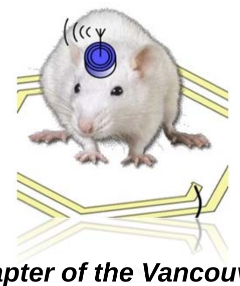
Implantable and Wearable Microelectronic Devices to Improve the Quality of Life for People with Disabilities



Joint Applied Physics Chapter of the Vancouver Section, Oct. 30, 2015

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Some Events and Their Consequences

Motivation

- Healthy People 2020: 54 million Americans (~20%) living with disabilities and the number is on the rise especially among elderly (Age 65+).
- 11,000 cases of severe Spinal cord injury (SCI) per year add to a total pop
- 55%
spe
- Mos

Advanced technology development to improve the quality of life for individuals with the most severe disabilities.

Injury or Disease	Population	Annual Incidence in USA
Paralysis of extremities	2,000,000	N/A
Severe spinal cord injuries	250,000	11,000
Effects of stroke	4,000,000	600,000
Multiple sclerosis	350,000	N/A
Cerebral palsy	500,000	~10,000
ALS	30,000	5,600

Source: Christopher and Dana Reeve Foundation

Outline

Implantable Microelectronic Devices (IMD)

- Efficient power and wideband data transmission
- Wireless Integrated Neural Recording (WINeR) system
- Switch-Capacitor based Stimulating (SCS) system

Modern Assistive and Rehabilitation Technologies

- *Tongue Drive System (TDS)*: A wireless and wearable Brain-Tongue-Computer Interface
- TDS Hand Mentor Exoskeleton
- Tongue Tracking System (TTS)

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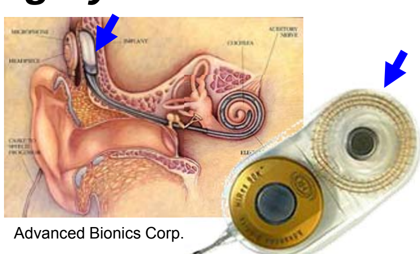
Highly Efficient Inductive Power Transmission



Advanced Bionics Corp.

Second Sight Inc.

Medtronic Corporation

University of Southern California

Alfred Mann Institute - USC

- Battery powered devices:
  - Low stimulus pulse rate
  - Autonomous (after initial adjustments)
  - Small number of stimulating sites
- Inductively powered devices:
  - High current (Neuromuscular stimulators)
  - High stimulus rate (Cochlear implants)
  - Large number of sites (Visual prostheses)
- All implants should be wireless.

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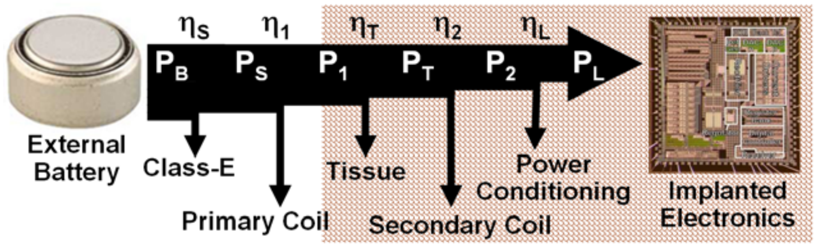
Transcutaneous Link Power Losses



P_B: Power drained from battery

η_1 { P_S: Power delivered to the primary coil
P_1: Transmitted power }

η_2 { P_T: Power passed through the tissue
P_2: Received power }

P_L: Power delivered to the load (implanted electronics)

Overall Efficiency: $\eta = \eta_S \eta_1 \eta_T \eta_2 \eta_L$

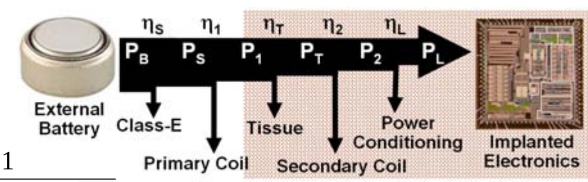
Inductive Power Transfer Efficiency

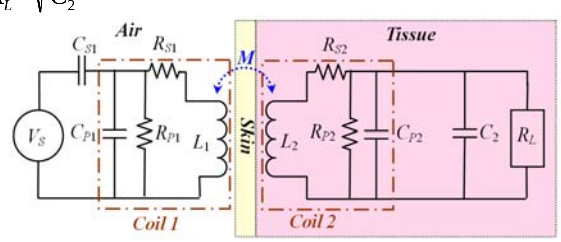
$$\eta_1 = \frac{k^2 Q_1 Q_L}{1 + k^2 Q_1 Q_L}$$

$$Q_L = \frac{1}{\frac{R_2}{\omega L_2} + \frac{\omega L_2}{R_L}} = \frac{1}{R_2 \cdot \sqrt{\frac{C_2}{L_2}} + \frac{1}{R_L} \cdot \sqrt{\frac{L_2}{C_2}}}$$

$$\eta_L = \frac{Q_2^2 R_{S2}}{Q_2^2 R_{S2} + R_L}$$

$$\eta = \eta_1 \cdot \eta_L$$





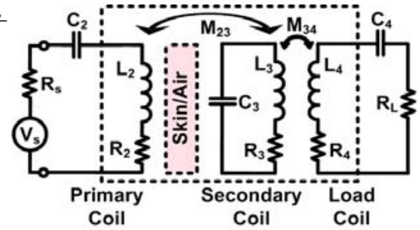
Power efficiency is a strong function of the coupling coefficient (***k***) and quality factor (***Q***) of the external and implanted coils.

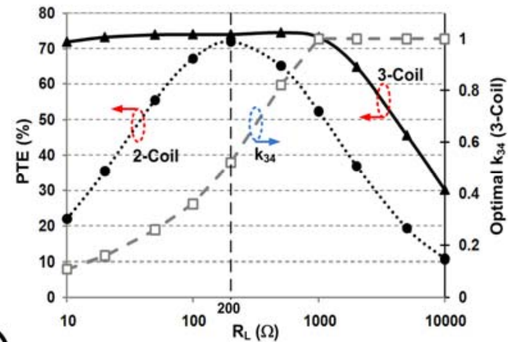
Ko et al., *Med. Biol. Eng. Comput.* 1977

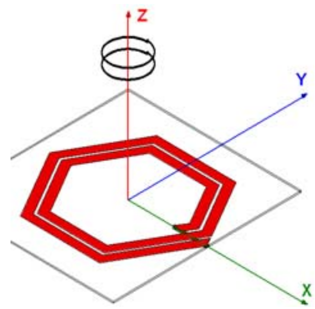
3-Coil Inductive Link

$$\eta_{3-coil} = \frac{(k_{23}^2 Q_2 Q_3)(k_{34}^2 Q_3 Q_{4L}) + k_{24}^2 Q_2 Q_{4L}}{\cos(\theta)\left(1 + k_{34}^2 Q_3 Q_{4L}\right)\sqrt{A^2 + B^2}} \cdot \frac{Q_{4L}}{Q_L}$$

$$\begin{cases} A = 1 + k_{23}^2 Q_2 Q_3 + k_{34}^2 Q_3 Q_{4L} + k_{24}^2 Q_2 Q_{4L} \\ B = 2 Q_2 Q_3 Q_{4L} k_{23} k_{24} k_{34} \\ \theta = \tan^{-1}(B/A) \end{cases}$$







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Kiani, Jow, and Ghovanloo, TBioCAS 2011

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PTE and PDL in 3-Coil Link

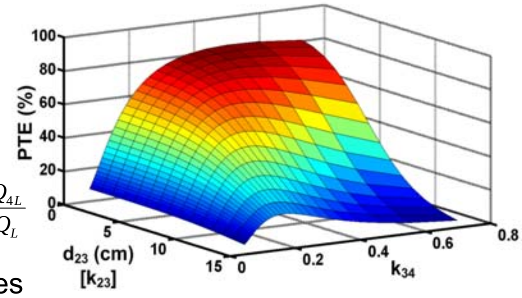
Maximizing PTE should not be at the cost of decreasing PDL. ☺

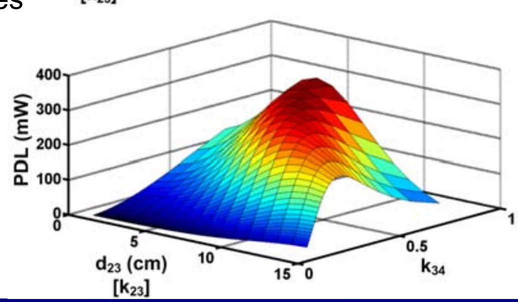
$$P_{L,3-coil} = \frac{V_s^2}{2R_2} \frac{(k_{23}^2 Q_2 Q_3)(k_{34}^2 Q_3 Q_{4L})}{(1 + k_{23}^2 Q_2 Q_3 + k_{34}^2 Q_3 Q_{4L})^2} \cdot \frac{Q_{4L}}{Q_L}$$

The optimal design maximizes both PTE and PDL.

$$k_{23,PDL} = \left(\frac{1 + k_{34}^2 Q_3 Q_{4L}}{Q_2 Q_3}\right)^{1/2}$$

$$k_{34,PDL} = \left(\frac{1 + k_{23}^2 Q_2 Q_3}{Q_3 Q_{4L}}\right)^{1/2}$$ ☺





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Kiani, Jow, and Ghovanloo, TBioCAS 2011

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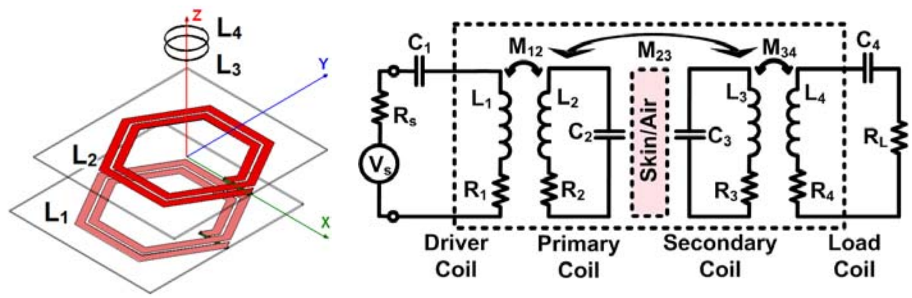
4-Coil Inductive Link



$$\eta_{4-coil} = \frac{(k_{12}^2 Q_1 Q_2)(k_{23}^2 Q_2 Q_3)(k_{34}^2 Q_3 Q_{4L})}{[(1+k_{12}^2 Q_1 Q_2).(1+k_{34}^2 Q_3 Q_{4L})+k_{23}^2 Q_2 Q_3].[1+k_{23}^2 Q_2 Q_3 + k_{34}^2 Q_3 Q_{4L}]} \cdot \frac{Q_{4L}}{Q_L}$$

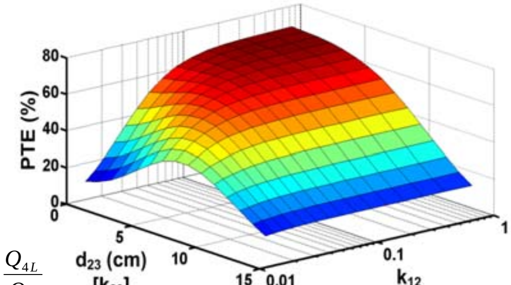
- 4-Coil link adds an additional DoF for impedance matching on the source side.
- If k_{12} is large, the reflected load onto L_1 increases dramatically, which helps maximize the PTE at the cost of reducing PDL.

www.GTBionics.org

Kiani, Jow, and Ghovanloo, TBioCAS 2011

PTE and PDL in 4-Coil Link

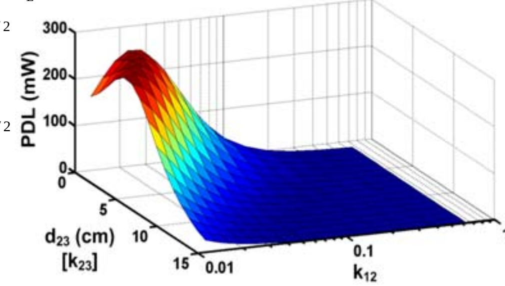
If k12 is large enough, 4-coil can tolerate variations in coil separation (k23) and maintain a large PTE. ☺



$$P_{L,4-coil} = \frac{V_s^2}{2R_1} \times \frac{(k_{12}^2 Q_1 Q_2)(k_{23}^2 Q_2 Q_3)(k_{34}^2 Q_3 Q_{4L})}{[(1+k_{12}^2 Q_1 Q_2).(1+k_{34}^2 Q_3 Q_{4L})+k_{23}^2 Q_2 Q_3]^2} \cdot \frac{Q_{4L}}{Q_L}$$

$$k_{23,PTE} = \left(\frac{\sqrt{1+k_{12}^2 Q_1 Q_2}.(1+k_{34}^2 Q_3 Q_{4L})}{Q_2 Q_3} \right)^{1/2}$$

$$k_{23,PDL} = \left(\frac{(1+k_{12}^2 Q_1 Q_2).(1+k_{34}^2 Q_3 Q_{4L})}{Q_2 Q_3} \right)^{1/2}$$

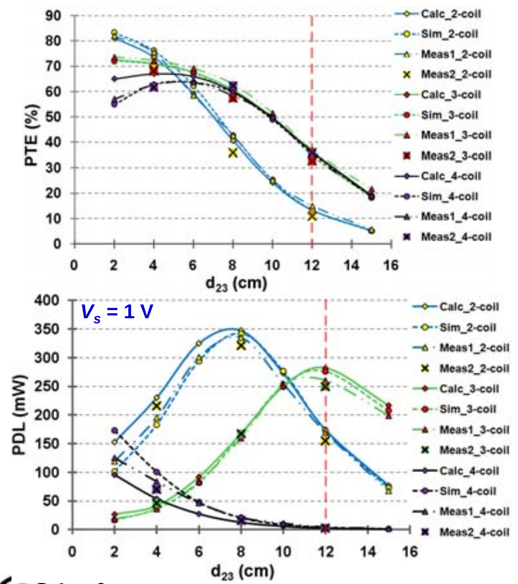


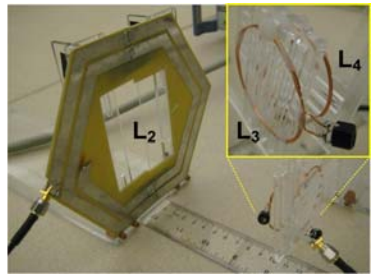
Small overlap between high PTE and PDL areas. ☹

www.GTBionics.org

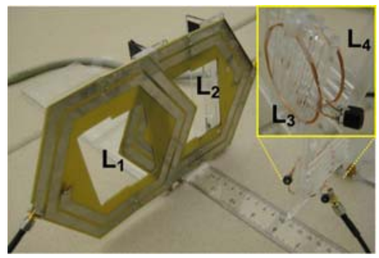
Kiani, Jow, and Ghovanloo, TBioCAS 2011

3-Coil vs. 4-Coil Link Measurements





3-coil link (PDL = 260 mW)



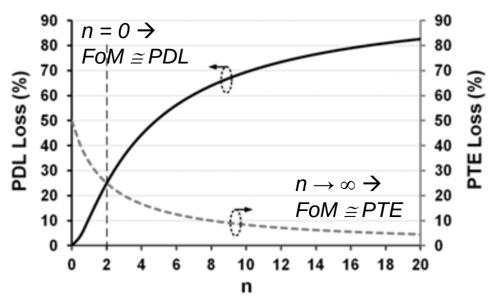
4-coil link (PDL = 4.4 mW)

Kiani, Jow, and Ghovanloo, TBioCAS 2011

New Figure of Merit (FoM) for Inductive Power Transmission Links

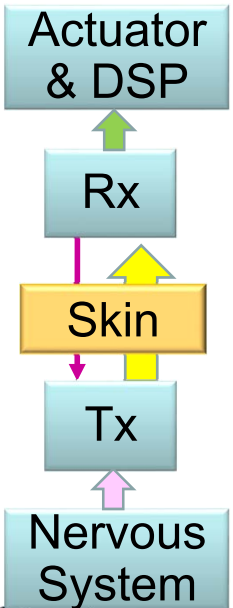
- Trade-offs between high **PTE** and sufficient **PDL**
- High PTE to reduce:
  - Reduce heat dissipation
  - Tissue exposure to magnetic field (safety)
  - Interference with nearby electronics (FCC)
- Sufficient PDL to:
  - Small PA transistors
  - Reduce Vs (safety)

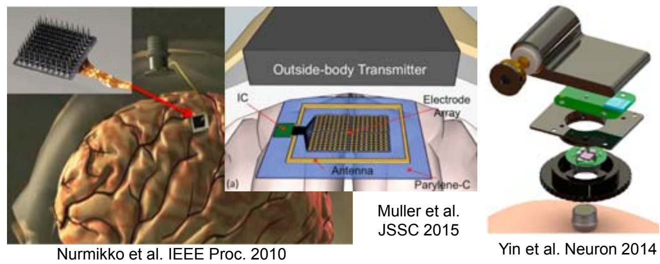
$$FoM = \frac{\eta_{m-coil}^{n} \times P_{L,m-coil}}{V_s^2}$$



Kiani and Ghovanloo, *TIE* 2013

Wideband Transcutaneous Back Telemetry (Uplink)

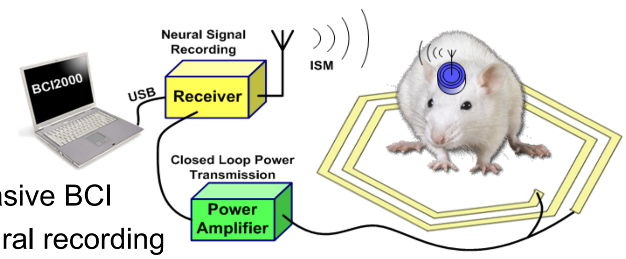




Nurmikko et al. IEEE Proc. 2010

Muller et al. JSSC 2015

Yin et al. Neuron 2014



- Invasive BCI
- Neural recording

Lee and Ghovanloo, TBioCAS 2013

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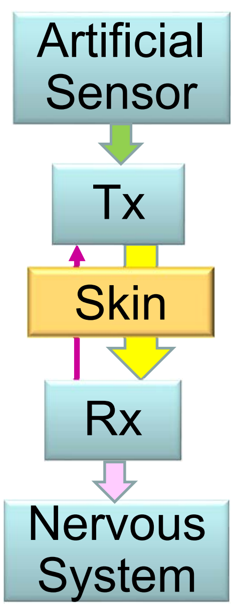
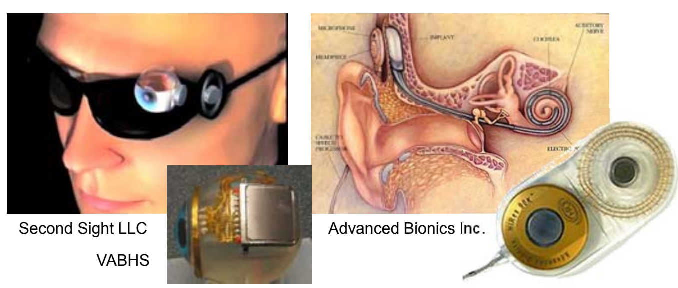
Wideband Transcutaneous Forward Telemetry (Downlink)





Second Sight LLC

VABHS

Advanced Bionics Inc.

- Wideband and robust forward telemetry links are needed for sensory substitute neuroprostheses such as retinal implants and cochlear implants
- Limited space and power available to the IMD for establishing a wideband and robust connection to the outside world

Ghovanloo, EMBC 2011

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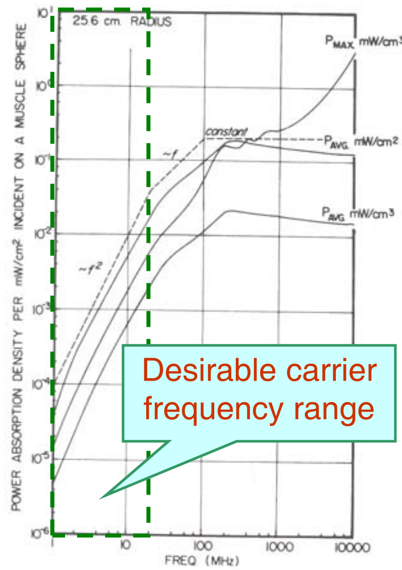
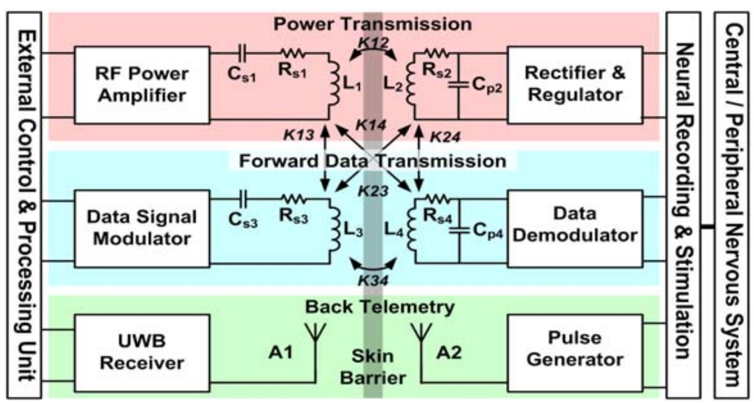
Power Carrier Freq. as Low as Possible

- Carrier frequency should be below the coil self resonance frequency.
- More power loss in the power transmission and conditioning circuitry at higher frequencies.
- 0.1 MHz < Carrier Freq. < 20 MHz Average density of electromagnetic power absorption in tissue increases as f^2.
- Tissue is more transparent to EM field at lower frequencies.
- Carrier Frequency↑ ⇒ Penetration Depth↓



J. C. Lin et al. IEEE Trans. Microwave Theory, 1973
17

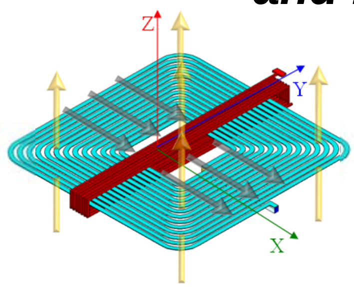
Wireless Link Using Multiple Carriers



- Low frequency for power transmission (125 kHz ~ 20 MHz)
- Medium frequency for forward data transmission (50 ~ 100 MHz)
- High frequency for back telemetry (0.4 ~ 2.4 GHz)

Ghovanloo and Atluri, TCAS-I 2007
18

Minimizing Interference between Power and Data Carriers



Vertical coils

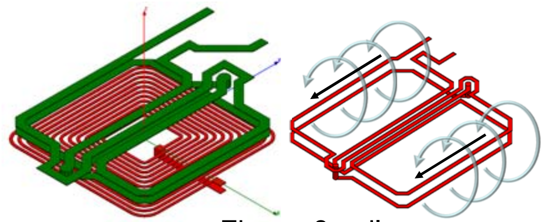
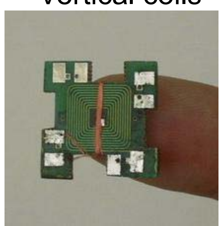
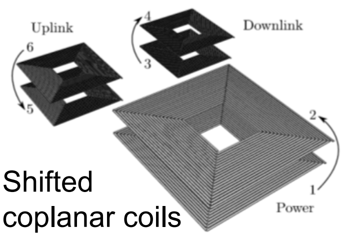
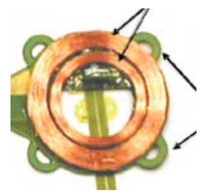


Figure-8 coils





Shifted coplanar coils
Simard and Sawan



Coaxial coils
S. Kelly et al.

www.GTBionics.org

Jow and Ghovanloo, TBioCAS 2010

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Carrier Based vs. Pulse Based

- Near-field inductive coupling
  - ASK → **Low data rate** due to limitations in high order filter integration at low frequency end of RF
  - FSK, QPSK, DPSK → **High power consumption** due to carrier-based modulation
  - LSK → Reduction of the received power due to **duty cycling of the power carrier**
- Far-field radiation
  - IR-UWB → Commercial IR-UWB in 3.1-10.6 GHz is **highly absorbable in water (tissue)**

Replicate IR-UWB in the near-field

www.GTBionics.org

Win and Scholtz, Comm. Letters,1998

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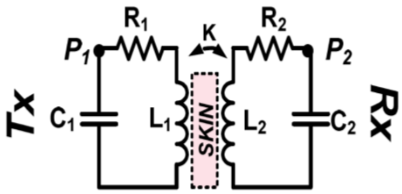
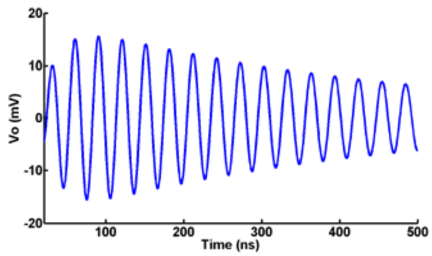
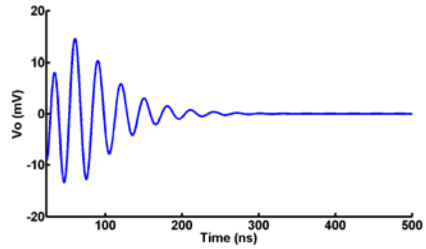
Effect of Q-Factor in Pulse-Based Data Transmission



- Tail of the oscillation $\propto e^{-(f_t . t)(\frac{\pi}{Q_2})}$
- $Q = \frac{f_t}{BW}$ → $Q\uparrow$ → $BW\downarrow$ → $Noise\downarrow$ → $SNR\uparrow$

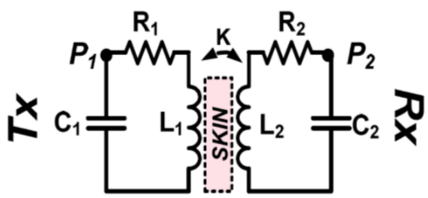


$Q_2 = 44.8$

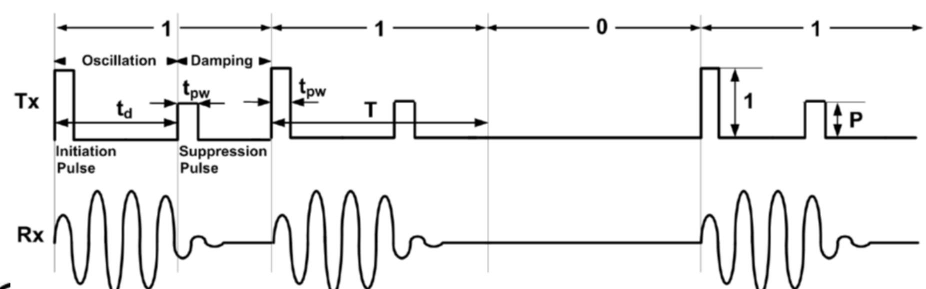


$Q_2 = 4$

Pulse Harmonic Modulation (PHM)

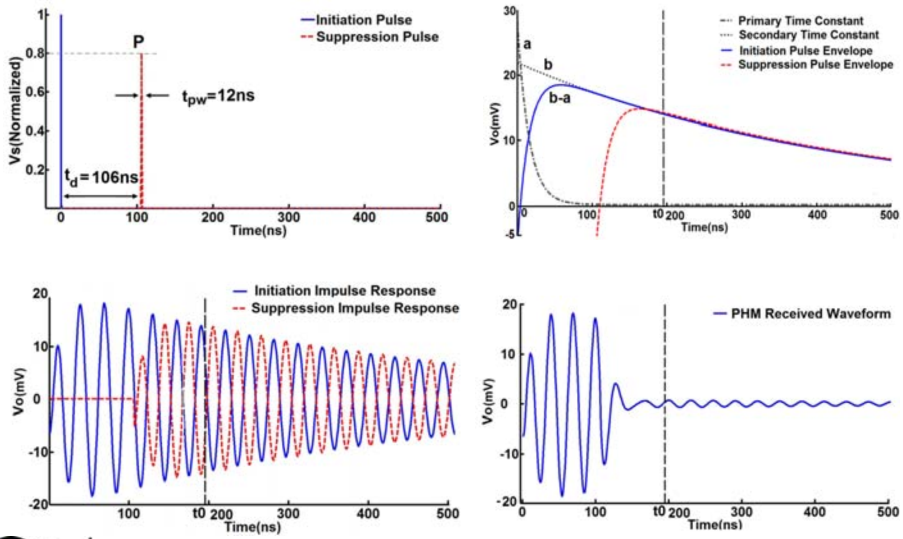


- First pulse initiates oscillation on the Rx side at the tuned frequency of L_2C_2-tank, f_t
- Second pulse suppresses the oscillation of the first pulse by being 180° out of phase



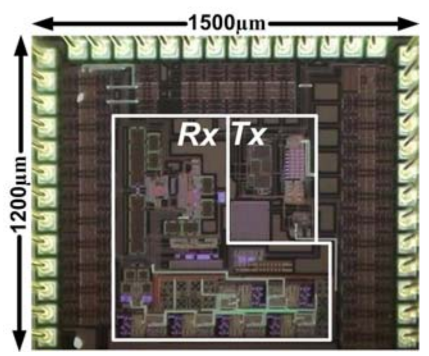
Patent Pending

PHM Simulations in MATLAB



Ghovanloo and Inanlou, TCAS-I 2011

PHM-Based Transceiver ASIC

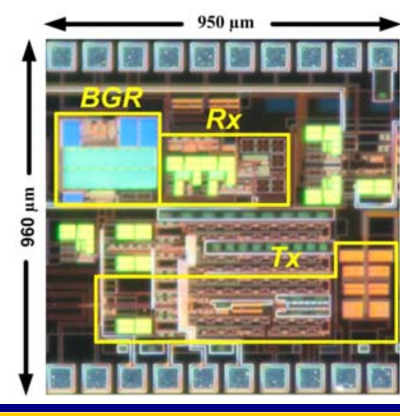


**TSMC 0.35 µm Std. CMOS

Transceiver layout area = 0.23 mm^2

Supply voltage: 1.8V

Data rate: 20.0 Mbps



*ON-Semi 0.5 µm Std. CMOS

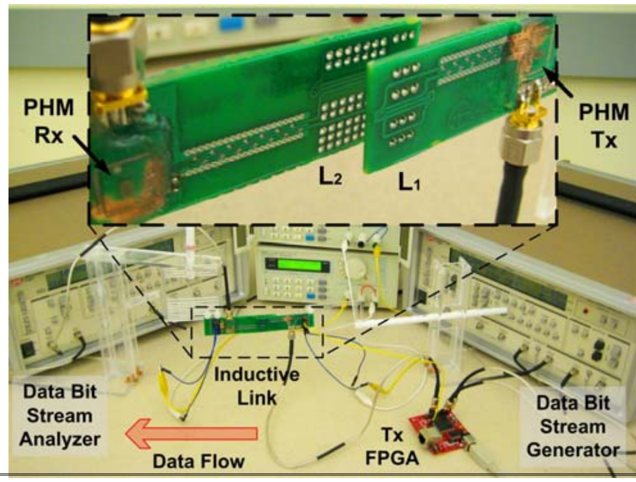
Transceiver layout area = 0.61 mm^2

Supply voltage: 3.3V

Data rate: 10.2 Mbps

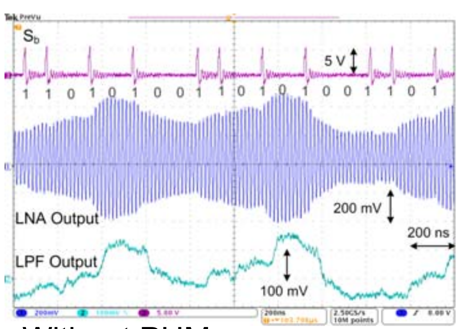
*Inanlou et al, JSSC 2011, **Kiani et al, TCAS-II 2012

PHM Test Setup

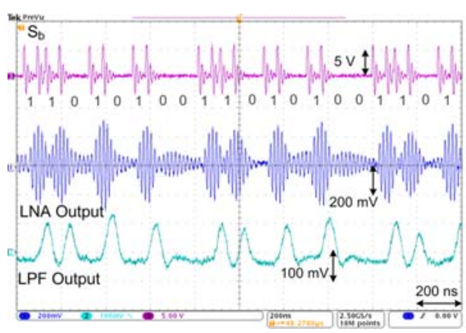


Coil (Fig-8)	Size (cm)	#Turns(n)	L (nH)	R (mΩ)	C_p (pF)	C_t (pF)	SRF (MHz)
L_1 (Tx)	1×1	2	105	85	2.1	-	338*
L_2 (Rx)	1.5×1.5	2	230	180	3.2	24.1	184.5*

Measurement Results

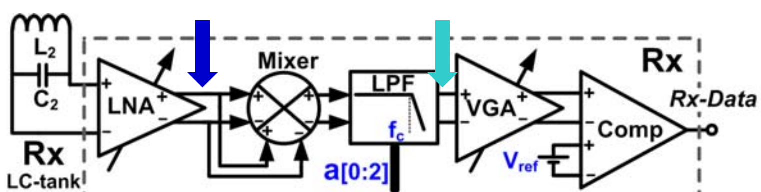


Without PHM



Data Rate: 10.2 Mbps

With PHM



Inanlou, Kiani, and Ghovanloo, JSSC 2011

PHM Benchmarking

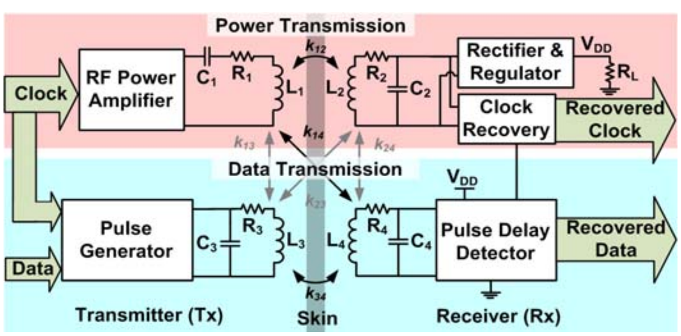
Ref.	Modulation Scheme	Tx/Rx (cm)	Coils Distance (mm)	f_r (MHz)	Data Rate (Mbps)	Tx Power (pJ/bit)	Rx Q at low freq	BER
Ghovanloo 2004	pcFSK	2/1.2	5	5/10	2.5	N/A	N/A	10^{-5}
Sawan 2005	BPSK	3.5/2.7	15	10	1.12	N/A	N/A	10^{-5}
W. Liu 2008	BPSK	N/A	10~15	20	2	N/A	N/A	10^{-7}
Sawan 2010	QPSK	1.2/1.2	5	13.56	4.16	N/A	65.6**	2×10^{-6}
Sarpeshkar 2008	LSK	3.5/3.5	20	25	2.8	35.7+	30	10^{-6}
H.J. Yoo 2009	BPM++	1.5/1.5	0	-	10	2.9	15	N/A
Inanlou 2011	**PHM**	**1/1.5**	**10**	**67.5**	**10.2**	**345**	**48**	**6.3×10^{-8}**
Kiani 2013	**PHM**	**1/3**	**10**	**66.6**	**20**	**180**	**96**	**8.7×10^{-8}**

www.GTBionics.org

Kiani and Ghovanloo, TCAS-II 2013

Pulse Delay Modulation (PDM) using a Dual-band Power/Data Link

- Pulse-Based data transmission using a **separate** data link
- Modulate the **zero-crossings** of the undesired power carrier across L_4C_4 with short decaying oscillations
- Increasing R_4 (***Q_4***↓) to facilitate decay of L_4C_4 oscillations



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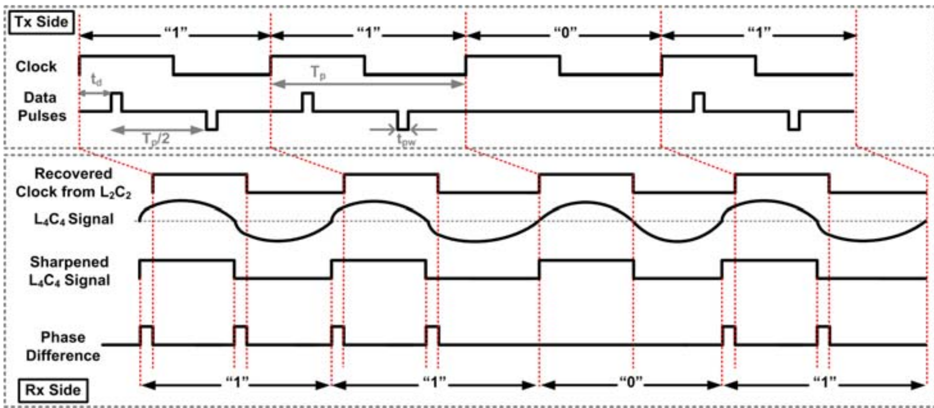
Kiani and Ghovanloo, TBioCAS 2015

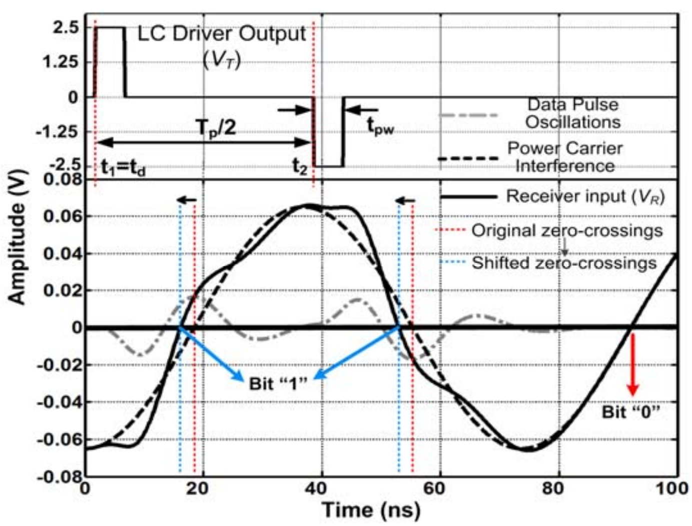
Pulse Delay Modulation (PDM)

- Two short pulses to coincide the power carrier interference zero-crossings across L_4C_4 for "1" bits
- Comparing power signal with delayed interference on L_4C_4



Patent Pending

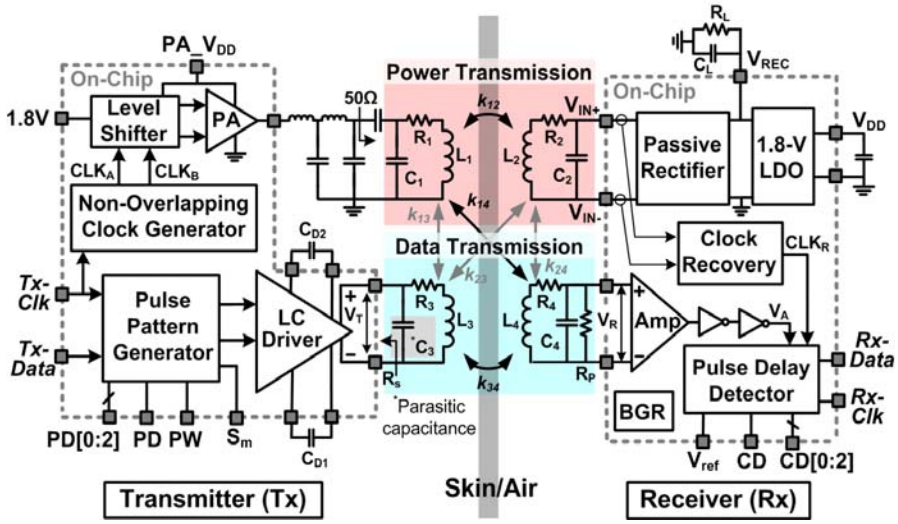
PDM Simulation in MATLAB



Shift in zero crossings = 2.5 ns

Kiani and Ghovanloo, TBioCAS 2015

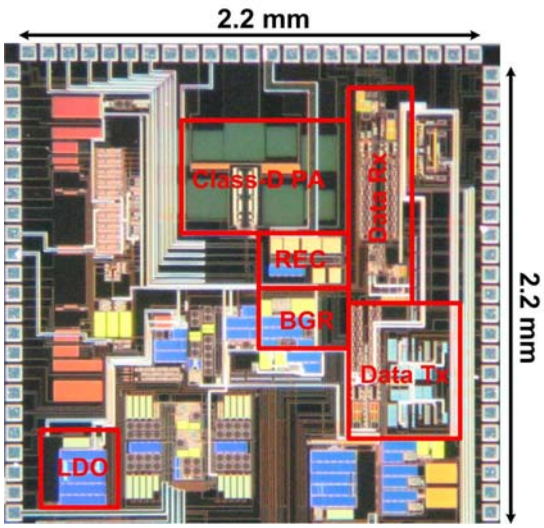
PDM-based Transceiver Diagram



Kiani and Ghovanloo, TBioCAS 2015

PDM-based Transceiver ASIC

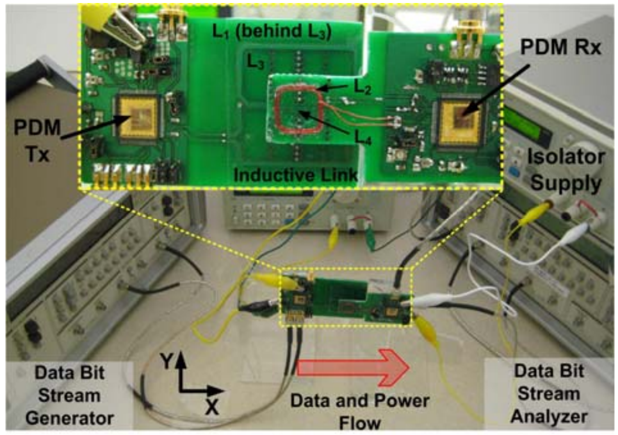
- Fully on-chip power/data transceiver
- CMOS tech: TSMC 0.35-µm
- Transceiver die area = 4.8 mm^2
- Nominal supply voltage = 1.8 V
- Operating freq. = 13.56 MHz
- Data rate = 13.56 Mbps



Kiani and Ghovanloo, TBioCAS 2015

PDM Test Setup

- Power link: printed-spiral and wire-wound coils
- Data link: a pair of planar figure-8 coils on FR4 PCB



Link	Coil	Size (mm)	#Turns	Line Width (mm)	L (nH)	**R (Ω)	f (MHz)	Q	SRF (MHz)	Mutual Coupling $(k)\times10^{-3}$			
										L_1	L_2	L_3	L_4
Power	L_1	32 × 32	5	2	500	0.5	13.56	85.2	116	-	37	9	6.4
	*L_2	10 × 10	3	0.255	195	0.34	13.56	48.8	237	37	-	4.2	8.5
Data	L_3	30 × 30	1	1	165	0.48	50	108	255	9	4.2	-	19
	L_4	10 × 10	1	0.4	56.8	0.44	50	+40.5	550	6.4	8.5	19	-

* L_2 was an AWG30 wire-wound coil. ** From measurements at the operating frequency, f.
+ Q_4 was reduced to 5 by adding R_P = 100 Ω.

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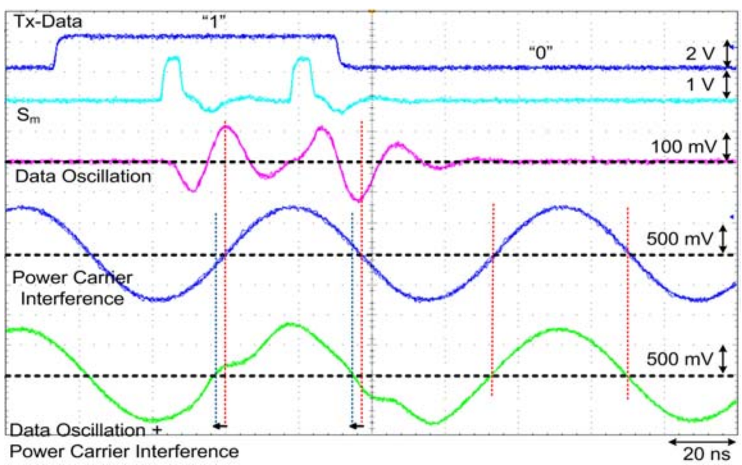
PDM Measurement Results



- Data rate = 13.56 Mbps
- Distance = 10 mm
- Data osc. freq. = 50 MHz
- Signal-interference ratio (SIR) = -18.5 dB
- Shift in zero crossings = 2.3 ns
- Power delivered to load (PDL) = 42 mW

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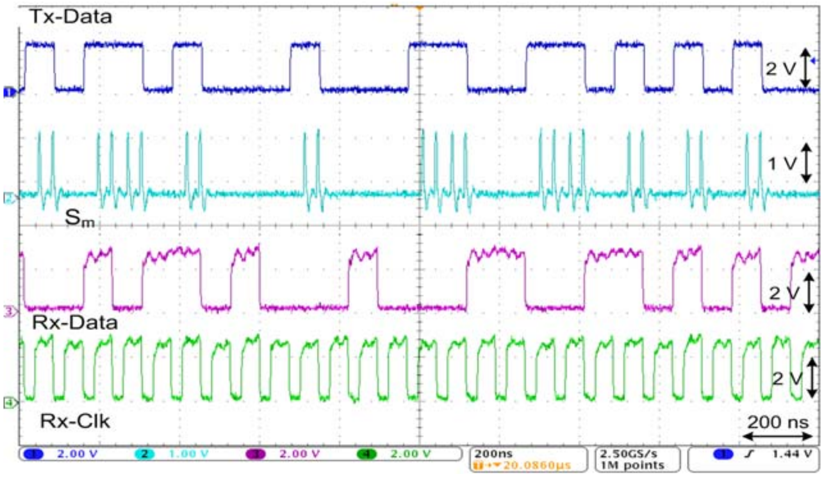
Kiani and Ghovanloo, TBioCAS 2015

PDM Measurement Results



- Data rate = 13.56 Mbps
- Distance = 10 mm
- SIR = -18.5 dB
- Bit error rate (BER) = 4.3×10^{-7}

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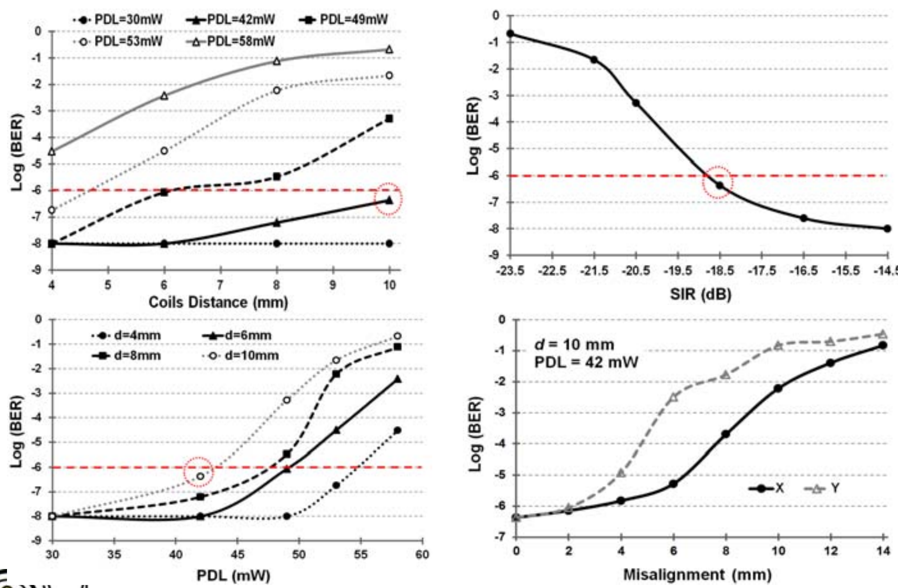
PDM Measurement Results



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PDM Benchmarking

- PDM advantages:
  - First inductively-powered pulse-based transceiver
  - Low data transmitter and receiver power consumption
  - Robustness against power carrier interference and Small die area

Reference	Mod.	d (mm)	Data Carrier (MHz)	Power Carrier (MHz)	Data Rate (Mbps)	Tx/Rx Power (pJ/bit)	CMOS Tech. (µm)	SIR (dB)	Die Area (mm^2) (Data Tx/Rx)	V_{DD} (V)	BER
Ghovanloo, 2004	pcFSK	5	5/10	5/10	2.5	-/152	1.5	-	-/0.29	5	10^{-5}
Hu, 2005	BPSK	15	10	10	1.12	-/625	0.18	-	-/0.2	1.8	10^{-5}
Mandal, 2008	LSK++	20	25	25	2.8	35.7/1250	0.5	-	2.2/2.2**	2.8	10^{-6}
Rush, 2012	FSK	20	-/5	5	1.25	-	0.8	-	-	2.7	-
Rush, 2012	BPSK	20	48	5	3	1962/-	0.8	-	2.3**	2.7	2×10^{-4}
Simard, 2010	QPSK	5	13.56	1	4.16	-	-	-	-	-	2×10^{-6}
Zhou, 2008	BPSK	15	20	2	2	-/3100	0.35	-12*	-/4.4	4.5	10^{-7}
Chen, 2013+	DPSK	-	20	2	2	-	0.18	-	-	1.8	10^{-7}
This Work	**PDM**	**10**	**50**	**13.56**	**13.56**	**960/162**	**0.35**	**-18.5**	**0.34/0.37**	**1.8**	$\mathbf{4.3\times10^{-7}}$

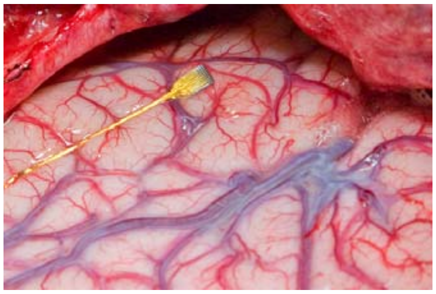
* A 1st-order off-chip filter was used to improve SIR to -6 dB. ** Including pads.
+ Second-order filter was used to improve SIR. ++ LSK is only used for uplink.

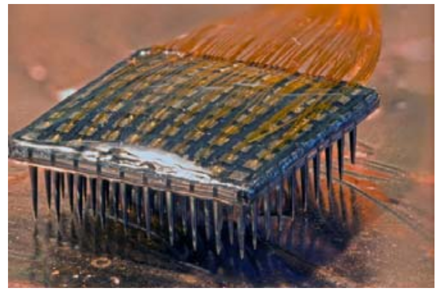
Kiani and Ghovanloo, TBioCAS 2015

Tongue Drive System

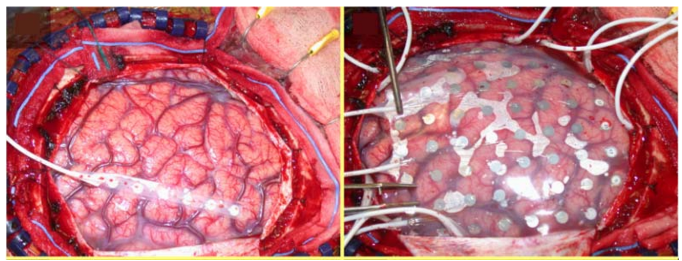
A Brain-Tongue-Computer Interface for Environmental Control and Computer Access

Invasive BCI for Clinical Use





Intracortical electrodes (Single Unit Recording)



Subdural electrodes (ECoG Recording)

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Switch Based Systems

- ✓ Simple and relatively low cost
- ✓ Easy to use

- ✗ Requires limb movement
- ✗ Slow and cumbersome
- ✗ Inflexible

Grasp Switch

Microlight Switch

Sip-n-puff Switch

e-talk Speech Tablet

Chin Control Switch

Flex Switch

Voice activated switches

Infrared (IR) Switch

Pillow Switch

EMG Switch

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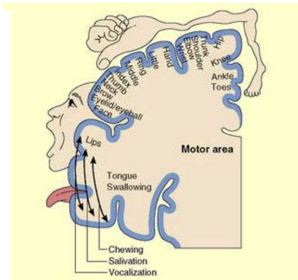
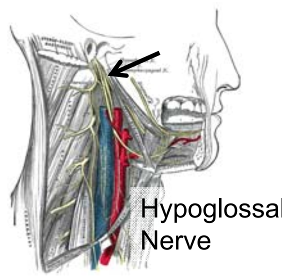
Why Using Tongue?

- Along with mouth occupies the amount of sensory and motor cortex that rivals fingers and hand: sophisticated motor control capability evident in speech and ingestion
- Fast movement with many degrees of freedom (DoF). Very flexible
- Connected to brain by a cranial nerve: escapes even high level spinal cord injuries
- Noninvasive access to tongue is possible.
- Not afflicted by repetitive motion disorders
- Does not fatigue easily. Very low rate of perceived exertion
- Cosmetic advantage and privacy. It is all inside the mouth
- Not influenced by the position of the rest of the body
- Unlike BCIs does not need concentration.



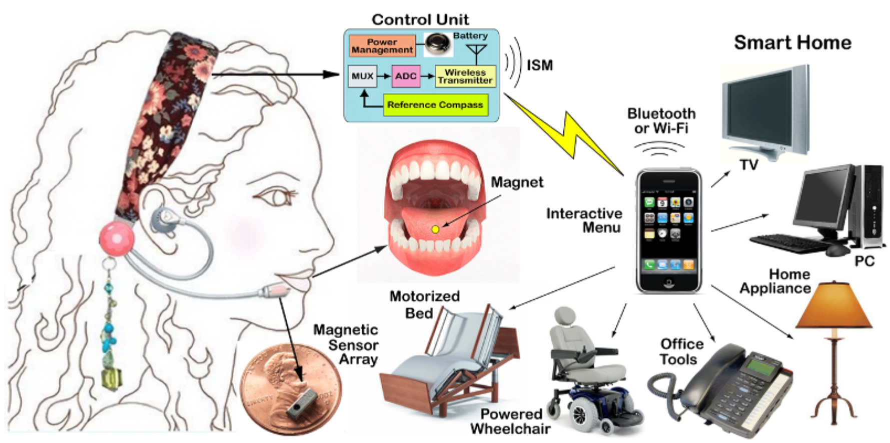
Motor Homunculus



Hypoglossal Nerve

Ghovanloo, IEEE EMBC 2007

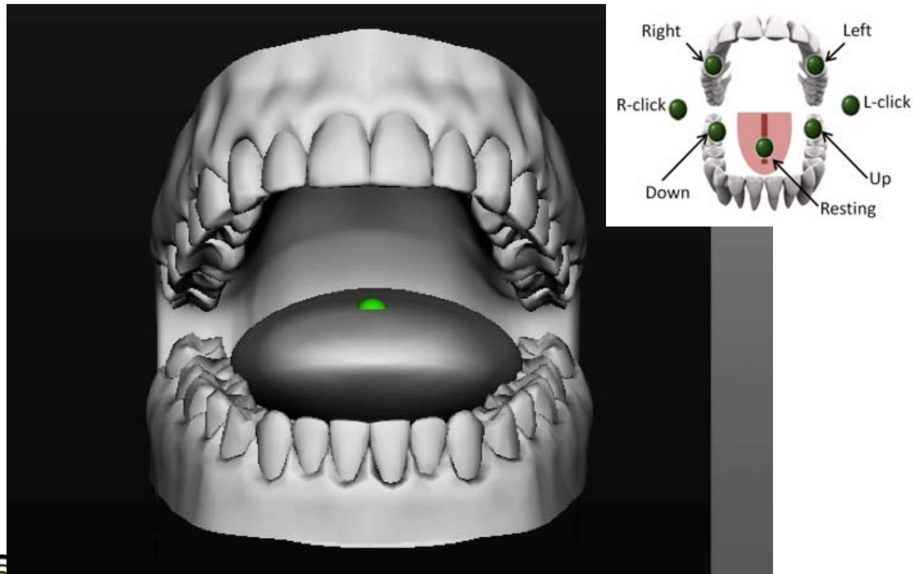
Tongue Drive System (TDS)



An array of magnetic sensors detect the magnetic field variations resulted from the movements of a small magnetic tracer attached to the tongue, and wirelessly send that information to a portable computer where these tongue movements are translated to user commands.

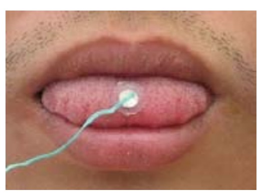
US Patent 8044766, Other patents pending

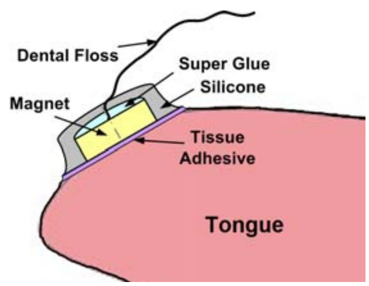
Tongue Commands



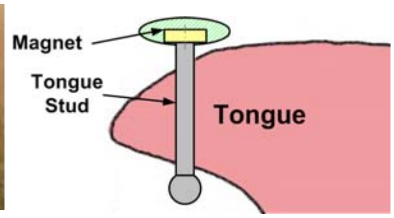
Magnetic Tracer Attachment

Temporary attachment:
By ***tissue adhesives***
to test-drive the TDS

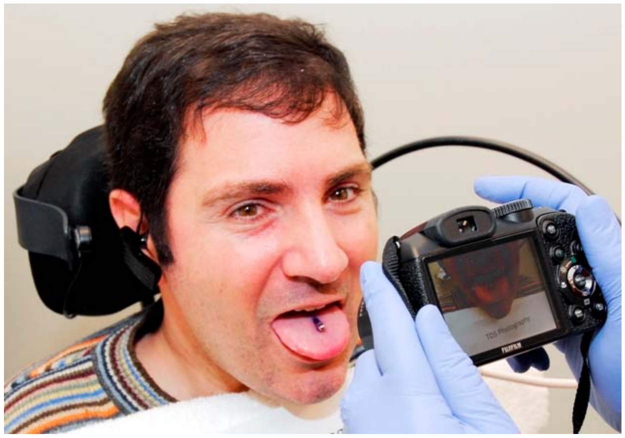


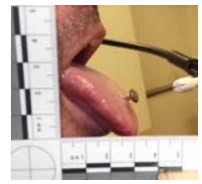


Semi-permanent attachment:
By ***magnetic tongue piercing*** to use the TDS on a regular basis



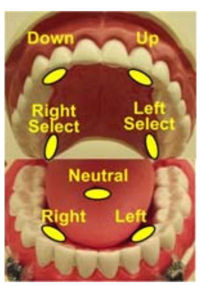
TDS Clinical Trials

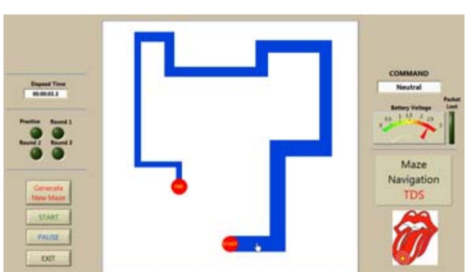


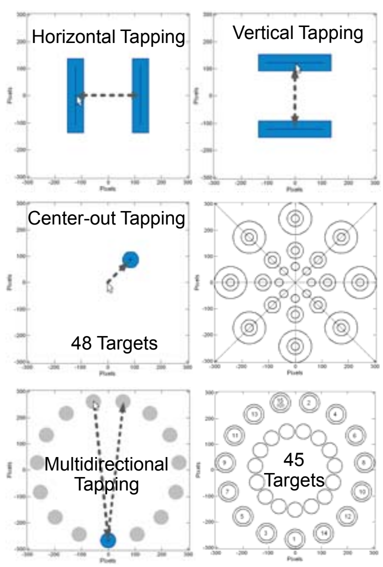


After screening, participants receive a magnetic tongue piercing, recover for 4 weeks, and participate in a 6-week trial including one computer access and one wheelchair navigation session per week.

Experimental Methods (Computer Access)

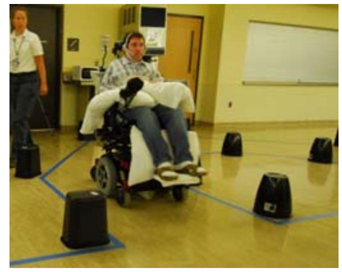




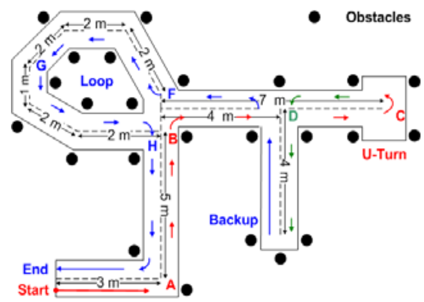


Experimental Setup (Wheelchair Navigation)

TDS
↓ Wireless
iPod
↓ Dongle
Wheelchair



- Q6000 electric-powered wheelchair from Pride Mobility Inc.
- Subjects' drove in a ~50m obstacle course using 3 driving strategies:
  - Unlatched
  - Latched
  - Semi-proportional



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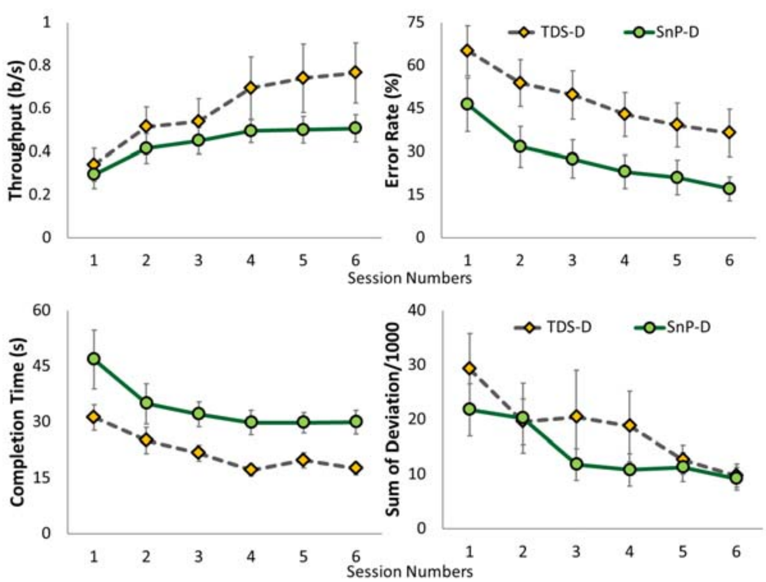
Tongue Drive System vs. Sip-and-Puff

Center-Out Tapping Task Over 6 Sessions

Maze Navigation Task Over 6 Sessions



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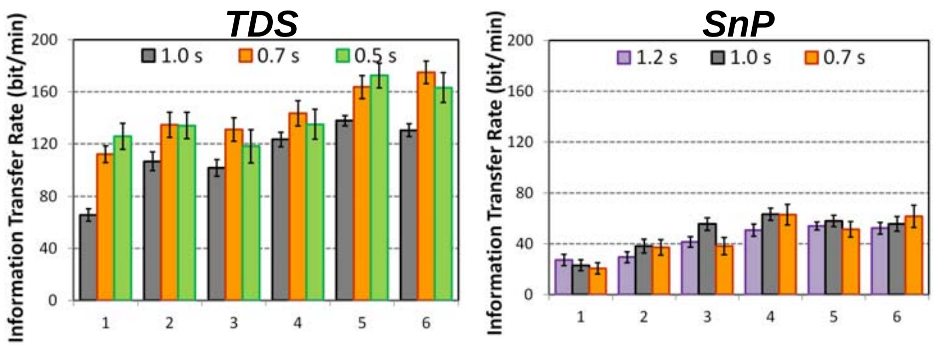
Kim et al., Sci. Trans. Med. 2013

Tongue Drive System vs. Sip-and-Puff



$$ITR = \frac{1}{T}\left(\log_2 N + P \log_2 P + (1-P)\log_2 \frac{1-P}{N-1} \right)$$

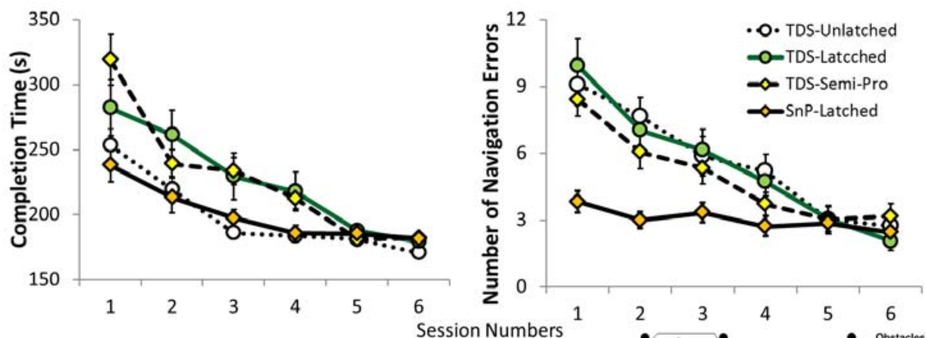
N: number of individual commands N_{TDS}=6 N_{SnP}=4

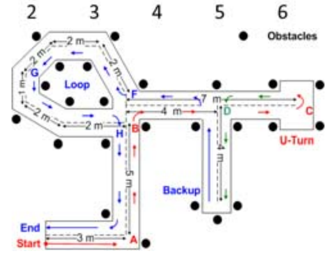
P: System accuracy

T: System response time

Wolpaw et al., Clinical Neurophysiology 2002

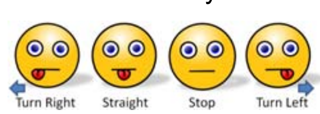
Tongue Drive System vs. Sip-and-Puff





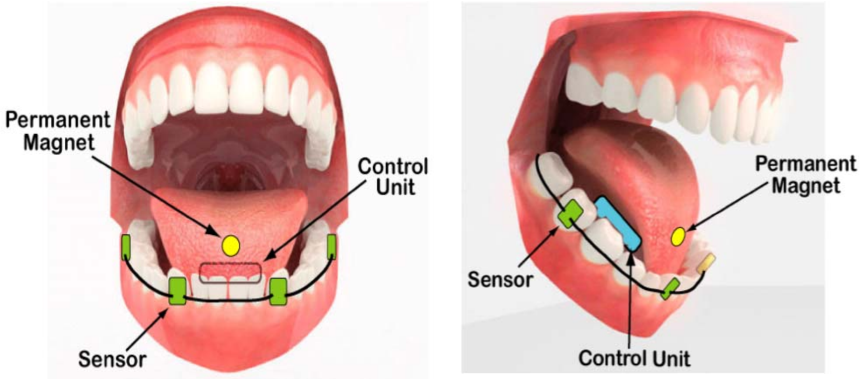
Powered Wheelchair Control Task Over 6 Sessions

Subjects perform considerably better over time.



Kim et al., Sci. Trans. Med. 2013

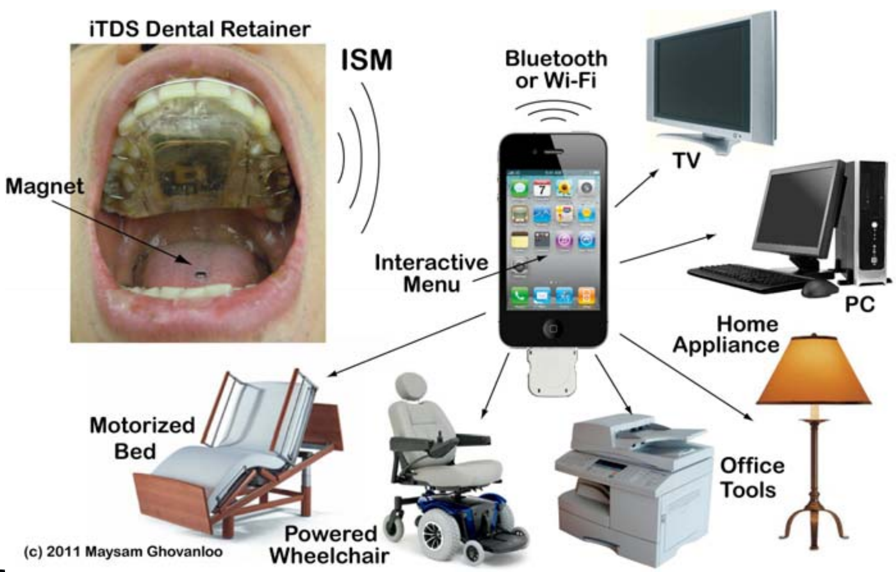
Intraoral Tongue Drive System (iTDS)



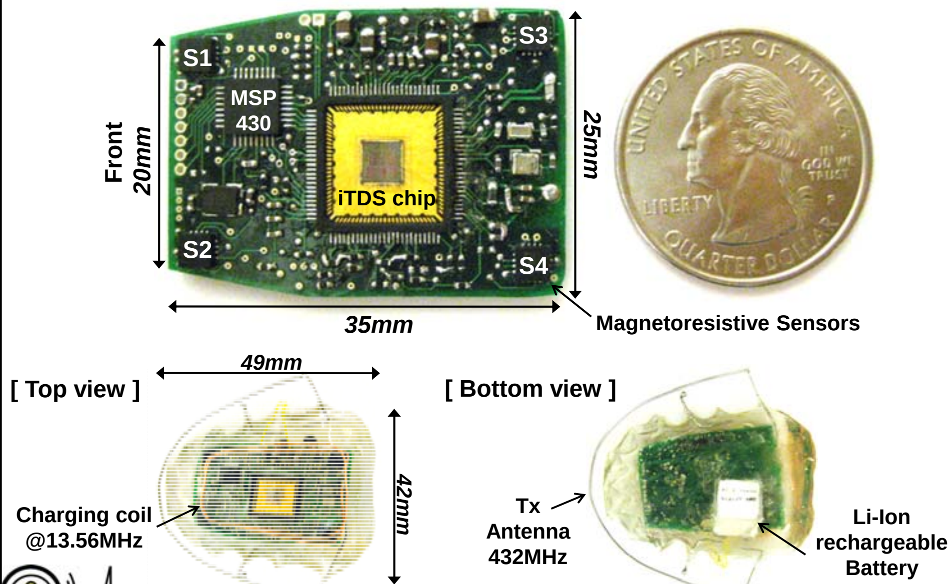
- Sensors, all the electronics, and a small rechargeable battery will be integrated in a comfortable dental retainer.
- Completely hidden from sight → Gives users more privacy and confidence
- More stability inside the mouth. Protected against external mechanical interference and possible damage.

US Patent 8044766, Other patents pending

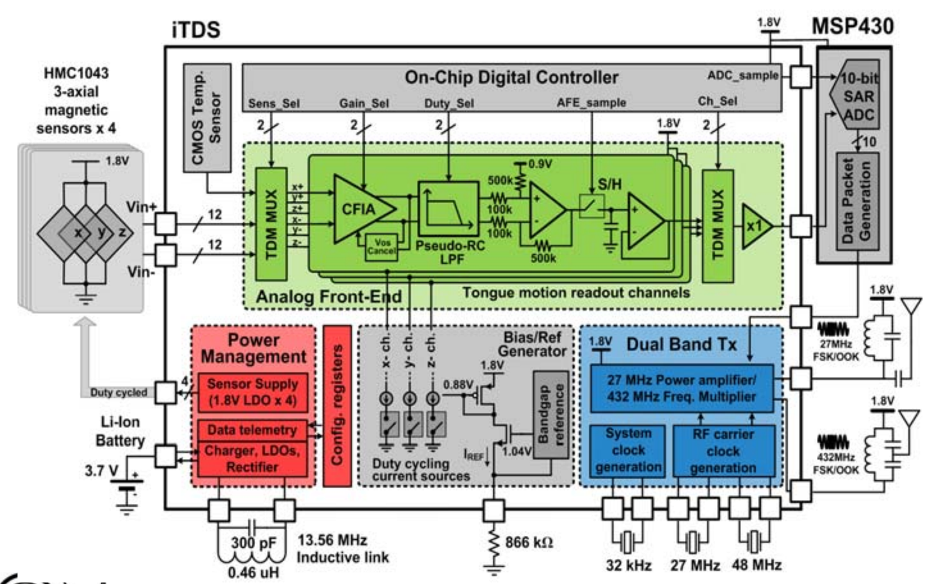
Intraoral Tongue Drive System (iTDS)



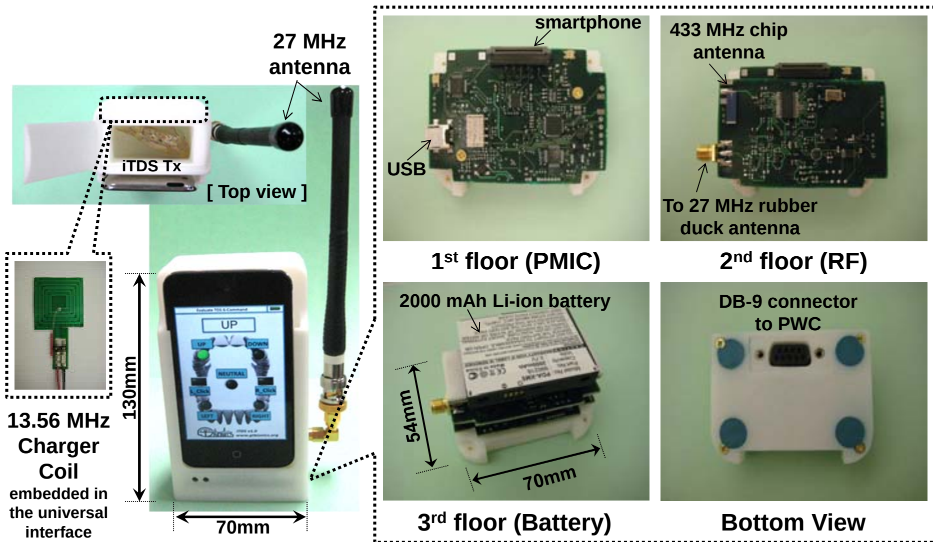
iTDS Implementation



iTDS Block Diagram



iTDS Wireless Universal Interface



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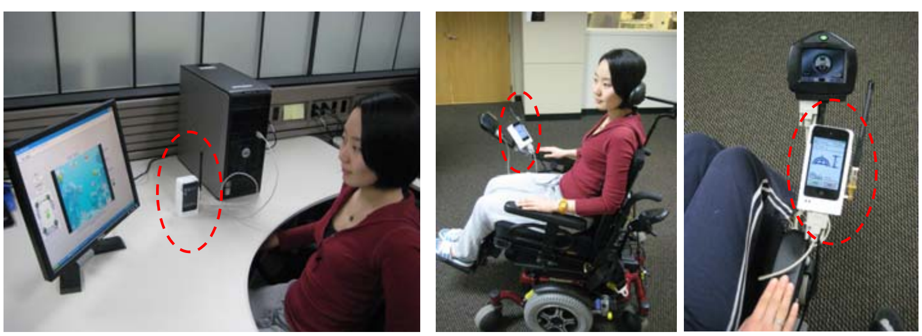
iTDS Common Applications

[Computer Access] **[Powered Wheelchair Control]**



- iTDS can substitute mouse or touch-screen, enabling full PC, tablet, or smartphone access with tongue motion
- iTDS can substitute joystick to provide control over powered wheelchairs (Forward/ Backward/ Left/ Right/ Neutral-stop).

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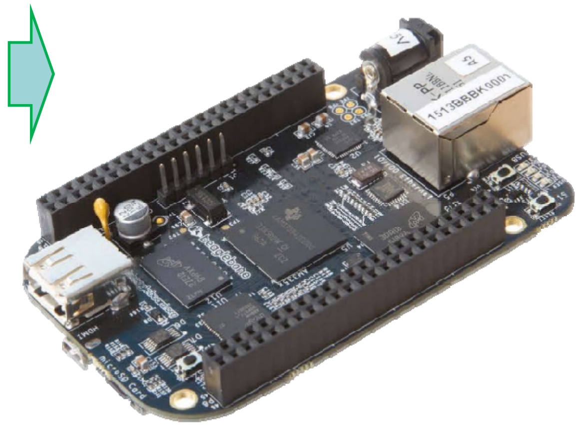
Substituting the Smartphone with Beagle Bone Black



To create a stand-alone TDS

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iTDS Special Applications

- iTDS can be used where physical motion has been hindered by the environment or by nature of the task.
- iTDS allows tongue to be used as a human motor output, like hands and fingers. Like the 3rd arm.

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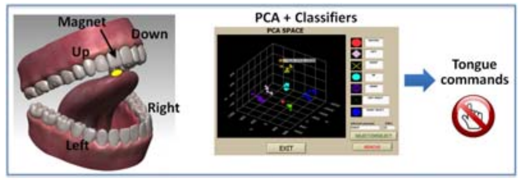
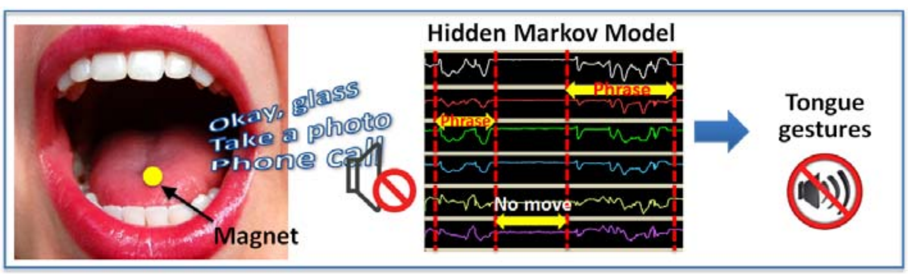
TDS + Head-Mount Display

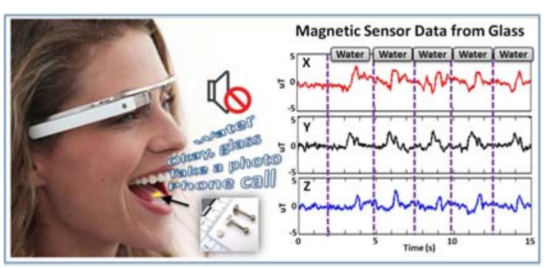
A Truly Wearable Computer



- Hands-free mode of access for wearable computers with head-mount displays and virtual reality glasses, e.g. Google GLASS

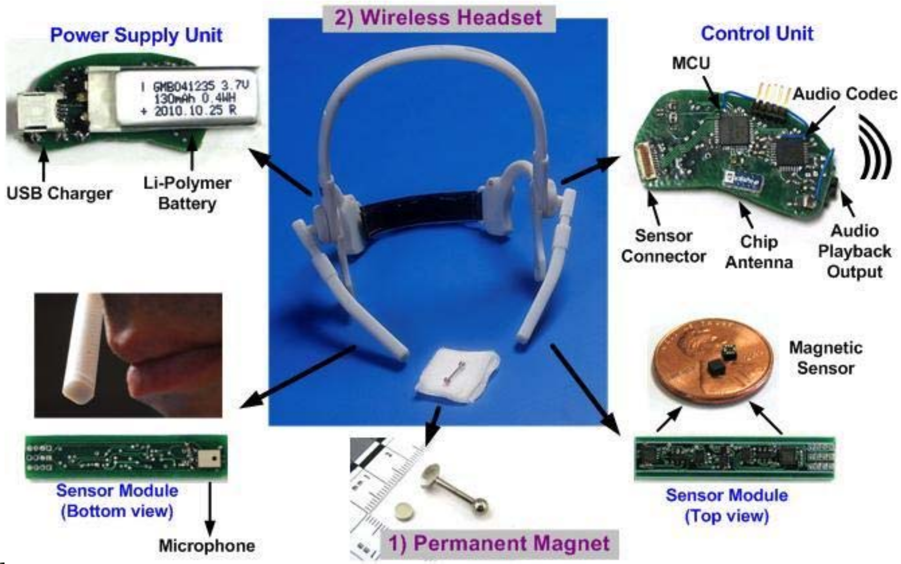
A Silent Speech Recognizer/Synthesizer





- Recognizing phonemes, words and sentences from the physical tongue motion during silent speech → Privacy
- Aphonia, weak voice, Laryngectomees

dTDS Wireless Headset



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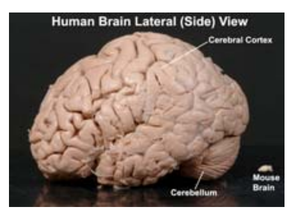
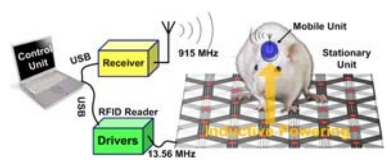
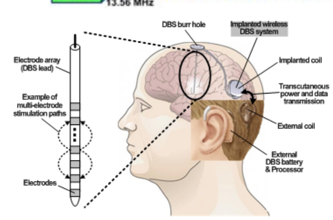
Huo et al., IEEE TNSRE 2013

Conclusions

- We have developed basic building blocks for high performance **implantable microelectronic devices** (IMD), particularly in the analog, RF, and power management units.
- We are building **invasive BCIs** (wireless neural recording, stimulation, smart wireless cage) as an advanced set of tools for **neuroscience** and **electrophysiology** research on freely behaving small animal subjects.







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Conclusions

- **Tongue Drive System** (TDS) is a wireless, wearable, and minimally invasive brain-tongue-computer interface (BTCI) that enables individuals with severe disabilities to access computers, drive wheelchairs, and control environments with their **voluntary tongue motion**.
- A **Multimodal TDS** (mTDS) is under development to capture any remaining abilities of the end users and give them more degrees of freedom and ease of use for various activities of daily living (ADL).

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  - Temilolua Olubanjo (PhD Student)
  - Muhammad Rashid (PhD Student)
  - Md. Sahadat Nazmus (PhD Student)
  - Yaoyao Jia (PhD Student)
  - Pyungwoo Yeon (PhD Student)
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  - Raymond Fu, Northeastern University, Boston, MA
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