Modeling and Design of High-Efficiency Power Amplifiers Fed by Limited Power Sources

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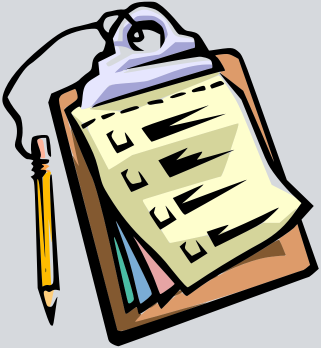
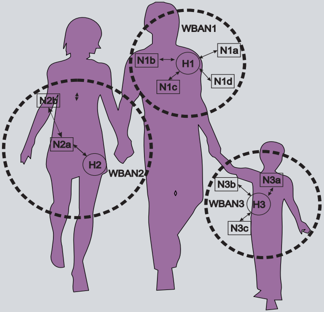
Agenda



- Introduction
- Proposed PA Modeling
- Design Methodology
- Study Case
- Conclusions
- Acknowledgment
- References

WBANs means?

- Networks which can be wearable, implanted or around the human body [1].



[1] S. Movassaghi, M. Abolhasan, J. Lipman, *et al.*, "Wireless body area networks: A survey", *IEEE Communications Surveys & Tutorials*, vol. 16, no. 3, pp. 1658–1686, 2014.

WBANs means?

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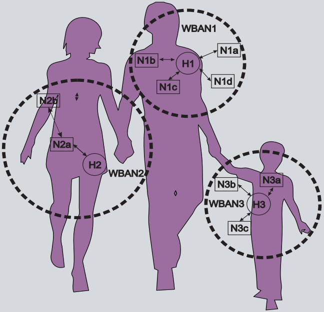
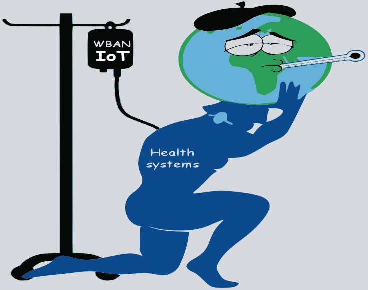


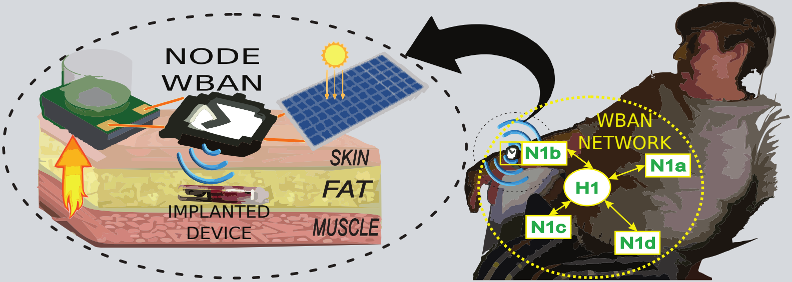


- Networking at human body level (WBANs + IoT) is expected to cause a dramatic shift in HcS [1].

[1] S. Movassaghi, M. Abolhasan, J. Lipman, *et al.*, "Wireless body area networks: A survey", *IEEE Communications Surveys & Tutorials*, vol. 16, no. 3, pp. 1658–1686, 2014.

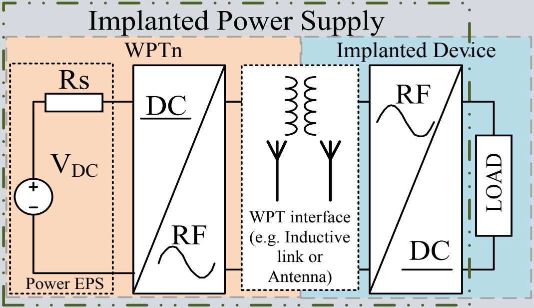
WPTn concept for implanted device autonomy

WPT node (WPTn) is an autonomous wearable WBAN node used as energy and communication solution for a passive implanted RFID tag that sense biomedical data.



Self-sustaining WPT system power chain

The maximum available power (P_{avs}) of the Implanted power supply is limited by BOTH power chain efficiency and P_{avs} of the Power EPS [2].



[2] A. Fajardo and F. Rangel de Sousa, "Ideal energy power source model and its implications on battery modeling",

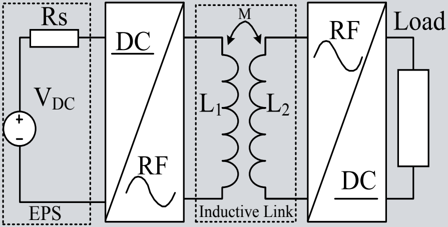
Self-sustaining WPT system Design

Traditional design approach:

- The system interactions are reduced to V or I specifications.
- The subsystems are optimized individually.

Non - Traditional design example:

- Regulator-less PA: A non regulated voltage between the EPS and the power amplifier (PA) was explored in [3].

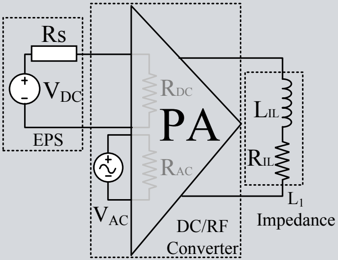


For Self-sustaining WPT system traditional design approach is inadequate, because maximum η does not necessarily means maximum P_{out}.

[3] J. C. Rudell, V. Bhagavatula, and W. C. Wesson, "Future integrated sensor radios for long-haul communication", *IEEE Commun. Mag.*, vol. 52, no. 4, pp. 101–109, 2014.

Modeling of the energy-flow process using the PA impedance ports

- At input power ports: R_{DC} and R_{AC} .
- A fraction of the power "dissipated" by PA are transfered to $R_L = R_{IL}$.



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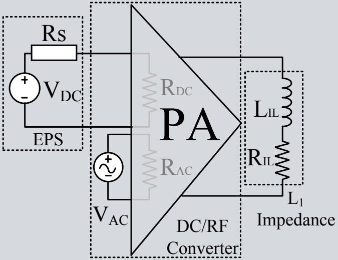

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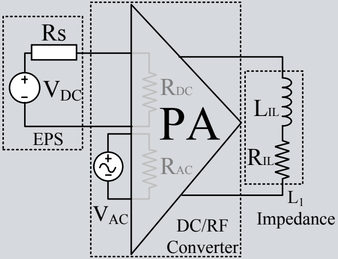
- The load power depends only on the external elements connected to the PA.

Modeling of the energy-flow process using the PA impedance ports

- At input power ports: R_{DC} and R_{AC} .
- A fraction of the power "dissipated" by PA are transfered to $R_L = R_{IL}$.

- The load power depends only on the external elements connected to the PA.
- The output power port could be modeled by a AC circuit power source.



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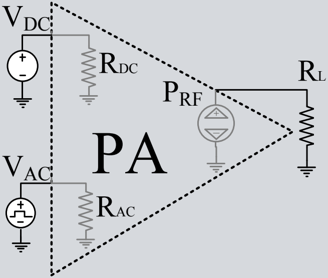
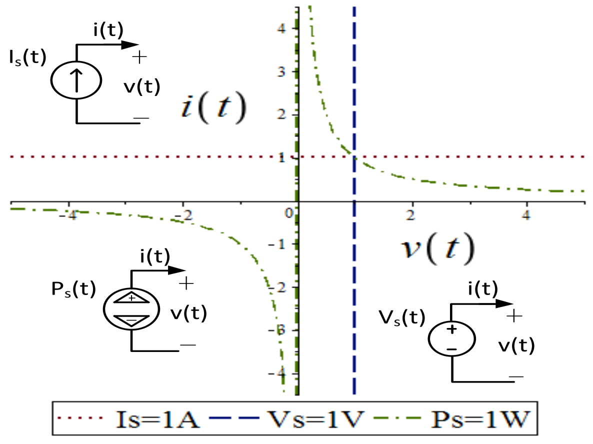


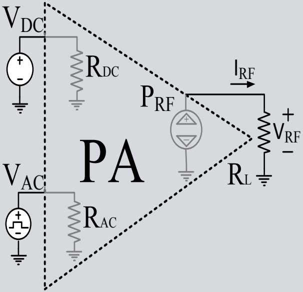
Circuit power source

A circuit power source imposes the power on its load [4].



[4] R. W. Erickson and D. Maksimovic, *Fundamentals of power electronics*. New York: Springer, 2001.

PA efficiency predicted by the Model I



$$I_{RF} = I_m sin(\omega_0 t)$$
$$V_{RF} = V_m sin(\omega_0 t)$$

$$P_{RF} = \frac{{I_m}^2}{2} R_L = \frac{{V_m}^2}{2R_L} = \frac{I_m \cdot V_m}{2}$$
$$P_{DC} = {I_{DC}}^2 R_{DC} = \frac{{V_{DC}}^2}{R_{DC}} = I_{DC} V_{DC}$$

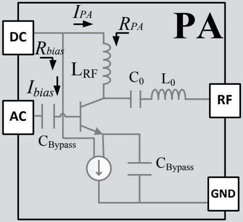
Output power and efficiency:

$$P_{RF} = PAE \cdot P_{DC} + P_{AC}$$
$$P_{RF} = \eta_D \cdot P_{PA}$$
$$P_{RF} = \eta \cdot (P_{DC} + P_{AC})$$

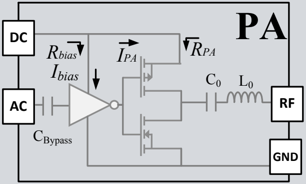
When P_{AC} is negligible compared to P_{DC}:

$$\eta \approx PAE \approx \eta_D \approx \frac{P_{RF}}{P_{DC}} = \frac{R_L}{2R_{DC}} \left(\frac{I_m}{I_{DC}}\right)^2 .$$

PA efficiency predicted by the Model



Class-A PA



Class-D PA

DC power= Bias circuit (or the driver circuit) + PA power stage. Therefore, η can be rewritten as:

$$\eta = \frac{1}{2}\frac{R_L R_{DC}}{{R_{PA}}^2}\left(\frac{I_m}{I_{PA}}\right)^2 = f\left(G_R\right)$$

G_R is the PA impedance factor defined as $G_R = R_{DC}/R_L$, and $f(x)$ is a function dependent on the PA topology.

Class-D Modeling Example I

Considering ideal components, D=50% in the AC-port, high loaded quality factor, the MOSFET (N and P type) as an ideal switch an R_{on}.

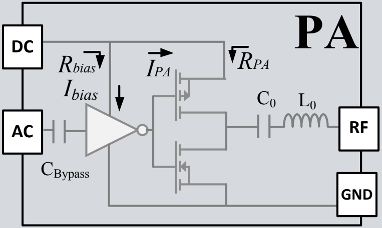
$$I_m = \frac{V_m}{(R_L + R_{on})} = \frac{4V_{DC}}{\pi(R_L + R_{on})}$$

$$I_{PA} = \langle i_{PA}(t) \rangle_{T_0} \approx 2I_m/\pi$$

$$R_{PA} = \frac{V_{DC}}{I_{PA}} = \frac{\pi^2}{8}(R_L + R_{on})$$

$$R_{bias} = \frac{R_{on}}{f_0 \cdot \alpha \cdot a \cdot b}$$

where, α represents the capacitance excess due to the driver implementation. The technology parameters (i.e., $a = \frac{C_G}{W}$ and $b = R_{on}W$) were proposed in [5].

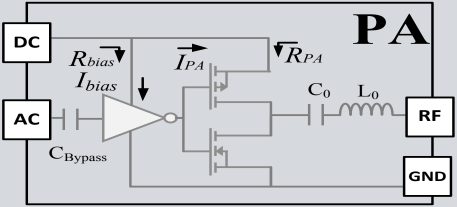


Moving average

$$\langle x(t) \rangle_{T_0} = \frac{\omega_0}{2\pi} \int_{t_0}^{t_0+\frac{2\pi}{\omega_0}} x(t)dt$$

[5] B. R. W. Stratakos Anthony J. and S. R. Sanders, “High-efficiency low-voltage dc-dc conversion for portable applications.”, in *Proc. Int. Workshop on Low-Power Design*, Napa, CA. 1994, pp. 21–27.

Class-D Modeling Example II



$$\eta = \frac{1}{\left(1 + m\left(G_R\right)\right)\left(1 + k\left(1 + \frac{1}{m(G_R)}\right)\right)}$$

where the function $m(x)$ is given by:

$$m\left(x\right) = \frac{1}{2}\left(\left(A + B\right)x - 1 \pm \sqrt{1 + \left(2A - 2B\right)x + \left(A + B\right)^2 x^2}\right)$$

$$A = f_0 \cdot \alpha \cdot a \cdot b\,;\, B = \frac{8}{\pi^2}\,;\, k = \frac{A}{B};\, G_R = \frac{R_{DC}}{R_L}.$$

This efficiency is maximum when:

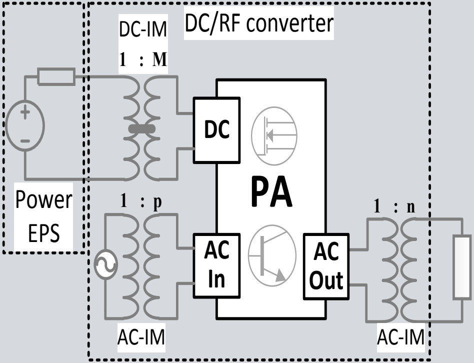
$$G_{opt} = \frac{\sqrt{\left(k+1\right)k} + k}{\left(A + B\right)\sqrt{\left(k+1\right)k} + A\left(k+1\right)} \quad (1)$$

its maximum value is:

$$\eta_{max} = \frac{\sqrt{k^2 + k}}{\left(k + \sqrt{k^2 + k}\right)\left(k + 1 + \sqrt{k^2 + k}\right)} \quad (2)$$

Proposed Design Methodology I

- For maximizing the power delivered to the load, the methodology maximize BOTH the power supplied by the harvester and the PA efficiency.
- The methodology uses PA modeling based on its ports and impedance matching concepts.
- The DC-IM implementation could be an DC/DC converter, and the AC-IM implementation could be a L or π network.



Proposed Design Methodology II

Step	Step Description	Equation
1	Find the P_{avs} of the power EPS and its related variables: optimum load impedance (R_{pavs}), load voltage (V_{pavs}) and current (I_{pavs}).	e.g. for a thermoelectric generator, the internal series resistor of the EPS (R_s) is constant, therefore: $R_{pavs} = R_s$, $V_{pavs} = \frac{V_{DC}}{2}$ and $I_{pavs} = \frac{V_{DC}}{2R_s}$.

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2	Fix the voltage in the PA DC-port as the highest for a particular implementation restriction (e.g. V_{max} CMOS process.)	$V_{DC_{opt}} = V_{\max}$

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3	Find the DC current that extracts the P_{avs} of the EPS.	$I_{DC_{opt}} = \frac{P_{avs}}{V_{\max}}$

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3	Find the DC current that extracts the P_{avs} of the EPS.	$I_{DC_{opt}} = \frac{P_{avs}}{V_{\max}}$
4	Find the impedance of the PA DC-port that maximizes the power extracted from the harvester.	$R_{DC_{opt}} = \frac{V_{DC}}{I_{DC}} = \frac{V^2{}_{\max}}{P_{avs}}$

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5	Find the optimum load value for maximizing PA efficiency.	$R_{L_{opt}} = G_{R_{opt}} R_{DC_{opt}}$

Proposed Design Methodology II

RF Laboratory

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4	Find the impedance of the PA DC-port that maximizes the power extracted from the harvester.	$R_{DC_{opt}} = \frac{V_{DC}}{I_{DC}} = \frac{V^2{}_{\max}}{P_{avs}}$
5	Find the optimum load value for maximizing PA efficiency.	$R_{L_{opt}} = G_{R_{opt}} R_{DC_{opt}}$
6	Find the specifications of the DC and AC impedance matching networks (DC-IM and AC-IM).	$M = \sqrt{\frac{R_{DC_{opt}}}{R_{pavs}}} = \sqrt{\frac{V^2{}_{\max}}{P_{avs} \cdot R_{pavs}}}$

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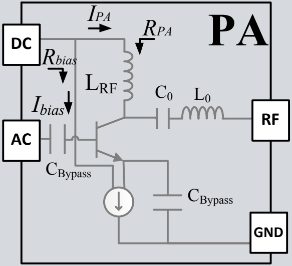
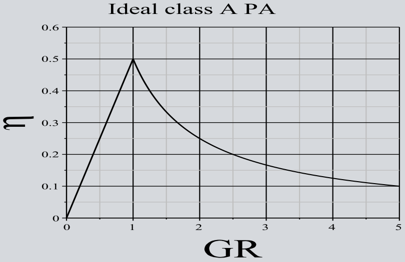
Class A Study Case - PA Modeling I



$$\eta = \begin{cases} 0.5 \cdot G_R & G_R < 1\,; \Rightarrow I_m = I_{PA} \\ \frac{1}{2G_R} & G_R \geq 1; \Rightarrow V_m = V_C \end{cases} .$$

Where, $G_R = \dfrac{R_{DC}}{R_L}$.



This efficiency is maximum when:

$$G_{R_{opt}} = 1$$

its maximum value is:

$$\eta_{max} = 50\%$$

Class A Study Case - PA Modeling II

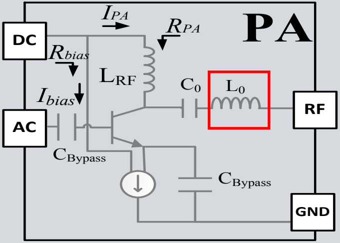
As a proof of concept a class A PA was designed, simulated and implemented.

I_{PA}	f_0	R_L
1mA	100 kHz	1kΩ

The simulation setup uses the harmonic balance simulation technique in the Advanced Design System (ADS®) software. V_{AC} and R_{PA} sweeps were implemented.

PA simulation results

R_{PA} (Ω)	Limit type	$\lvert v_{ac}\rvert_{\phi_t}$	P_{DC} w/o_LC (mW)	P_{DC} w_L (mW)	P_L w/o_L (mW)	P_L w_L (mW)	η w/o_L (%)	η w_L (%)
0.5	V_m=V_C	0.530	0.564	0.564	0.138	0.138	24.5	24.5
1.0	V_m=V_C	1.181	1.127	1.127	0.545	0.545	48.3	48.2
1.5	I_m=I_{PA}	1.180	1.691	1.691	0.545	0.545	32.2	32.1
2.0	I_m=I_{PA}	1.180	2.254	2.254	0.545	0.545	24.2	24.1



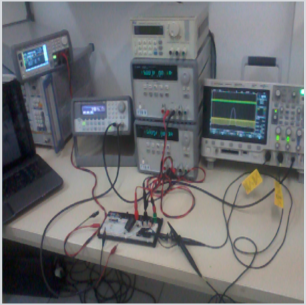
The R_{PA} sweep was implemented by a fixed current (I_{PA}=1mA) and a V_{DC} sweep. The circuit was simulated with and without the output LC tank filter (Only C_0).

Class A Study Case - PA Modeling III

In the experimental setup the I_{PA} was fixed to 1 mA and the R_{PA} was set with the V_{DC}. In this setup, V_{AC} was incremented until the PA operates at the limit of the class-A operation ($I_m = I_{PA}$ or $V_m = V_C$).

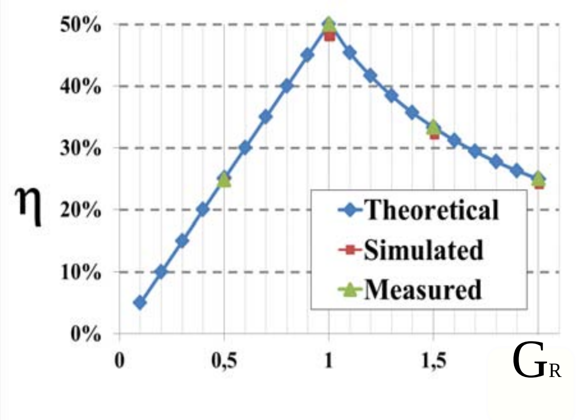
PA experimental results

R_{PA} (Ω)	Limit type	$\lvert v_{ac} \rvert_{\phi_t}$	LC tank	P_{DC} (mW)	P_L (mW)	η (%)
0.50	$V_m=V_C$	0.679	w/o	0.5002	0.1242	24.8
1.00	$V_m=V_C$	1.516	w/o	10.003	0.5004	50
1.50	$I_m=I_{PA}$	1.516	w/o	15.002	0.5010	33.3
2.00	$I_m=I_{PA}$	1.516	w/o	2.002	0.5010	25



Class A Study Case - PA Modeling IV

The predicted efficiency by the proposed PA model and the results (simulated and experimental) are plotted in the Figure



Class A Study Case - Proposed Methodology (PA + Power EPS)

In order to verify experimentally the proposed methodology without the practical limitations of the commercial harvesters and the impedance matching networks, we choose a scenario with the following specifications: a emulated power EPS with $P_{avs} = 1$mW and $R_{pavs} = 1$kΩ, a resistive load of $R_L = 1$kΩ, and $f_0 = 100$ kHz.

Metodology Results

$V_{DC_{opt}}$	$I_{DC_{opt}}$	$R_{DC_{opt}}$	$R_{L_{opt}}$	M	n
1V	1mA	1kΩ	1kΩ	1	1

Experimental results

R_{DC}	P_{EPS}	P_{DC}	P_{RF}	η_{EPS}	$\eta_{DC/RF}$
1.001kΩ	2.004mW	1000.3 μW	500.4μW	50%	50 %

Conclusions

- A design methodology for a generic PA fed by a power EPS was proposed.

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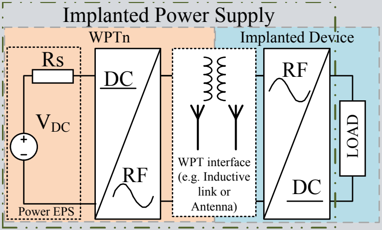
Conclusions

- A design methodology for a generic PA fed by a power EPS was proposed.
- As a proof of concept a class-A PA was designed, implemented and tested.
- The results reflect that the designed PA extracts the maximum available power of the source with its maximum efficiency.
- For maximizing the power on the load in a system powered by Power EPSs, the traditional approach based only the system efficiency is inadequate. Furthermore, the designing of EPSs, Energy converters (i.e. PAs) and circuits that could take advantage of the use of power specifications instead of predefined voltage or current condition is a open challenge.



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