Analog Circuits for Biochip L06

Wireless power and data transmission to implanted systems

Short Review

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Biomedical and neuromorphic microelectronic systems

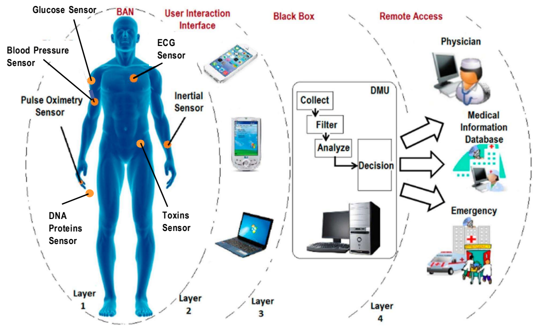
Outline of the course

- Implantable biomedical devices: system architecture and examples
  - Impedance matching
- NRIC (inductive coupling, power and data transmission)
  - Tx (transmitter)
    - Architecture and circuits
    - Analog and digital modulations, line encoding
  - Rx (receiver)
    - Active circuits
    - Inductive load modulation (passive)
- NRMRC (magnetic coupling, power)
- NRCC (capacitive coupling, power and data)
- Ultrasound coupling (acoustic power coupling)
- Optical coupling (power and data)
- Far-field telemetry (data)
  - Active Tx
  - Passive Tx: backscattering
  - Active receivers (non-coherent, super heterodyne, super regenerative)

Architecture of a eHealthcare system

Four-layer architecture

- Layer 1, BAN (Body Area Network)
  - Vital parameters are captured by on-body (wearable) and in-body (implantable) sensors
- Layer 2, user interaction devices/interface
  - Access points (AP), data is collected and transferred to an upper layer
  - Dedicated lines, Powerline Communication (PLC), or existing wireless infrastructure
- Layer 3, Decision Measuring Unit (DMU)
  - Major computation and decision regarding patient status
  - Connection to the internet
- Layer 4, Healthcare services
  - Medical professionals have access to DMU computed data



Four-layer typical architecture of an eHealthcare system

(adapted from Ghamari, M. *et. al*. A Survey on Wireless Body Area Networks for eHealthcare Systems in Residential Environments. Sensors 2016, 16, 831)

Architecture of a closed-loop implant and system

Functional modules: analog technology compliant

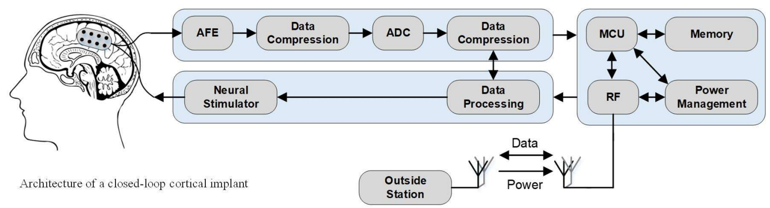
- Electrodes (recording and stimulation)
  - Fabrication, materials
- Recording, and stimulation channels
  - CMOS, high-voltage/current
- Power management
  - Temperature sensing

Functional modules: digital technology compliant

- Digital electronics and memory
  - Deep-submicron CMOS and memory, new devices
- External base station and antennas

Functional modules: RF technology compliant

- RF (radio-frequency, power and data telemetry)



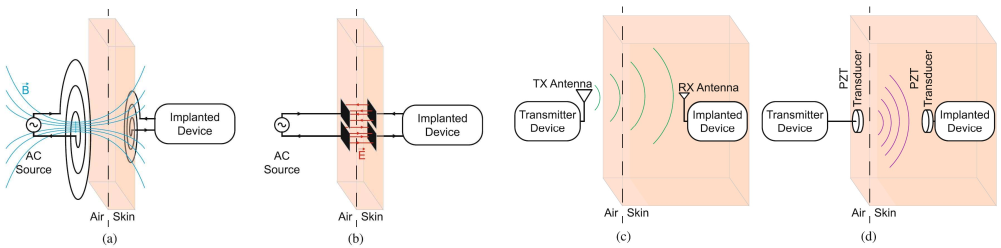
Architecture of a closed-loop cortical implant

General rules

- Autonomy
  - System should allow patients autonomy: major impact on circuits
- Simplicity
  - Reduce circuit complexity and current consumption
  - Increasing circuit robustness and reliability
- Complexity shifting
  - When only little power is available at the (implanted) transmitter, circuit complexity and signal processing should be shifted towards the receiver side

Wireless power transfer (WPT) techniques

- Methods to transmit power to the implanted system
  - Near-field (NF) coupling, $d \leq \lambda/2\pi$ (d, separation distance, and λ, wavelength of signal)
    - Magnetic coupling, inductive link (a)
    - Electric field coupling, capacitive link (b)
  - Far-field (FF) radiation, $d \geq \lambda/2\pi$, or radio-frequency (RF) transmission (c)
  - Ultrasound (US) (d)



Wireless power transfer strategies for implantable bioelectronics. (a) Schematic of inductive coupling method. (b) Schematic of capacitive coupling method. (c) Schematic of far-field method. (d) Schematic of ultrasound method

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Impedance matching, maximal power transfer

- Low-frequency analysis focuses on current, voltage values
- In RF, parasitic store energy and thus, it is important to also consider power
  - Transfer the maximum amount of power generated at a source to the load
  - Complex algebra can be used to model the transfer
    - complex source impedance $Z_0 = R_0 + jX_0$
    - complex load impedance $Z_L = R_L + jX_L$
    - ideal voltage source V_0
    - The average power P_L is dissipated in the resistive part of the load, while the current is complex

$$P_L = I_{RMS}^2 R_L = \frac{1}{2}|I|^2 R_L = \frac{1}{2}\left(\frac{|V_0|}{|Z_0 + Z_L|}\right)^2 R_L = \frac{1}{2}\frac{|V_0|^2}{(R_0+R_L)^2 + (X_0+X_L)^2} R_L$$

    - Mathematical manipulations are applied to find the condition of maximal power transfer P_L
    - The two resulting conditions for reactances, $X_0 = -X_L$, and resistances, $R_0 = R_L$, are combined into the conjugate matching

$$Z_0 = Z_L^*$$

  - In case matching is not achieved, maximal power is not transmitted which is measured by the reflection coefficient (gamma Γ)

$$\Gamma = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

Z_1 and Z_2 are arbitrary impedances

$$0 \leq |\Gamma| \leq 1$$

    - The power transfer is represented as a sum of two power waves: the incident power originating from the source and reflected power that was not delivered to the load

Single-circuit branch impedance matching networks

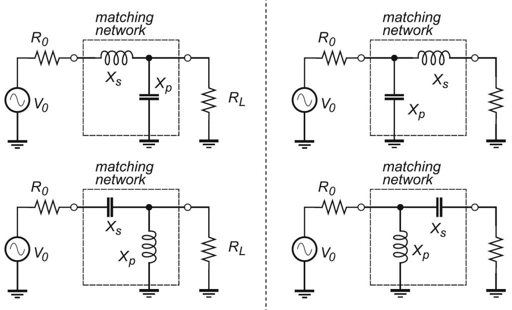
- Because there are only two initial resistances to compare, R_0 and R_L, and two possible flavors of reactances that can be used ($j\omega L$) and ($1/j\omega C$), there are only four possible combinations that can be made
  – Reactances are used instead of purely resistive networks because they dissipate less power and offer better noise performances

$R_0 < R_L$ | $R_0 > R_L$ ← Input vs load condition

Matching network behavior ↓

Low-pass behavior

High-pass behavior



  – Alternate passive matching network topologies are also possible

(Homework HW01)

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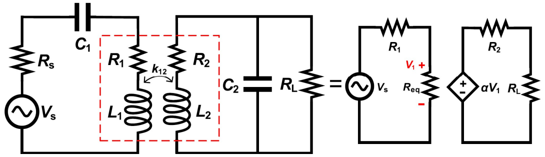
NRIC design (1)

- A systematic procedure is mostly applied
  – Iterative process, based on optimization steps
  – Analytical model used in each step
- Relevant variables that are sought to be optimized



  – PTE, Power Transmission Efficiency
    - percentage of the transmitted power from the source is delivered to the load
    - helps calculate the power loss and prevent the heat damage caused by the power losses

$$PTE = \frac{P_{out}}{P_{in}}$$

Pout output power which is delivered to the IMD
Pin input power which is sent through the external unit

  – PDL, Power Delivered to the Load
    - enough power is delivered to the load to provide the power needed for the stimulation or sending data back

$$PDL = R_L I_{out}^2 = \frac{V_{out}^2}{R_L}$$

Iout, *Vout*, and R_L are the output current, output voltage, and load resistance, respectively

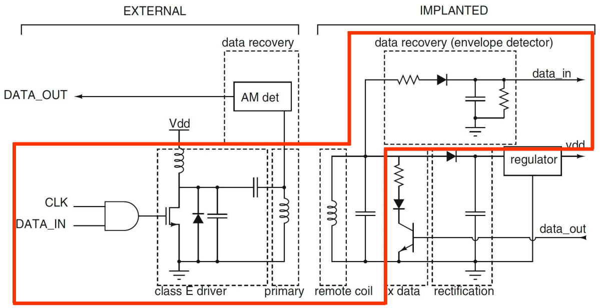
Modulation techniques

- The carrier signal (single tone) does not contain/carry any information
- Modulation by a source signal adds information to the carrier
- Analog vs. digital modulation depends on the nature of the source signal
  – Amplitude modulation (AM)
  – Frequency modulation (FM)
  – Phase modulation (PM)

  – Note that, modulation techniques are well-established techniques and are described using a rigorous mathematical apparatus. In the following, we take a practical approach of the topic

Classical bio-telemetry link (1)

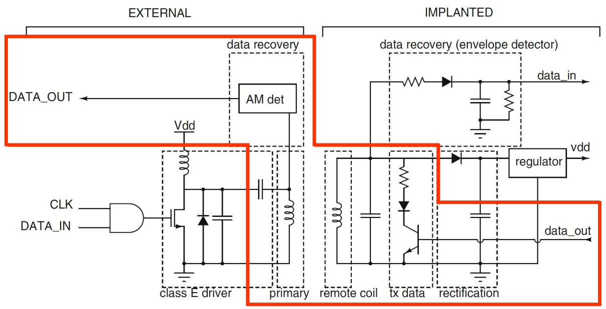
- Fully inductive link, general scheme
  - Data is transferred from the primary to the remote coil by amplitude modulation (OOK = 100% ASK) of the power carrier. Demodulation at the remote coil is achieved by envelope detection of the carrier amplitude
  - To transmit data from the remote implant to the primary coil, the load current of the primary coil is modulated, by intermittently switching a load at the remote coil. Another possibility is intermittent detuning of the remote coil, causing a similar effect (load modulation) on the primary coil
  - Power transmission



Generalized circuit diagram of a class E inductive link system, with two-way communication

Classical bio-telemetry link (2)

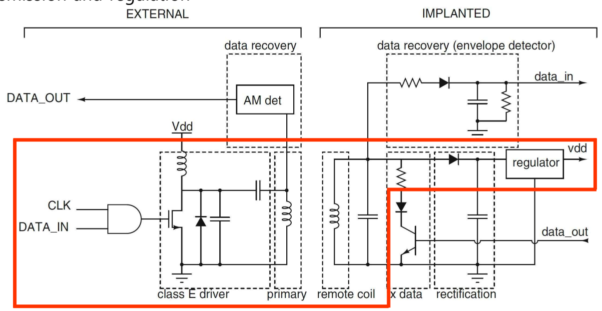
- Fully inductive link, general scheme
  - Data is transferred from the primary to the remote coil by amplitude modulation (OOK = 100% ASK) of the power carrier. Demodulation at the remote coil is achieved by envelope detection of the carrier amplitude
  - To transmit data from the remote implant to the primary coil, the load current of the primary coil is modulated, by intermittently switching a load at the remote coil. Another possibility is intermittent detuning of the remote coil, causing a similar effect (load modulation) on the primary coil
  - Power transmission



Generalized circuit diagram of a class E inductive link system, with two-way communication

Classical bio-telemetry link (3)

- Fully inductive link, general scheme
  - Data is transferred from the primary to the remote coil by amplitude modulation (OOK = 100% ASK) of the power carrier. Demodulation at the remote coil is achieved by envelope detection of the carrier amplitude
  - To transmit data from the remote implant to the primary coil, the load current of the primary coil is modulated, by intermittently switching a load at the remote coil. Another possibility is intermittent detuning of the remote coil, causing a similar effect (load modulation) on the primary coil
  - Power transmission and regulation



Generalized circuit diagram of a class E inductive link system, with two-way communication

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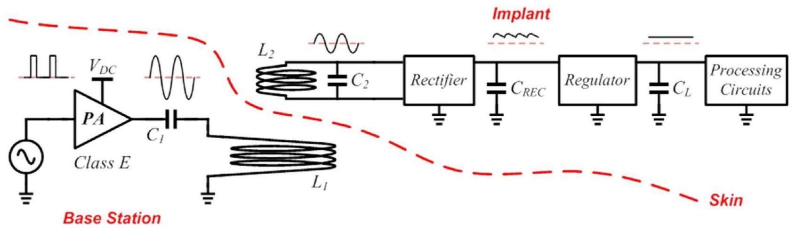
Wireless power transmission chain, and receiver power control chain

- Full-system architecture of an inductive power transmission system



- Link power efficiency

$$\eta_T = \eta_{PA} \times \eta_k \times \eta_{REC} \times \eta_{REG}$$

where $\eta = P_{OUT}/P_{IN}$ is the power efficiency of each individual consecutive stage in the chain

in the following, we study each individual element of the power transmission chain

(Homework HW02)

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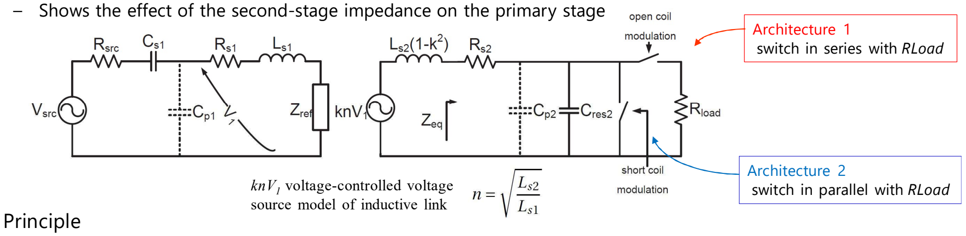
Load modulation principle

- Reflected impedance model
  - Shows the effect of the second-stage impedance on the primary stage



- Principle
  - One unique switch is placed parallel or in series with the load that allows changing/modulating the value of the load
  - Data-bits control the switch state (open/close)
- Architecture 1: the switch is in series with R_{load}
  - Switch is closed: no effect of the switch (neglecting the resistance R_{on} of the switch)
  - Switch is open: R_{load} is disconnected (neglecting the parasitic capacitors of the switch)
- Architecture 2: the switch is in parallel with R_{load}
  - Switch is closed: R_{load} is shortened (neglecting the resistance R_{on} of the switch)
  - Switch is open: no effect of the switch (neglecting the parasitic capacitors of the switch)

Load modulation, *V1* at the primary side and High/Low States

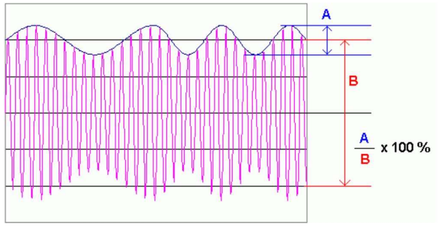
- Changing the position of the secondary-stage switch induces a change in the secondary-stage load
- Consequently, two different reflected loads Z_{ref} show at the primary stage
  - Voltage *V1* (primary) reflects the change of the load R_{Load} (secondary)
  - A high (higher) amplitude of *V1* (primary) yields a "High State" V_{1H}
  - A low (lower) amplitude of *V1* (primary) yields a "Low State" V_{1L}
- Z_{refH} and Z_{refL} are two reflected impedances that correspond to the secondary-stage switch open or closed, considering Architecture 1 or Architecture 2
  - Numerical component values are used to determine *V1* and the switch position that corresponds to a High State and a Low State

Load modulation, Modulation index

- A modulation index can be defined
  - In voltage MI_V or current MI_C domains

$$MI_V = \frac{V_H - V_L}{V_H + V_L}100\% \qquad MI_C = \frac{I_H - I_L}{I_H + I_L}100\%$$

  - The modulation index is an expression of the difference between the High State and Low State
  - Example, considering ASK modulation



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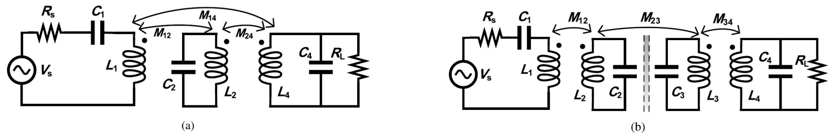
Non-radiating EM field: (inductive) magnetic resonance coupling (NRMRC)

- Non-radiative inductive coupling (NRIC) relies on magnetic coupling of the two coils
  - The NRMRC technique uses three or four coil-based architectures, not just two as in inductive coupling
- Improvement with respect to the inductive link (NRIC)
  - Better impedance matching capability to optimize the system power transfer
  - Higher Q-factor
    - compensates for the sharp decline of PTE caused by the reduced coupling coefficient due to the increasing separation distance
  - Higher bandwidth of operation
- Architectures



Single inductive link equivalent circuit with (a) one or (b) two additional resonators

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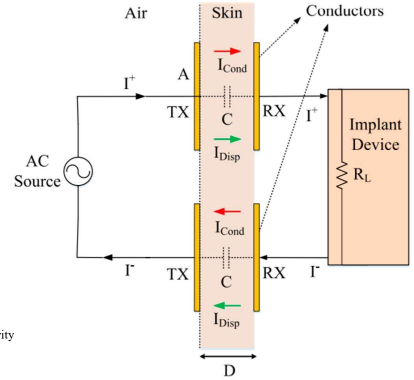
Near-field coupling, non-radiating EM field: capacitive coupling (NRCC)

- The coupling system consists of
  - a pair of conductors placed on each side of the skin, of area *A* and separated by a distance *D* (< 5 mm) and connected to the implant device with a load resistance R_L
  - a second pair of conductors creates a current closing loop
- Energy transfer
  - Time-varying electric fields produced by the transmitting metal TX support displacement currents I_{Disp} that enable wireless transfer of energy to an implanted RX
  - However, conduction currents I_{Cond} are induced in the skin and the surrounding tissues

$$\mathbf{I}_{\text{disp}} = \varepsilon_0 \varepsilon_r(\omega) A \frac{\partial \vec{E}}{\partial t} \qquad \mathbf{I}_{\text{cond}} = \frac{V(t)\sigma(\omega)A}{D}$$

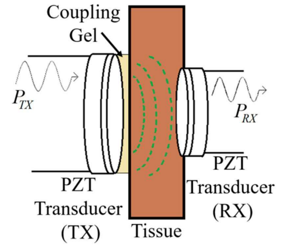
ε0 is the permittivity of free space and εr(ω) and σ (ω) are the frequency-dependent relative permittivity and conductivity of the medium between the pair of conductors, respectively



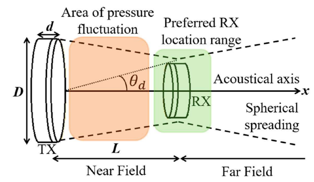
- Usage
  - Telemetry system using digital modulation techniques, such as frequency shift keying (FSK) or binary phase shift keying (BPSK)
  - Power transmission is only in early stages of study

Ultrasound coupling, acoustic power transfer

- APT (acoustic power transfer) uses a pair of piezoelectric transducers to transfer energy in the form of ultrasound waves through tissue to an implanted device where it is converted to electric power
  - TX ultrasonic oscillator is outside the body: produces surface vibrations resulting in acoustic pressure waves in the frequency range of 200 kHz to 1.2 MHz
  - The pressure field is directed towards the RX transducer
  - The RX is implanted and converts acoustic energy to electrical energy



- Location of the receiver
  - Near field, closest to the TX transducer
    - the pressure field envelope oscillates in this zone resulting in several minima and maxima of power.
  - Far-field
    - The pressure field behaves as a smooth spherically spreading wave decaying with increasing distance
  - Transition between near and far fields
    - the beam waist of the acoustic beam is at its smallest
    - preferred location where the RX should be installed



$$L = \frac{(D^2 - \lambda^2)}{4\lambda} \approx \frac{D^2}{4\lambda}, D^2 \gg \lambda^2 \qquad \theta_d = \sin^{-1}\left(\frac{1.22\lambda}{D}\right)$$

D is the aperture width of TX and λ is the wavelength (acoustic, in the tissue) and θ is the divergence angle

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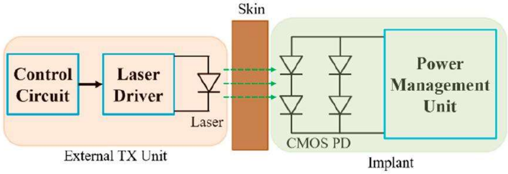
Optical power transfer

- An external TX unit is used to power the implant utilizing an external laser
- The laser light is received and converted to electric power by a CMOS photodiode (PD) array embedded under the skin



- The maximum output power is claimed to be 168 μW for a 500 x 500 μm^2 PD array
- Thus, a small power transfer efficiency with respect to the large silicon area

- New techniques under study
  - Near-infrared wavelengths
  - Photovoltaic technique

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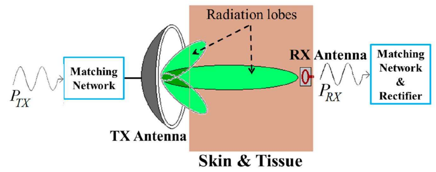
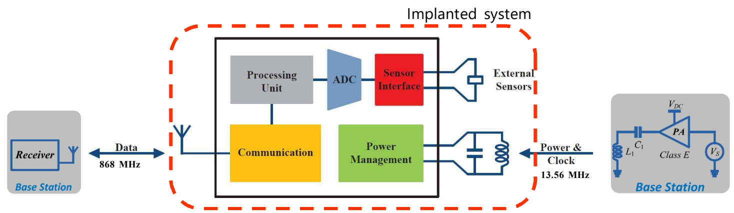
Radiative far-field (RFF) coupling

- Radiative far-field (RFF) WPT relies on electromagnetic coupling of an RX antenna positioned at a large separation distance ($d >> \lambda$) from the TX antenna
  - Recent in the biomedical field
  - Transfer technique demonstrates robustness against misalignment of the TX and RX coils
- Method
  - The radiated fields are modeled as plane waves with electric and magnetic field components as E_θ and H_φ respectively
  - The radiated field is incident on the matched RX antenna and generates a current across the RX antenna terminals



Dual frequency transfer method

- Dual frequency approach, one frequency for remote power and another one for data communication
  - Power transfer is independent of data communication
  - Extra power is required due to the active transmitter of the sensor node
  - An extra antenna is used for data communication

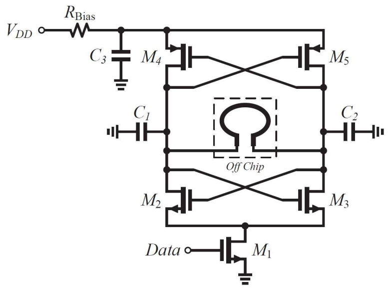


Example of far-field medical communication system with dual-frequency data and power transmission

- Major blocks
  - Implant: remotely powered IC (integrated circuit), discrete-component or integrated sensors and antennas
  - External base station, transceivers ,antennas, control circuits

Implanted active data transmitter

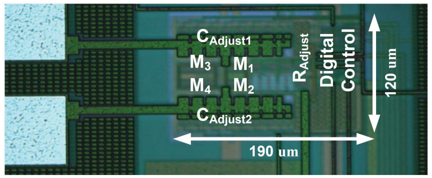
- Free-running LC-tank oscillator
  - LC cross-coupled pair oscillator (M_2-M_3)
  - Off-chip inductor used as radiating antenna
  - Oscillation frequency is determined by C_1, C_2 and the off-chip inductive antenna
  - Resistive loss (finite Q of C and L) compensated by the negative resistance of the MOSFETs cross-coupled pair



Free-running LC-tank oscillator schematic

Spcification	Design value
Center frequency	868 MHz
Modulation	OOK
Power	144 μ W
Supply	1.3 V
Data rate	1.7 Mbps
Turn-on time	< 10 ns
Frequency drift	< 1 MHz
Fabrication technology	180 nm

Design of the circuit: Homework #4

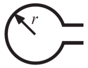


Free-running LC-tank oscillator microphotograph

Loop antenna design

- Selection of the appropriate frequency
  - Frequency band in ISM
  - Considering the transmission of electromagnetic waves in free space, the path loss is proportional to the square of the carrier frequency according to Friis equation
  - At fixed antenna size, the radiation efficiency improves as frequency increases. Equivalently, the capacitor of the LC tank should be minimized

- Antenna efficiency
  - Assuming that the antenna is isotropic, which means that it radiates the same intensity in all directions, then the gain of the antenna G_T can be approximated by the efficiency η_{ant}



$$\eta_{ant} = \frac{R_{rad}}{R_{loss} + R_{rad}} \qquad R_{rad} = 20\pi^2 \left(\frac{2\pi r}{\lambda}\right)^4$$

$$R_{\text{loss}} \approx \frac{r}{r_o \delta \sigma}, \quad \text{if } r_o \gg \delta$$

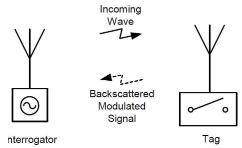
R_{rad} (radiated resistance) and R_{loss} (radiated loss) model power radiation and losses of the antenna, respectively
λ is the is the wavelength of the radiated signal
r is the coil radius
r_o, σ and δ are the cross-section radius, conductivity, and skin depth of the wire, respectively

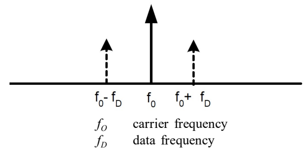
  - For a fixed antenna size r, R_{rad} increases with the carrier frequency
  - However path loss and body tissue absorption losses are also higher at higher frequencies
  - Therefore, the optimum operation frequency depends on how deep the implant is inside the body and the size of antenna

(Homework HW04)

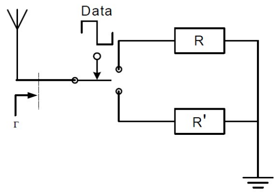
Principle of the backscattering data communication

- The RF carrier is generated in the interrogator also called reader (transmitter side)
- The tag, also called transponder, modulates and re-radiates the RF carrier that originates from the reader upon occurrence of a high impedance mismatch
- The power consumption of the tag is minimized because it does not include an RF oscillator to generate the carrier





- Block-level system
  - **If Data = Bit "1"**
    - $Zin = R'$ is not matched to the tag antenna
    - All the power of the RF incoming signal is reflected to the interrogator
  - **If Data = Bit "0"**
    - $Zin = R$ is matched to the tag antenna
    - All the power of the RF incoming signal is absorbed by the tag

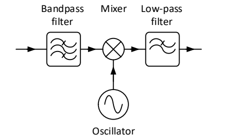


Outline of the course

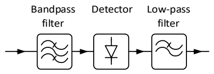
- Implantable biomedical devices: system architecture and examples
  - Impedance matching
- NRIC (inductive coupling, power and data transmission)
  - Tx (transmitter)
    - Architecture and circuits
    - Analog and digital modulations, line encoding
  - Rx (receiver)
    - Active circuits
    - Inductive load modulation (passive)
- NRMRC (magnetic coupling, power)
- NRCC (capacitive coupling, power and data)
- Ultrasound coupling (acoustic power coupling)
- Optical coupling (power and data)
- Far-field telemetry (data)
  - Active Tx
  - Passive Tx: backscattering
  - Active receivers (non-coherent, super heterodyne, super regenerative)
  - Power receivers considerations

Receiver example, Non-coherent Receiver

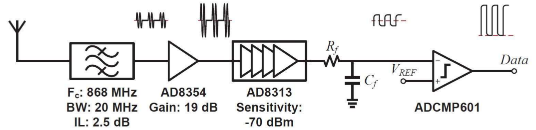
- Coherent receiver
  - Carrier recovery for demodulation; phase synchronization between the carrier of the received signal and the local oscillator is needed
- Non-coherent receiver
  - No carrier recovery for demodulation
  - Narrowband filters and envelope detectors are used to determine which frequency is received
  - Generally preferred due to an easier design
  - Poorer bit error rate than the coherent receiver system



Synchronous (coherent) receiver concept



Incoherent receiver concept

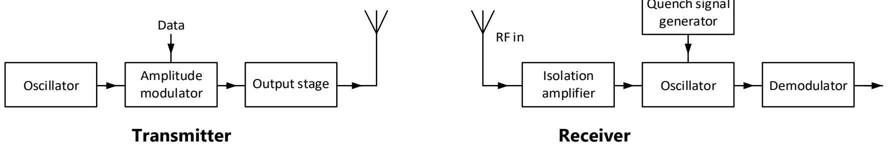


Block diagram of the non-coherent receiver used to receive and demodulate the data sent using the free-running LC-tank oscillator transmitter (OOK)

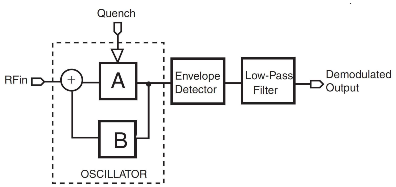
Band-Pass filter: 4DFB-860D-10, TOKO; Centered freq. of 868 MHz, large -3dB bandwidth (BW) of 20 MHz, Insertion loss of 2.5 dB (IL, loss of the signal travelling through the block)
Amplifier AD8354: gain of 19 dB
Logarithmic amplifier AD8313; similar to an envelope detector; the sensitivity corresponds to the minimum detectable signal; - 70 dBm of sensitivity corresponds to 0.1 nW
Comparator ADCMP601; 100 mV build-in hysteresis to avoid noisy transition

Super-regenerative receiver architecture

- Architecture of the transceiver



- Operation principle
  - Based on the variation of the start-up time of an oscillator which depends on the RF input signal
  - The gain *A* of the amplifier is controlled by a quench signal
  - *B* is a band-pass filter
  - The oscillation signal is periodically suppressed by the quench signal

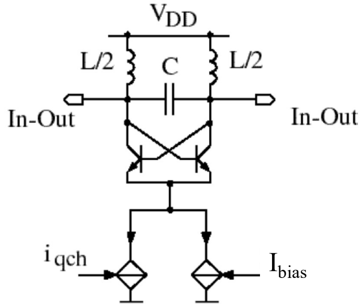


Super-regenerative oscillator, operation principle

- Upper section
  - High-Q LC resonator for low current
  - Differential inputs and outputs
  - Admittance presented to the resonator $Y = - gm / 2$
  - The losses of the LC resonator are equivalent to a positive conductor g_{pos}
- Middle section
  - Cross-coupled pair of bipolar transistors
- Lower section, biasing
  - Quench signal, ac current source i_{qch}
  - Bias current source I_{bias}
  - Total current $I_{tot} = i_{qch} + I_{bias}$

$$g_{neg} = -\frac{i_{qch}}{4U_T} - \frac{I_{bias}}{4U_T}$$

- Oscillation criteria
  - The resistance loss in the LC is compensated by the cross-coupled pair
  - Definition of the critical current (condition) $g_{pos} + g_{neg} = 0$



(Homework HW05)

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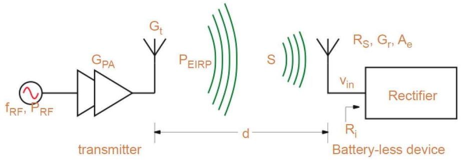
  - Passive Tx: backscattering
  - Active receivers (non-coherent, super heterodyne, super regenerative)
  - Power receivers considerations

Power transmission in far field: Maximum available input power

- Expression of the maximum power using Friis Transmission Relation

$$P_{AV} = S.\frac{\lambda^2}{4\pi}.G_R = P_{EIRP}.G_R.\frac{\lambda^2}{(4\pi d)^2}$$



- Practical example
  - 2.45 GHz
  - λ = 0.1224 m
  - P_{EIRP} = 4 W
  - Antenna gain: G_R = 1 (0 dB)

d(m)	P_{AV}(W)
1 m	379 μW
5 m	15.17 μW
10 m	3.79 μW
12 m	2.6 μW