Design Rules for a Weakly Coupled Inductive Link avoiding the "Black Hole" in Passive Telemetry Data Transmission for an Implantable Thermal Flow Sensor

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ABSTRACT

Passive Telemetry by Absorption Modulation is based on two coupled coils, with energy transfer from the outer base unit to the implanted transponder and with bi-directional communication. The extracorporeal feeding coil (FC) is weakly coupled to the implanted transponder coil (TC) at a variable working distance (WD), which has to be defined at the very beginning of a new project.

In practice an unexpected loss of telemetry communication occurs at several specific working distances: The carrier supplies the transponder with sufficient energy, but no signal modulation can be detected any more. We call such areas here "Black Hole".

Following the presented design rules a system can be realized that shows a power transmission efficiency of > 20% and a telemetry bandwidth of > 5 % of the carrier frequency *fo* at distances from 0 to maximum WD, without falling into the Black Hole.

The paper describes an optimized coupled coil system for a ∅ 14 x 4 mm transponder with experimental data, model evaluation and pSpice simulation. This coil system belongs to a passive telemetry system for an implantable thermal flow sensor for neurological application. The RF to DC conversion efficiency is 28 %; the sensor signal is A/D converted with 12 Bit resolution during a RF interruption of 1 msec and transmitted every 20 msec by remote control.

INTRODUCTION

The principle of Passive Telemetry by Absorption Modulation by varying the DC-load has already been presented at the 10th ISOB Symposium (Neukomm et al. 1988). Successful biomedical applications cover implantable pumps for drug delivery to intracranial pressure monitoring. Transcutaneous energy transmission up to 20 W is possible at DC-DC power transfer efficiency of 75% (Vandevoorde et al. 2000). Functional electrical stimulation (FES) with implantable RF-CMOS circuits will be ready soon (Gudnason et al, 2002).

Passive Telemetry is based on resonant structures which extract energy from an external electro-magnetic or alternating magnetic field in two ways: a.) constant for power supply of the implant and b.) pulsating by absorption modulation for telemetry. This modulation is detected as a very small AM or PM at the RF-source of the extracorporeal base unit, allowing a high information capacity. Data transmission from base unit to implant for remote control is usually performed by ASK of the RF-Source, but the bandwidth of usable ISM carrier frequencies is limited and not exactly the same in all jurisdictions (Gudnason et al. 2002, pp. 40).

The following investigation shows the telemetry performance of a ∅ 14 x 4 mm transponder at the ISM Band 27.12 MHz with experiments and pSpice simulations at small coupling factors $0.02 < k < 0.1$. These coupling factors correspond to working distances from 6 to 26 mm for a feeding coil of ∅ 35 mm. For easier interpretation and due to our restrictions of our FCC license the carrier is here 28 MHz at a power of 1 W. 3D-field calculations of the coupling factor k between a feeding coil and a transponder coil around a conductive transponder box, as well as analytical computations of tuning methods, are described by (Benedetti 1997, Limacher 2002).

METHODS

Principle and Application of Passive Telemetry

Figure 1 shows the principle of a weakly coupled Passive Telemetry system. The maximum working distance WD should be less than the diameter of the feeding coil FC for robust operation. Beyond this relative distance the generated magnetic energy reduces with $1/r^5$ (see Figure 3); the coupling factor becomes too small for the telemetry signal demodulation with acceptable S/N ratio. The signal bandwidth (BW) for both Remote Control (Rx) and Telemetry (Tx) depends on the System Quality Factor (Q).

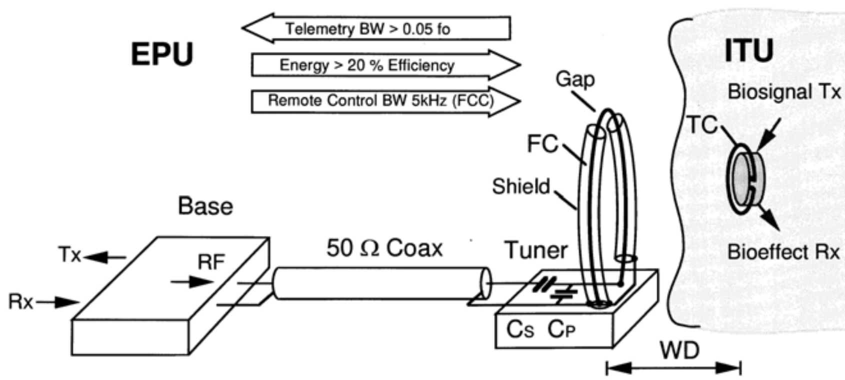


Figure 1. Passive Telemetry Set-up with weakly coupled coil system.
EPU: Extracorporeal Processing Unit
FC: Feeding Coil, shielded with gap
Tuner: Match for coil to 50 Ω
fo: RF carrier frequency 1 < fo < 100 MHz
ITU: Implantable Transponder Unit
TC: Transponder Coil
WD: Working Distance
FCC: BW limit by national legislation

The important practical features of this system are:
- Base RF output and Tuner input are matched to 50 Ω, allowing a coaxial cable interconnection as well as AC-analysis with a network analyzer and other RF tools.
- The Feeding Coil, a shielded H-field loop, prevents detuning effects by biological material and prevents unbalanced currents on the outside of the coaxial cable.
- The Transponder Coil is close to the metallic case of the transponder.

	Feeding Coil	Transponder Coil
Material	RG 316 ∅outer 2.5 Coax 50 Ω	Cu ∅ 0.425 + 0.08 insulation
Number of turns	3	4
Diameter (mean)	35 mm	13.3 mm
Inductance	609.5 nH	254.8 nH
Impedance at 28 MHz	107 j Ω	45 j Ω
Quality Factor QL of L	77	38
System Quality Factor Q	17	10
Lead wires to tuning box	2 x 45 mm	2 x 55 mm, twisted
Parasitic Parallel Capacity	95 pF/m, screen to conductor	80 pF/m for parallel wires
Coil former	PETP-Ertalyte, εr: 3.2	PETP-Ertalyte, εr: 3.2
Specialty	Shielded with gap at 1.5 turns	Stainless steal core 10 x 3.8

Table 1. Characteristics of the coils used, note the parasitic capacities!

The investigated coupled coil system and the power transfer efficiency measured at 1 W RF power is shown in Figures 2 and 3. The experimental electronic circuits of EPU (left) and ITU (right) are well protected within metallic cases. The stainless steel cylinder within the transponder coil serves as a simulator for the final implant.

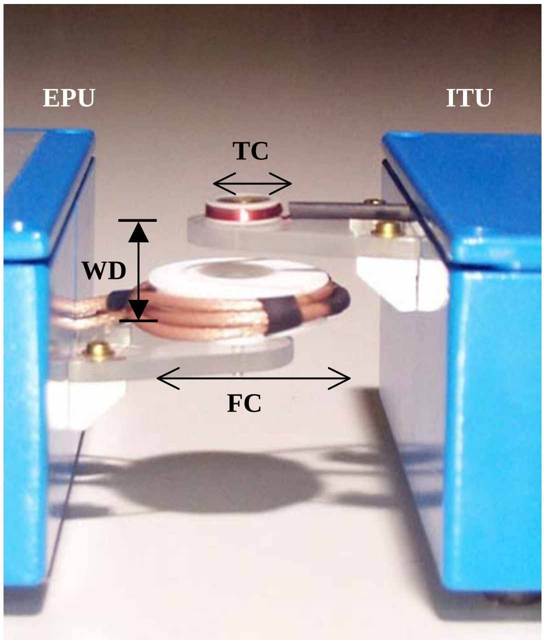


Figure 2. Coupled Coil System.
Left EPU with FC, right ITU with TC

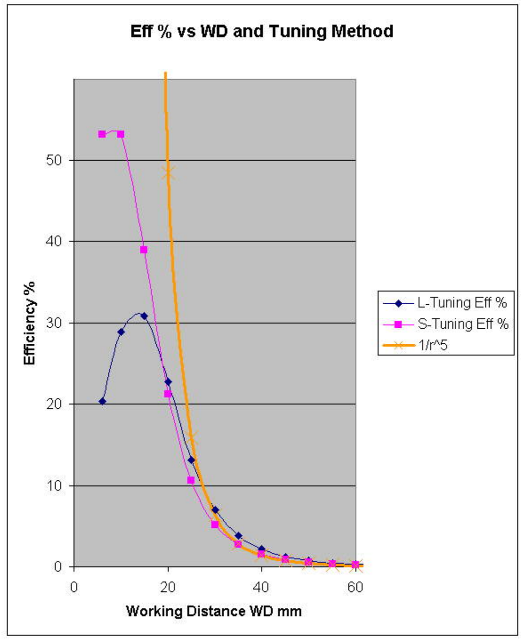


Figure 3. Power Transfer Efficiency versus Working Distance and $1/r^5$ Law.

The coils are arranged with their axis parallel to the vertical z-axis, the working distance WD is the spacing between the two centers. The minimal accessible distance is here WD = 6 mm.

Two different tuning methods are used:

- Long-Range Uncoupled Tuning (L-Tuning): Each coil for itself is individually matched to the RF-Source, resp. AC-Load, like a stand-alone antenna for maximum far field radiation.

- Short-Range Coupled Tuning (S-Tuning): Both coils are coupled at WD = 17 mm, both tuners are matched for maximum power transfer.

L-Tuning is good for large WD > 20 mm, but the maximum efficiency is only 31 % @ 15 mm and drops to 20% @ 6 mm due to excessive coupling of the two coils. Both remote control and telemetry operate within 6 mm < WD < 35 mm, under the condition of elevated RF input power to supply the electronics of the transponder.

S-Tuning seems to be good for 6 mm < WD < 20 mm, with a very high maximum efficiency of 53 % @ 10 mm. However, there is a Black Hole near WD = 19 mm which limits the telemetry application to 6 mm < WD < 18 mm (see later in this paper).

The Biot-Savart law for circular current loops predicts a $1/r^3$ dependence of the magnetic far field at the transponder coil. The received energy is $\frac{1}{2}\int B\,H\,dV$, varies with $1/r^5$ and correlate at WD > 25 with the efficiencies in Figure 3. The small error is caused by the capacitive coupling of the coils when measured with common ground. Further experiments with isolated, battery powered RF sources with 3dB output attenuator showed a good correlation for 30 < WD < 80.

Telemetry System with models of the inductive link and absorption modulation

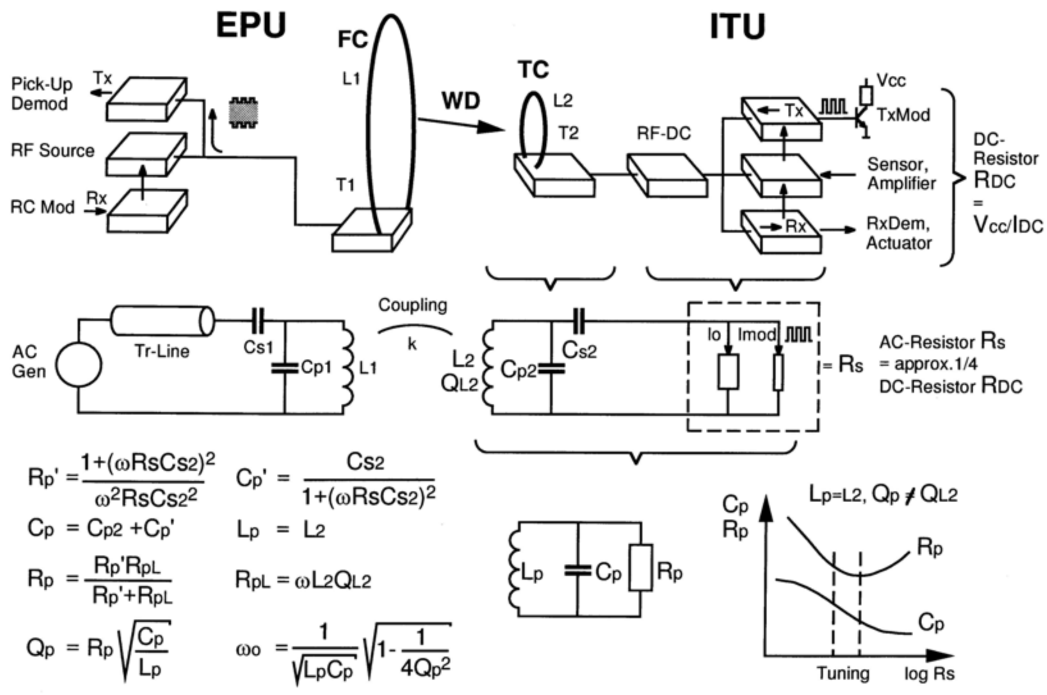


Figure 4. Principle schematic diagram with AC model of the transponder system.
TxMod: Telemetry Absorption Modulator
RxDem: Remote Control Demodulator
RF Source: 28 MHz, 1 W
Formulae: for the calculation of an equivalent parallel resonance circuit (without coupling).
RF-DC: Halve-wave voltage doubling rectifier. The equivalent AC-resistor is about ¼ of the DC resistor. This AC-resistor is here 50 Ω for AC-tests with standard RF-equipment. The loss in the RF-DC diodes is about $2V_F{*}I_{DC}$.

The telemetry function is effected by a variable load on the DC-side of the transponder. The corresponding AC-resistor is the variable Rs, which transforms into a variable Rp and Cp in the equivalent parallel resonance circuit (see diagram in the lower right in Figure 4).

The Rp vs. log Rs characteristic shows a minimum at an Rs above the tuning condition. One would expect a lower Rp at lower Rs, but the opposite is the case. In short, Rp vs. log Rs is responsible for the amplitude modulation (AM) at the RF source.

The Cp vs. log Rs characteristic shows a steady change of Cp. Since Cp controls the resonance frequency, it becomes evident that the resonance frequency increases with increasing Rs. At constant frequency, here 28 MHz, Rs controls the phase and is responsible for the phase modulation (PM) at the RF source.

For a coupling factor k > 0.01, the absorption modulation generates an AM and PM, which can be detected and demodulated by a pick-up circuit at the RF source. In the “Black Hole” situation or at lower coupling conditions, these modulations are missing or below the noise level.

The tuner T1 matches L_1 to the generator and the tuner T2 matches L_2 to the AC load Rs, using the tuning methods explained before. Thus, we obtain a first set of values for C_{s1}, C_{p1}, C_{p2} and C_{s2}. However, simulation (especially with pSpice) is only possible with the full knowledge of all parasitic components and losses.

Measuring Method, Equipment and Set-up

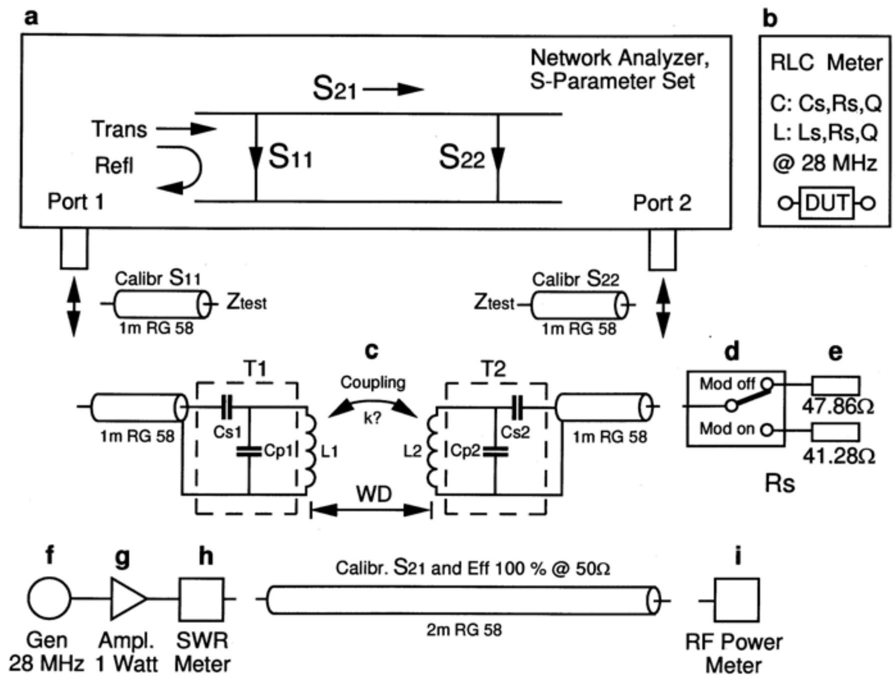


Figure 5. Measuring Setup for AC parameters and RLC Data.
a.) Network Analyzer HP 4396A with S-Parameter Set HP 85046 for S_{11} Smith Chart and S_{21} transmission charts b.) RLC-Meter HP 4285A for detailed component specifications.
c.) Coupled Coil System d.) Coaxial Switch e.) Mismatches for two Rs modulation steps.
f.) RF Gen. HP 8643A g.) Power Amp. ENI 604 L h.) SWR Meter i.) RF Meter HP 437 B.

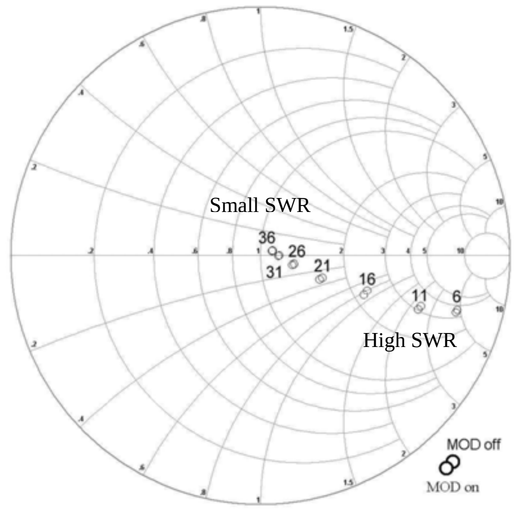
Figure 5 shows some of the RF equipment for precise AC analyses. The coupled coils system c.) includes the tuners T1 and T2 and is accessible by RG 58 coaxial cables (transmission lines) of exactly 1 m. The ports of the network analyzer have to be calibrated to the end of a transmission line of 1 m (S_{11}, S_{22}), resp. of 2 m for transmission (S_{21}).

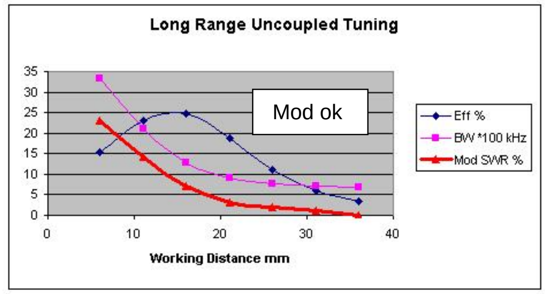
After L- or S-Tuning the T2 output is connected to the coaxial switch d.) where Rs can be switched with the mismatches e.) from 47.86 to 41.28 Ω for a calibrated absorption modulation (measured values with switch, data sheet tells 50 and 42.88 Ω!).
The S_{21} transmission measurement is accurate, but on a 0 dBm (1 mW) level. For efficiency measurements at 1 W the equipment f.) g.) h.) and i.) have to be used, calibrated by a 2 m coaxial cable. The results are comparable, as long as the mismatch, generated by the coupled coil system, is negligible. However, at strong coupling with high Standing Wave Ratio (SWR) the results are misleading. What is the basis of 100 % efficiency for an amplifier at variable SWR? Monitoring of the DC power consumption of the RF amplifier will tell the truth.

Finally the L- and the evaluated C-components are measured with the RLC Meter at 28 MHz. It should be mentioned that even with this expensive RLC meter the measuring accuracy can drop down to 5%, depending on the actual component value and test frequency (see manual of HP 4285A). The measurements may also fail due to parasitic effects, e.g. negative Q at small C-values of trimmer capacitors or capacitive loading of inductors.

And last but not least: the very important parasitic components (internal capacities of the coils, see Table 1, and stray capacities of the circuit board) must be determined by time consuming comparative simulations with winSMITH, pSpice or other simulation programs.

Experimental Result with first occurrence of the Black Hole





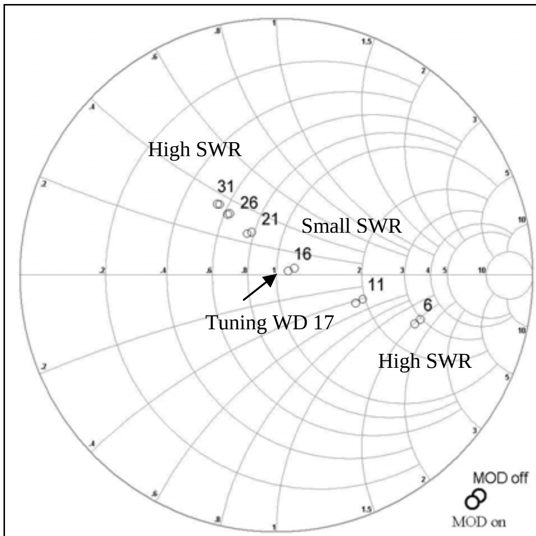
Efficiency > 15 % for 6 < WD < 22 mm
-3dB Bandwidth > 0.7 MHz
Modulation SWR > 2 % up to WD < 26 mm

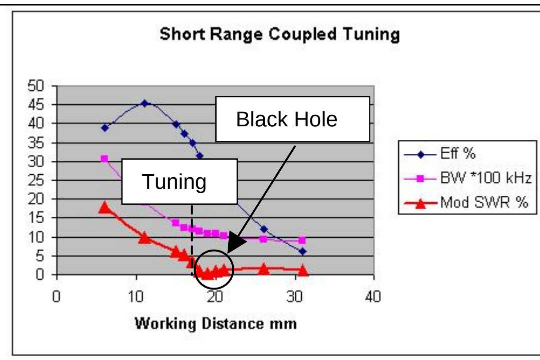
Not very efficient, but robust operation

Note: Mod SWR % = ABS (SWR_{Off}-SWR_{On})*100

a.) Smith Chart for L-Tuning, S11 vs. WD

b.) Performance with L-Tuning @ 28 MHz



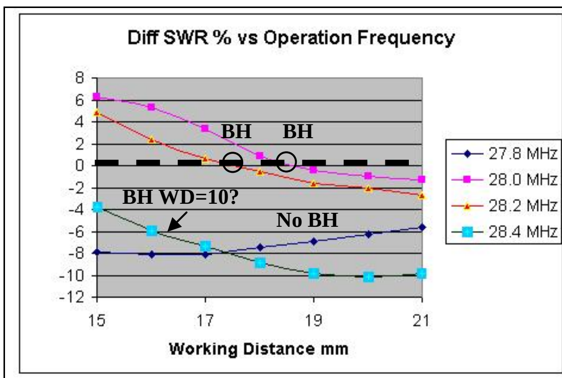


Efficiency > 35 % for 6 < WD < 17 mm
-3dB Bandwidth > 0.9 MHz.
Modulation SWR is ok for WD < 17 and for WD > 22, but **Black Hole** in between!

Note: Mod SWR % = ABS (SWR_{Off}-SWR_{On})*100

c.) Smith Chart for S-Tuning, S11 vs. WD

d.) Performance with S-Tuning @ 28 MHz



Note: Diff SWR % = (SWR_{off}-SWR_{on})*100

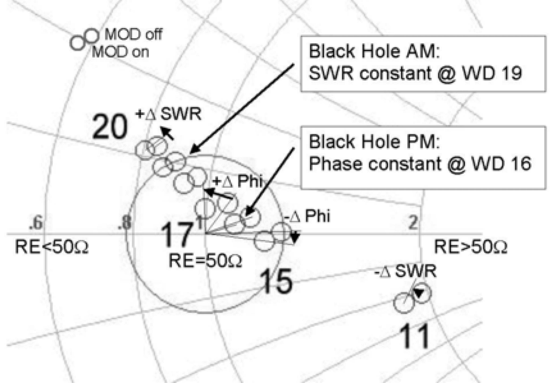
The diagram e.) reveals that the Black Hole (BH) appears with S-Tuning only at operation frequencies of 28 MHz and slightly above. The lower frequency 27.8 MHz promises a good telemetry performance within the measured bandwidth of 0.9 MHz. However, it is not advisable to tune the system at WD = 17 mm @ 28.2 MHz and to operate at 28 MHz, since lossy material in the vicinity of the coils will detune the system and the BH appears again at a unforeseen WD.

e.) Black Hole location vs. Frequency

f.) Nature of Black Hole Location at S-Tuning

Figure 6. Coupled Coil System with Modulation of the AC- Load at the transponder side.
Rs-Step from "MOD off" = 47.86 Ω to "MOD on" = 41.28 Ω .

Description of the Black Hole and its consequences for telemetry operation

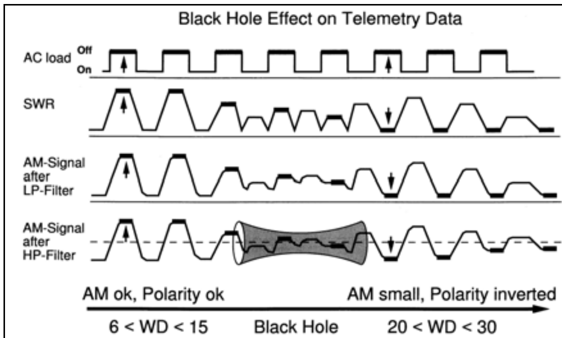


* Note: Definition Mod SWR = (SWR_{Off}-SWR_{On})

AM performance:
At working distances 6 < WD < 15 the Δ SWR is negative, giving a positive Mod SWR *.
At WD = 19 the SWR remains constant thus there is no AM detection possibility.
At WD > 20 the Δ SWR becomes positive. There is a small, but negative Mod SWR *.

PM performance:
At WD = 16, that is within the operation range, the phase changes its polarity, too. So it is not advisable to try here a PM-demodulation.

Figure 7. Smith Chart with **Black Holes** at Short Range Coupled Tuning (S-Tuning @ WD 17). AM detection is possible only for 6 mm < WD < 18 mm, PM only for 6 mm < WD < 15 mm.



Below WD = 15 the modulation of SWR is **positive**, the signal can be amplified by an active bandpass filter and processed e.g. by a Phase Look Loop (PLL).
Within the Black Hole there is no chance to recover useful information.
Above WD = 20 the modulation of the SWR is **negative** and small.
Traveling fast through the small region of the Black Hole the PLL will loose the track.

Figure 8. Black Hole Effect on Telemetry Data

Figure 8 shows the consequences of the Black Hole on Telemetry Data. Traveling through the Black Hole leads to loss of data, although the transponder is supplied with enough power.

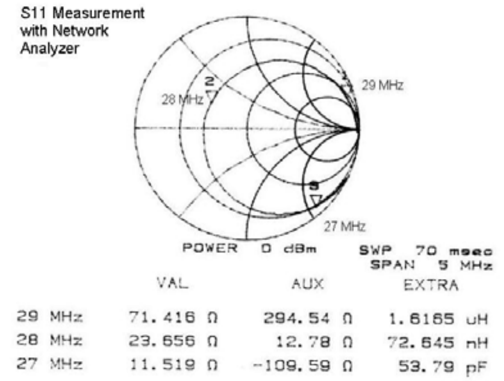
Technicians of Passive Telemetry and RF-ID Equipment consider the Black Hole a temporary accident. In case of data loss (at sufficient transferred RF power!) they change the tuning of the feeding antenna slightly, improve the grounding of the system, reposition the coaxial feeding cable or mount a ferrite absorber on it. Sometimes “talisman devices” such as a metal plate near the feeding coil might help, at least at the specific working distance where the “Black Hole” was previously observed.

In fact, the **Black Hole** is so **small** and so **difficult** to **find** that all these procedures **slightly retune** the coupled coil system in such a way, that the Black Hole **changes** to **another location**, hopefully outside the designated working distance.

The reproducible method is to tune the coupled coil system at 120 % of the designated working distance, using a stable feeding coil with E-shielding against unbalanced currents on the coax.
A network analyzer for investigating the coupled coil system might be advantageous, but at low RF-power (standard 0 dBm) the diodes of the RF-DC converter transponder are not conducting, so the RF-analysis results will be unrealistic.

A very well tuned system still suffers from the problem that occasionally a nearby positioned resonating system will let you fall into the Black Hole trap again. Good luck!

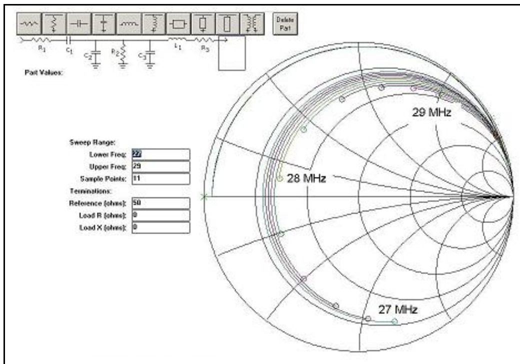
Measured component data and evaluation of the parasitic components with winSMITH



a.) Smith Chart of the Feeding System 1

Real RLC Data @ 28 MHz	Feed. Syst. 1	Transp. Syst. 2
L nH	609.50	254.80
Rseries of L Ohm	1.40	1.18
Cp pF	22.82	72.49
Rseries of Cp Ohm	0.56	0.42
Cs pF	12.76	26.08
Rseries of Cs Ohm	0.13	0.54
Derivated L and Cp Data		
Impedance of L jOhm	107	45
QL of L	77	38
Rparal. of L Ohm	8205	1701
Impedance of Cp jOhm	249	78
Qc of Cp	445	187
Rparal. of Cp Ohm	110904	14654

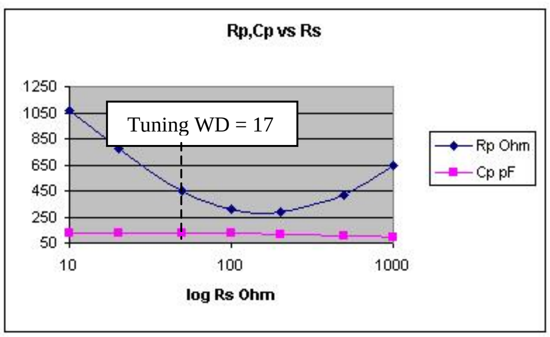
b.) Measured and derived RLC Data



c.) WinSMITH Simulation. Feeding System 1

winSMITH Data (Ohm, pF)	Feed. Syst. 1	Transp. Syst. 2
R1 = Rseries of Cs	0.13	0.54
C1 = Cs meas.+ **Csparasitic**	16.66	33.78
C2 = Cp meas.	22.82	72.49
R2 = Rparal of Cp	110904	14654
C3 = **Cpparasitic**	13.80	23.00
L1 = L	609.50	254.80
R3 = Rseries of L	1.40	1.18
Reference	50	50
Termination	0	0
Evaluated Parasitic Comp.		
Csparasitic = (C1-Cs) pF	**3.90**	**7.70**
Cpparasitic = C3 pF	**13.80**	**23.00**

d.) Initial and evaluated winSMITH Data



Note: Rp increases with decreasing Rs!
With S-Tuning Rp_{min} is at Rs ca. 140 Ω

Calc. Parallel Circuit	Feed. Syst. 1	Transp. Syst. 2
Rload/Source Ohm	50	50
Lp nH	**609.50**	**254.80**
Cs measured pF	12.76	26.08
Csparasitic pF	3.90	7.70
Cs (total) pF	**16.66**	**33.78**
Rp' Ohm	2380	617
RpL Ohm (of L)	8205	1701
Rp (total) Ohm	**1845**	**453**
Cp measured pF	22.82	72.49
Cp' pF	16.31	31.04
Cpparasitic pF	13.80	23.00
Cp (total) pF	**52.93**	**126.53**
QL measured	76.55	37.97
Qp (total) of Parallel Circuit	**17.19**	**10.09**
Check Res.Freq. MHz	28.02	28.01
Note: the minor losses in capacitors are here neglected		

e.) Rp and Cp of Transponder System 2

f.) Parallel Circuit Data (formulae Figure 4.)

Figure 9. Smith Chart measurement, winSMITH simulation and parallel circuit calculations for S-Tuning at WD = 17 mm. Shown are here the uncoupled data, for this investigations the Feeding System 1 and Transponder System 2 have been separated after tuning.

WinSMITH (Eagleware Corporation) enables the simulation of a ladder-network with up to 9 components. The simulations for the selected frequency points are displayed just after the input of a new component value. The goal is to get a good fit of the simulated with the measured Smith Chart. Cs determines the diameter of the S11 curve, Cp the resonance on the S11 curve.
At good match the winSMITH data C1 delivers the Cs-Parasitic and C3 the Cp-Parasitic values. Rp, Cp and Qp can be calculated now; the resonance frequency should be near 28 MHz.

Simulation with pSpice of the coupled coil system at S-Tuning condition

We know now the measured (Figure 9b) and the parasitic (Figure 9d) components, the measured power transmission efficiency (Figure 3) and also we know about the existence of the Black Hole at the working distance WD = 19 (Figure 7).

The goal of the pSpice simulation is to explore the system performance at various coupling factors k. There is a strong, but complex link between **Coupling Factor k** and **Working Distance WD** and**.** In a first step we have to find the specific coupling factor k which fits best with the experimental results WD = 17, where the system is perfectly tuned to the generator.

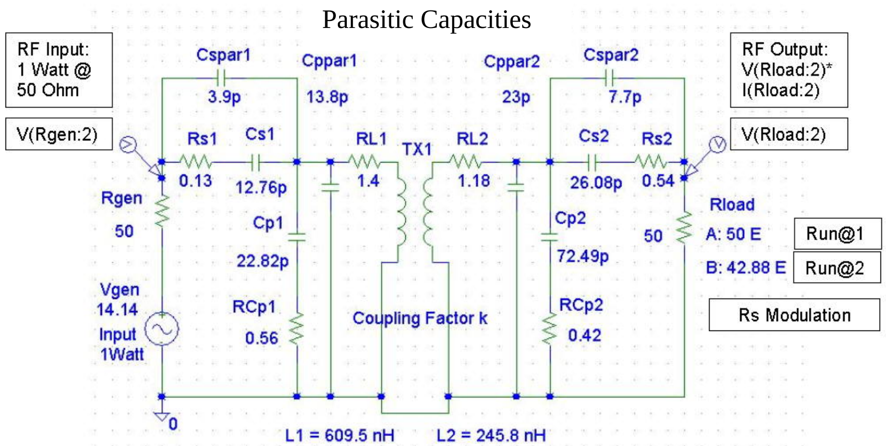
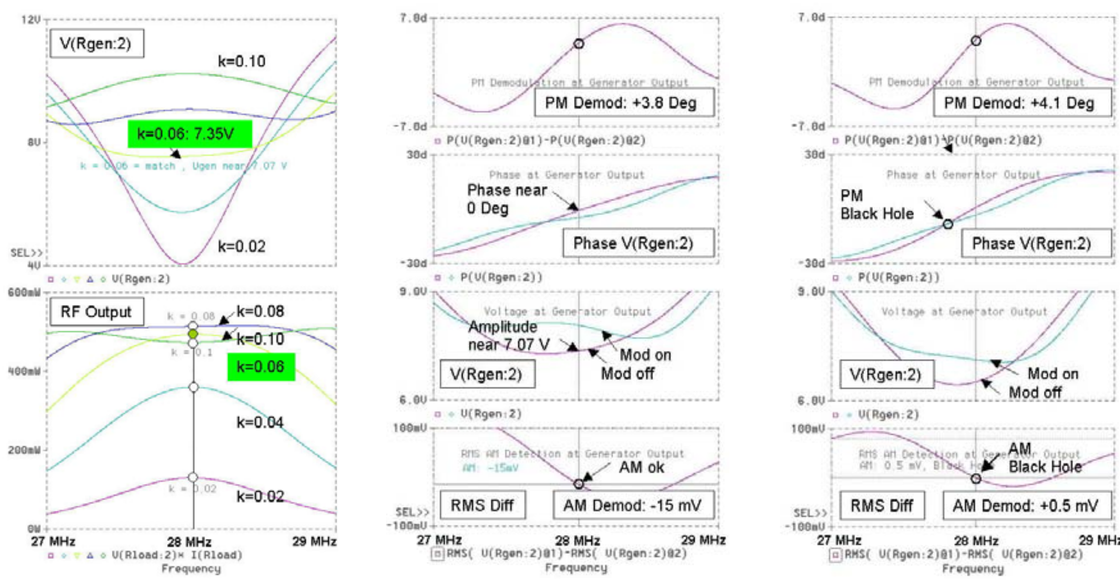


Figure 10. pSpice Model, AC Load modulation Rs: "MOD off" = 50, "MOD on" = 42.88 Ω.
The RF Source of 1 W is simulated by 14.14 V in series with a 50 Ω resistor.



a.) 0.02 < k < 0.1
Efficiency, Generator Voltage
note maximum Eff at k = 0.08

b.) k = 0.06, good tuning
Vgen ≈ 7.07 V, Phase ≈ 0
-AM and +PM Demod ok

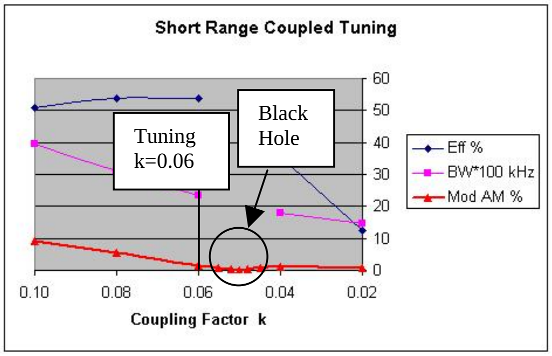
c.) k = 0.05, Black Hole
note AM Demodulation
< +1 mV, Changed Polarity

Figure 11. pSpice Results at 27 MHz < fo < 29 MHz, parameter 0.02 < k < 1.0 and Rs-steps.
AM Demodulation by RMS Ugen $_{mod\ off}$ – RMS Ugen $_{mod\ on}$ (do not use: Ugen $_{mod\ off}$ – Ugen $_{mod\ on}$).

The simulation program pSpice is not optimal for RF-analysis, thus the results should be interpreted with care. The fast AC sweep analysis may not take into account that the circuit should first approach the steady-state solution; transient analysis can accumulate errors when run for many RF wave periods. The pSpice model does not include the transmission lines and the S-parameter set as used in the experiments. Thus, we cannot compute the Smith Chart.

In our case the demodulation signal was calculated by comparing the root mean square (RMS) values of the displayed generator voltages at “MOD off” and “MOD on”. This makes sense, since a demodulator with standard envelope detector does not care about the shape and phase of an RF signal.

The results of the simulations are comparable with the results of the experiment:
A coupling factor of k = 0.06 means an optimal tuning, comparable with the experiment at the working distance WD = 17 mm. The voltage at the generator is close to 7.07 V (50 Ω match) and the phase at the generator crosses zero degrees at 28 MHz (Phase match).



Efficiency > 35 % for k > 0.04
-3dB Bandwidth > 1.4 MHz
Modulation ok for 0.1 > k > 0.055
and for k < 0.045
but:
Black Hole in between:
Modulation less than 0.3% for
0.052 > k > 0.048

Note: Mod AM % = ABS (RMS Ugen $_{mod\ off}$ – RMS Ugen $_{mod\ on)}$)*100, related to Ugen at match

Note: reversed k-scale: short distance = left

Figure 12. Performance of the simulated coupled coil system tuned at coupling factor k = 0.06.

The important results of the pSpice simulation show a good correlation with the experiments:

- Efficiency vs. k in Figure 12 is almost identical with the Efficiency vs. WD in Figure 3.

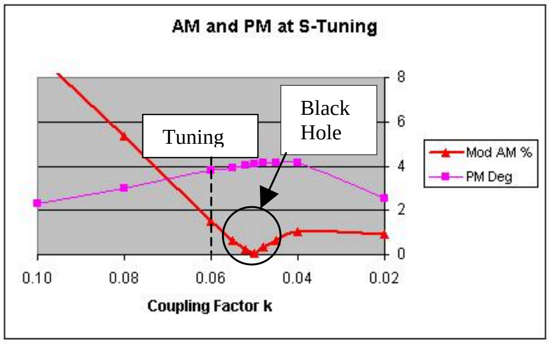
- Bandwidth vs. k in Figure 12 is comparable to the Bandwidth vs. WD in Figure 6d.
  The computed bandwidth is somewhat higher, probably due to the missing transmission line.

- The Mod AM in Figure 12 is comparable with the Mod SWR in Figure 6d.
  Within the designated coupling range from 0.055 < k < 0.1 we get an AM of > 1.5 %

- The **Black Hole** at k = 0.05 in Figure 12 is similar to the Black Hole at WD = 19 mm in Figure 6d, and with the same characteristics:
    - Occurrence only very close to the tuning point, at slightly weaker coupling
    - No signal within the Black Hole
    - Polarity changes by traveling through the Black Hole as shown in Figure 7

Thus, pSpice simulation gives a good analysis of the actual situation, but only if all parasitic components are taken into account.

An interesting feature is the behavior of the phase, measured directly at the generator.
The simulation promises a PM of 2 to 4 degrees throughout all coupling conditions:



AM performance:
Modulation ok for 0.1 > k > 0.055
and for k < 0.045 but
Black Hole in between:

PM performance:
Modulation seems to be ok
for 0.1 > k > 0.02

Note: PM Deg = Phase difference in Degrees:
Phase ($Ugen_{mod\ off}$) – Phase ($Ugen_{mod\ on}$)

Figure 13. Simulated AM and PM at RF Source, S-Tuning with k = 0.06.

In practice a phase demodulation is done with a directional coupler, a multiplier and a phase shifter. The output of such a phase demodulator is:

$$Vout\ (\Delta\varphi) = ½ \cdot \hat{U}f \cdot \hat{U}r \cdot \cos(\varphi_0+\Delta\varphi)$$

The output depends on the actual phase φ_0, but also on the amplitude of the forward (Ûf) and reflected (Ûr) waves. Within the Black Hole zone Ûr is very small, therefore Vout ($\Delta\varphi$) gets small too and the S/N ratio is bad. In addition, variable φ_0 within the Black Hole zone (see Figure 7) demands an adaptive phase shifter in order to keep ($\varphi_0+\Delta\varphi$) at $\approx 45^0$.

We used such phase demodulators in other telemetry applications with good success, but the coupled coil system needed to be tuned at a much larger maximum working distance.

Is it worthwhile developing an electronic phase demodulator, working on the basis of straight forward phase comparison (see Figure 13) ?

Figures 11c. gives the answer: There is an other unsuspected **PM Black Hole** waiting to pounce on you at about 27.8 MHz. Just a minor detuning of the coupled coil system, caused by nearby metallic objects, will let you fall into that trap!

Matching the Coil Impedance to the AC-Load Rs of the transponder

This investigation shows the performance with various inductor values but identical Q-factor:

Calculations for Parallel Circuit	0.25*Lopt	0.5*Lopt	Lopt	2*Lopt	4*Lopt
AC Load Rs Ω	50	50	50	50	50
Impedance (Lp) @ 28 MHz j Ω	**11**	**22**	**45**	**90**	**179**
Lp nH	**64**	**127**	**255**	**510**	**1019**
Csev (evaluated) pF	118	53	35	21	12
Rp' Ω	96	280	578	1589	4857
RpL (Rp of Lp) Ω	425	851	1701	3402	6805
Rp (total) Ω	**79**	**211**	**431**	**1083**	**2834**
Cpev (evaluated) pF	410	214	96	44	21
Cp' pF	57	44	32	20	11
Cp (total) pF	**467**	**258**	**127**	**64**	**32**
QL (kept constant)	38	38	38	38	38
Q (total) of Parallel Circuit	**7**	**9**	**10**	**12**	**16**
Check of Resonance Freq. MHz	29.1	27.8	27.9	27.9	27.8

Table 2. Variable Coil Impedance (constant Q) with evaluated matching Csev, Cpev by pSpice.

We assume here that the transponder inductivity L_2 = 254.8 nH, Q_{L2} = 38 used before is the optimal coil. The impedance @ 28 MHz is 45 j Ω, that means close to the AC-Load Rs of 50 Ω.

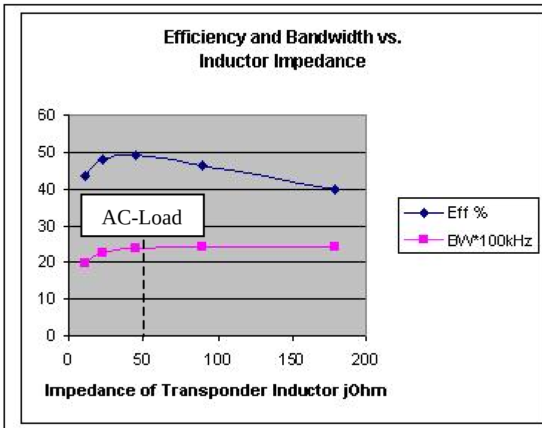
We prepare now a set of inductors with variable impedance, but constant Q:

L_y	$= x \cdot L_{opt}$	factor x = 0.25, 0.5, 1, 2 and 4
RL_y	$= x \cdot RL_{opt}$	RL_y = series resistance of L_y

In the pSpice Model (Figure 10) we set Cp_2+$Cppar_2$ = Cpev, Cs_2+$Cspar_2$ = Csev for easier evaluation. We assume that Cpev and Csev will change with ≈ 1/x ; thus we multiply the series loss resistor of both capacitors with the factor x in order to keep the quality factor of the capacitors constant.

With this set of RLC components we tune the Transponder System 2 for maximum efficiency, varying Cpev and Csev, but **without** changing anything at the Feeding System 1.

The evaluated Cpev and Csev for best tuning are given in Table 2. With the formulae of Figure 4 we calculate the Lp, Cp, Rp and Q of the equivalent, non coupled parallel resonance circuit. Finally, the resonance frequency check confirms the good tuning (see check for 0.25***** Lopt: Better tuning is not possible, experiments with adapting the Feeding System 1 failed also).



Impedance < AC-Load:
Low Efficiency, Low Q but Low System Bandwidth, difficult resonance tuning

Impedance = AC-Load:
Best Efficiency, High System Bandwidth

Impedance >AC-Load:
Less Efficiency, High System Bandwidth. Parasitic parallel capacities of the coil may prevent a proper tuning, since a part of Cpev is lost in the parasitic capacity.

Figure 14. Matching of the coil impedance to the AC Load (all coils Q-Factor = 38)

The impedance of the coils should be of similar magnitude as the output impedance of the RF-source, respectively ¼ of the DC-load of the transponder (with half-wave voltage doubling RF-DC converter) in order to get a system quality factor $5 < Q < 20$. The purpose of limiting the Q is to make the system robust against detuning effects from the surroundings and to provide enough system bandwidth for telemetry purpose. An important issue is the capacitive loading of a transponder coil by close windings on a dielectric spool or by the E-shield in case of the feeding coil: For large inductors these parasitic capacities may become larger than the evaluated Cpev, limiting the frequency tuning range.

The transponder coil is a compromise: a small coil with thin wires around a conductive case of an implant will show skin-effect and other losses, limiting the efficiency but giving a sufficient system bandwidth (see Limacher 2002).
The feeding coil is a compromise, too: on the one hand the coil should be designed for small losses, on the other hand for a quality factor QL < 100 for enough communication bandwidth.

APPLICATION

A Demonstrator of a Passive Telemetry for a thermal flow sensor was built and tested according to the presented design rules (Figures 15, 16). The thermal flow sensor (Burger 2003) needs a power of 10 mW, the signal acquisition 30 mW. In order to achieve a resolution of 10 % at a maximum flow rate of 300 ml/h, a resolution of about 5 mK is needed. This sensor signal is A/D converted with 12 Bit resolution during a RF interruption of 1 msec in order to avoid RF interference with the small sensor signal and is interrogated every 20 msec by remote control.

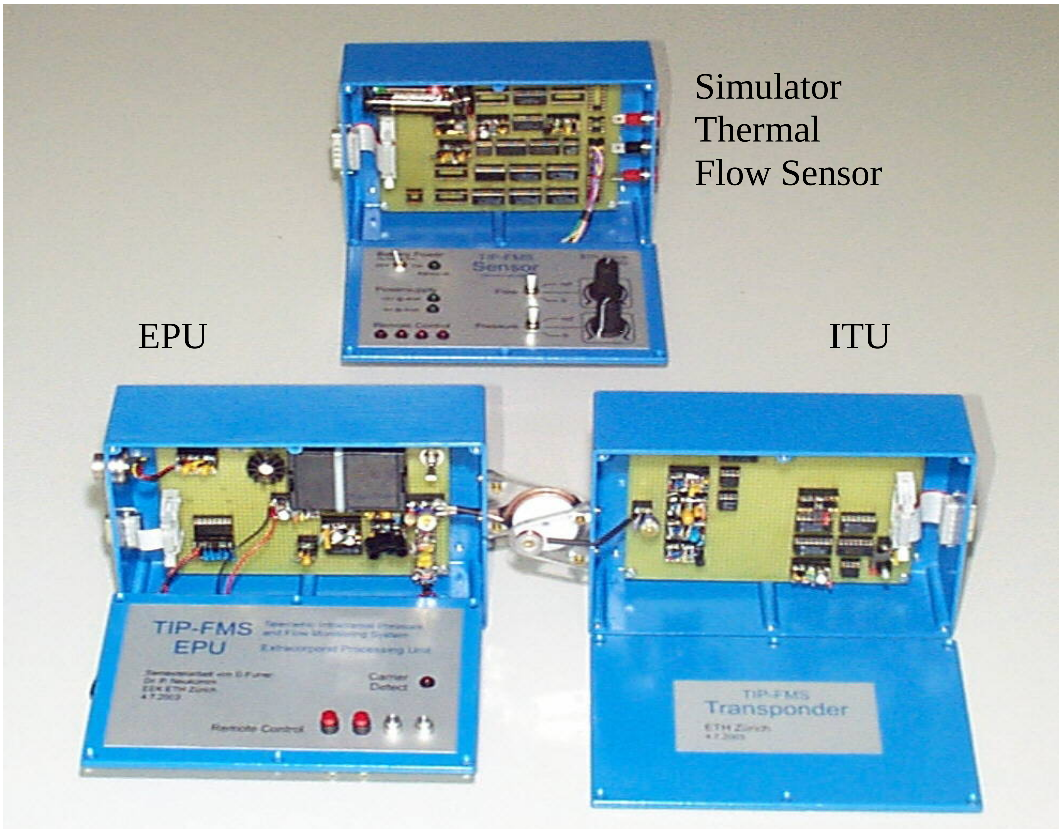
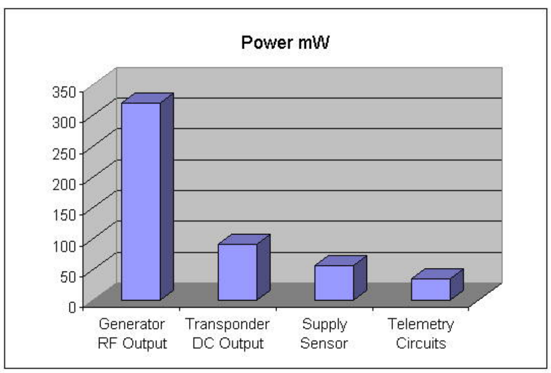


Figure 15. Demonstrator of a Passive Telemetry system for an implantable thermal flow sensor. Left: EPU with RF-source, Tuning System T1, RC-Modulator, Tx-Pickup, PLL, RS 232 Output. Right: ITU with Tuning System T2, RF-DC Converters, RC-Demodulator for Rx commands, Internal Clock Generator, Tx-FSK-Generator and Absorption Modulator.
Top: Simulator of the thermal flow sensor with 12 Bit A/D converter and data storage.



- Working Distance WD = 17 mm
  (center to center, free space 11 mm)
- RF Generator to DC **Efficiency = 28 %**
- Power supply for thermal flow sensor:
  Stabilized +/- 5 V, +/- 4 mA: **40 mW**
  Unstabilized supply voltage: 7V
  (Voltage drop of 1.5 V during the RF-interruption of 1 msec, duty cycle 1/20)
- Telemetry circuits with A/D conversion, data storage, remote control and FSK Absorption Modulation: **35 mW**

Figure 16. RF to DC Efficiency and Power Management of the transponder

DISCUSSIONS

Passive Telemetry is a key technology for medical implants. The presented design rules should help to avoid the Black Hole and help to create a robust system with acceptable efficiency and communication capabilities.

The following design rules should be respected:

- Start with a ratio of FC diameter to WD to TC diameter of 3 : 2 : 1 for a safe operation range $0 < WD < 2$. If your operation range is $1 < WD < 2$ and if you do not expect large lateral displacement of the coils, you may slightly reduce the FC diameter.

- Tune both resonant coils like radiating antennas for maximum far field output, and then retune the coil system at 120 % of the desired maximum WD for maximum energy transfer.

- The impedance of the coils should be of similar magnitude as the output impedance of the RF-source, respectively to ¼ of the DC-load of the transponder (with half-wave voltage doubling RF-DC converter) in order to get a system quality factor $5 < Q < 20$. The purpose of limiting the Q is to make the system robust against detuning effects from the surroundings and to provide enough system bandwidth for telemetry purpose.

The power consumption of integrated circuits becomes less and less, thus one might expect passive wireless systems for very large working distances in the near future. At very small coupling, but with very high RF power, there is enough energy transferred to the transponder in order to supply these circuits. However, the weakly coupled coil system follows distinct physical laws, therefore robust operation of telemetry communication beyond a distance, equal to the dimension of the feeding coil, is very difficult.

However, semi-passive telemetry in excess of that distance is possible by detecting the modulated 2^{nd} harmonic, generated by the RF-DC converter of the transponder. An example of such a signal processing was presented in the context of E-field-telemetry with a thin dipole transponder in (Neukomm et al. 2000).

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LITERATURE CITED

Neukomm, P. A., H. Kündig, H. Baggenstos and K. Zerobin. 1989, Passive Telemetry by Absorption Modulation, a New Principle for Long-Term Transabdominal Monitoring of Pressure and EMG of the Uteruses of Cows. Pages 487-496 *in* C.Amlaner (ed), Proc. of the 10th Symposium on Biotelemetry, July 31-Aug.5, 1988, Fayetteville, USA. University of Arkansas Press, Fayetteville, 1989

Vandevoorde, G., M.Catryssse, R. Puers, G. Beale, P. Smith and A. Sangster. 2000. Development of a Transcutaneous Energy and Data Transmission System for High Power Applications up to 20 Ws. Pages 580-592 *in* J-H. Eiler et al (ed), Proc of the 15th International Symposium on Biotelemetry, May 9-14, 1999 Juneau, Alaska, USA. International Society on Biotelemetry, Wageningen, The Netherlands, ISBN 0-0707533-0-6, 2000

Gudnason, G. and E. Bruun. 2002. CMOS Circuit Design for RF Sensors, *in* Kluwer Academic Publishers, Boston, ISBN 1-4020-7127-2, 2002

Benedetti, R. 1997: Untersuchung der Energieübertragung für die passive Telemetrie mit Absorptionsmodulation. Diss. ETH Nr. 12054, 1997

Limacher, R. M. 2002. Analyse- und Synthesewerkzeug für die Passive Telemetrie. Diss. ETH Nr. 14530, *in* Fortschritt-Berichte VDI, Reihe 8, Nr. 963, VDI Verlag GmbH Düsseldorf, ISBN 3-18-396308-6, 2002

Furrer, D. 2003. Passive Telemetrie für Pressure und Flow, Semesterarbeit an der Professur EEK, ETH Zürich, 2003

Burger, J. et al, 2003. Implantable Thermal Flow Sensor with RF Passive Telemetry for Neurological Applications, Proc of the 17th International Symposium on Biotelemetry, Sept 1-5, 2003, Brisbane, Australia

Neukomm, P. A, I. Roncoroni , D. Nanz and H.H. Quick. 2000. Passive E-field Telemetry: A New Wireless Transmission Principle in Minimally Invasive Medicine. Pages 609-617 *in* J-H. Eiler et al (ed), Proc of the 15th International Symposium on Biotelemetry, May 9-14, 1999 Juneau, Alaska, USA. International Society on Biotelemetry, Wageningen, The Netherlands, ISBN 0-0707533-0-6, 2000