of optimum capacitors. In these figures, by scanning the L_P and L_S in the defined ranges, the optimum values for capacitors (C_1, C_2, C_{in}) are found by GA method that maximize the sensitivity. As Fig. 5(a) suggests, the sensitivity in SS structure drops rapidly by L_P and also it is more sensitive to L_S comparing with other forms. Moreover, the maximum sensitivity in SS configuration is smaller than other structures by a factor of ~10. In SP form, shown in Fig. 5(b), the sensitivity is less susceptible to the L_S in comparison with SS structure, but still drops rapidly by L_P. The sensitivity of PP structure (Fig. 5(c)) has the lowest susceptibility to both L_P and L_S and it also shows the highest sensitivity value compared with the other configurations. Although sensitivity fluctuates with L_P, the minimum values are still higher than the other figures. According to Fig. 5(d), the PS design has almost the same maximum sensitivity as PP, but the sensitivity is more susceptible to L_P variations in comparison with PP. The sensitivity peaks in Fig. 5 and their associated components optimum values are listed in Table III. The qualitative susceptibility comparison as well as the maximum sensitivity for different configurations are summarized in Table IV.

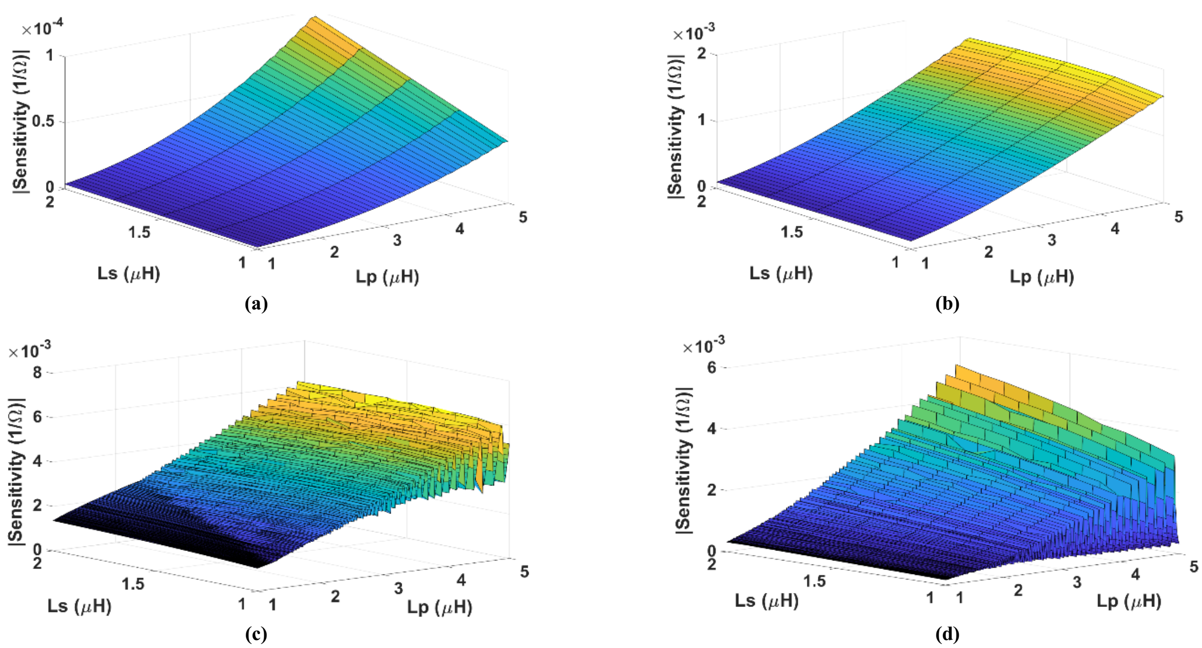

Fig. 5. The maximum sensitivity for each pair of L_P and L_S in the range of 1-5 µH and 1-2 µH, respectively, for different resonator configurations. For each pair of L_P and L_S, a set of optimum capacitors (C_1, C_2, C_{in}) maximize the sensitivity and they are shown in Table III. (a) SS, (b) SP, (c) PP, (d) PS.

Table III. The maximum possible sensitivity for L_P = 1–5 µH, L_S = 1–2 µH and the optimum capacitors. (R_P, R_S) = (1, 2) Ω and (C_P, C_S) = (2, 2) pF

Configuration	L_P (µH)	L_S (µH)	C_1 (pF)	C_2 (pF)	C_{in} (pF)	|Sensitivity| (m℧)
SS	5	2	-	157	25	0.095
SP	5	1.25	-	111	26	1.66
PP	4.88	1.55	24	48	4	6.3
PS	4.92	2	25	64	3	5.1

IV. Discussion

The gradient of sensitivity vs L_P and L_S are the important parameters to compare the resonator configurations. The application consideration may require to change the primary and/or secondary coil size other than the contemplated values. Therefore, the configuration with the minimum sensitivity to L_P and L_S variations is desirable from the susceptibility point of view. The sensitivity behavior with L_P and L_S can be observed from two perspectives: fast change and slow change. Fig. 5(a) and Fig. 5(b) do not show fast change while Fig. 5(c) and Fig. 5(d) show both fast and slow sensitivity variations. The slow changes of sensitivity correspond to the coil's dimension changes as for application consideration, while the fast changes associate with the coil tolerances.

Considering that the coil self-inductance is directly depends on the coil size, if the coil size is subject to change, the configuration with the smallest slow change is the most desirable one that shows stable sensitivity. According to Fig. 5, the PP configuration has the highest stability vs the coil dimensions (for both L_P and L_S).

Fig. 5(c) and Fig. 5(d) show the fast changes in the sensitivity with L_P that makes them highly susceptible to the primary coil fabrication tolerances. In PS configuration (Fig. 5(d)), the sensitivity drops to almost zero by a small variation in L_P, while in PP structure, any small deviation in L_P cannot reduce the sensitivity more than 30% and for smaller value of L_P, this fluctuation reduces significantly almost to zero for L_P less than 3 µH. Therefore, parallel format in primary (PP or PS) is more susceptible to the coil fabrication tolerances but while the sensitivity drops almost 30% for PP model this reduction is close to 100% in PS format.

From the sensitivity value, according to Fig. 5, PP and PS have the first and second highest sensitivities, respectively. As the result, the PP configuration has the highest sensitivity, minimum dependency to the coil physical modifications and relatively high susceptibility to the coil fabrication tolerances, but the sensitivity attenuation due to fabrication tolerance is still above the maximum sensitivity of the other configurations. In addition, SP is the second best model that shows both the stable sensitivity against fabrication tolerance and relatively high sensitivity.

V. Conclusion

The coil optimization details have been previously presented in [6] and [7]. In this report, the different configurations of primary and secondary resonator circuits have been studied and compared. The resonator models were compared from the maximum sensitivity and their susceptibility to the coils' self-inductance variations due to coil application modifications (slow changes) and coil fabrication tolerances (fast changes). The best model should show the highest sensitivity with minimum attenuation to coil variations. Tuning capacitors, C_1 and C_2, coupling capacitor, C_{in}, and PSC self-inductances, L_P and L_S, are the most influential components on the sensitivity. The optimum combination of the three capacitors (C_1, C_2, C_{in}) have been explored by a GA optimization program to maximize the sensitivity for each pair of L_P and L_S in the empirical range of 1 to 5 µH and 1 to 2 µH, respectively, for different resonator configurations. The results are evaluated based on the maximum sensitivity and minimum sensitivity deviation due to coil changes, which is called susceptibility. The results show that the parallel-parallel (PP) arrangement has the highest sensitivity (6.3 m℧) and lowest attenuation of PSC self-inductance changes (Table IV). The result of this study guarantees the Parallel-Parallel resonators as the best configuration and as the next step toward the completion of the WRAP sensors the effect of PSC's characteristics on coupling factor (k) will also be considered in the optimization calculation.

Table IV. The qualitative comparison between the different structure for their susceptibility to LP and LS changes

Model	Sensitivity Susceptibility to PSC Variation				Maximum Sensitivity (m℧)
	PSC Modification (Major changes: $\Delta L > 5\%$)		Fabrication Tolerance (Minor changes: $\Delta L < 5\%$)		
	L_P	L_S	L_P	L_S	
SS	High	High	Low	Low	0.095
SP	High	Low	Low	Low	1.66
PP	Low	Low	High*	Low	6.3
PS	High	High	High	Low	5.1

*: The sensitivity at maximum drop is still higher than other configurations.

References

[1] J. Liu, Y. Chen, Y. Wang, X. Chen, J. Cheng and J. Yang, "Monitoring Vital Signs and Postures During Sleep Using WiFi Signals," in *IEEE Internet of Things Journal*, vol. 5, no. 3, pp. 2071-2084, June 2018.

[2] H. Lin, Y. Shih, A. Pang and C. Chou, "Virtual Local-Hub: A Service Platform on the Edge of Networks for Wearable Devices," in *IEEE Network*, vol. 32, no. 4, pp. 114-121, July/August 2018.

[3] D. Brunelli, E. Farella, D. Giovanelli, B. Milosevic and I. Minakov, "Design Considerations for Wireless Acquisition of Multichannel sEMG Signals in Prosthetic Hand Control," in *IEEE Sensors Journal*, vol. 16, no. 23, pp. 8338-8347, Dec.1, 2016.

[4] D. P. Rose, M. E. Ratterman, D. K. Griffin, L. Hou, N. K. Loughnane, R. R. Naik, J. A. Hagen, I. Papautsky and J. C. Heikenfeld, "Adhesive RFID Sensor Patch for Monitoring of Sweat Electrolytes," in *IEEE Transactions on Biomedical Engineering*, vol. 62, no. 6, pp. 1457-1465, June 2015.

[5] G. Marrocco, "The art of UHF RFID antenna design: impedance-matching and size-reduction techniques," in *IEEE Antennas and Propagation Magazine*, vol. 50, no. 1, pp. 66-79, Feb. 2008.

[6] B. Noroozi and B. I. Morshed, "PSC Optimization of 13.56-MHz Resistive Wireless Analog Passive Sensors," *in IEEE Transactions on Microwave Theory and Techniques*, vol. 65, no. 9, pp. 3548-3555, Sept. 2017.

[7] B. I. Morshed, B. Harmon, M. S. Zaman, M. J. Rahman, S. Afroz, and M. Rahman, "Inkjet Printed Fully-passive Body-worn Wireless Sensors for Smart and Connected Community (SCC)", J. *Low Power Electron. Appl.*, vol. 7, no. 4, article 26, pp. 1-21, Nov. 2017.

[8] B. Noroozi and B. I. Morshed, "Sensitivity optimization of Printed Spiral Coil for Wireless Resistive Analog Passive (WRAP) Sensors using Genetic Algorithm," *2018 40th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, Honolulu, HI, 2018, pp. 4653-4656.