Theoretical Model for Maximum Throughput of a Radio Receiver with Limited Battery Power

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Where innovation starts

Receiving a signal consumes more power than transmitting it…

Radio systems transmit over shorter and shorter distances

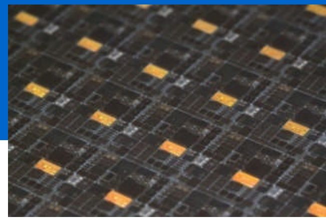
- 1904 Marconi: across the Atlantic
- AM radio (200 km: 2,000,000 watt)
- FM radio (50 km, 50,000 watt)
- 1980 Cellular radio (3km, 10 watt)
- 2000 WLAN (10 meters, 0.1 watt)
- 2010 Body area Network (1 meter, 0.01 watt)

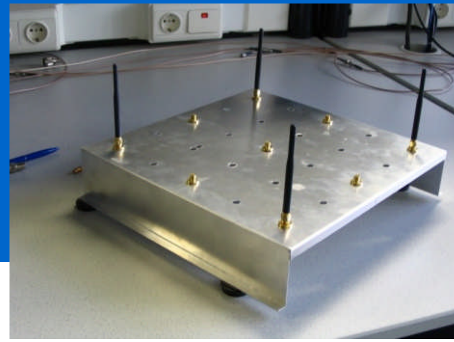
Path loss is no longer a limitation to performance, radiated power is becoming very small

Power consumption in RX is due to

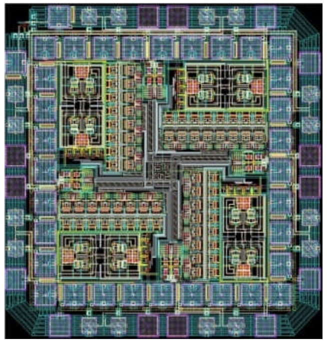
- Signal amplification, mixing, ADC, digital processing,
- Receivers needs to be in standby
- Increasing neighboring channel interference

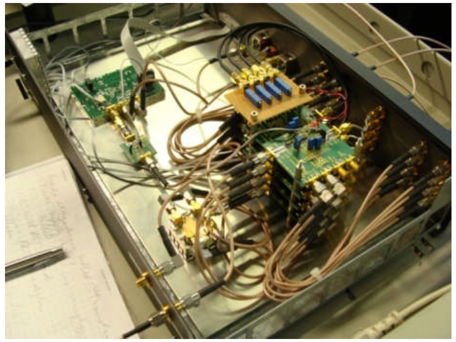
Project Mimo for a mass market
IOP Gencom

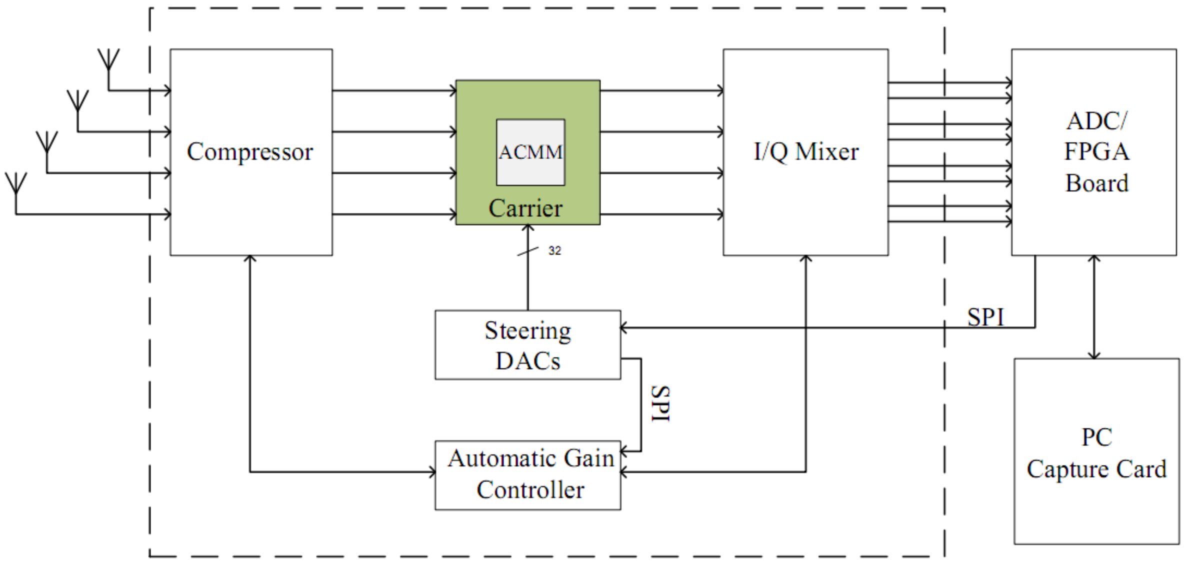


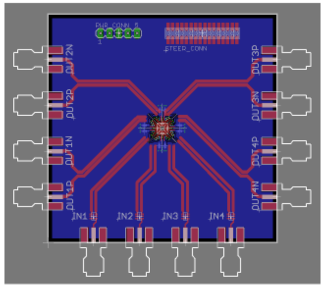


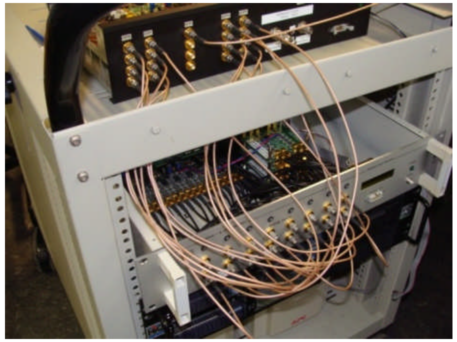
Scientific Innovations in
- Handling interference in crowding bands
- Reducing power consumption by analog matrix operations

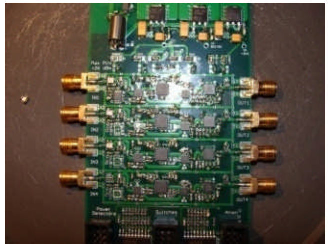






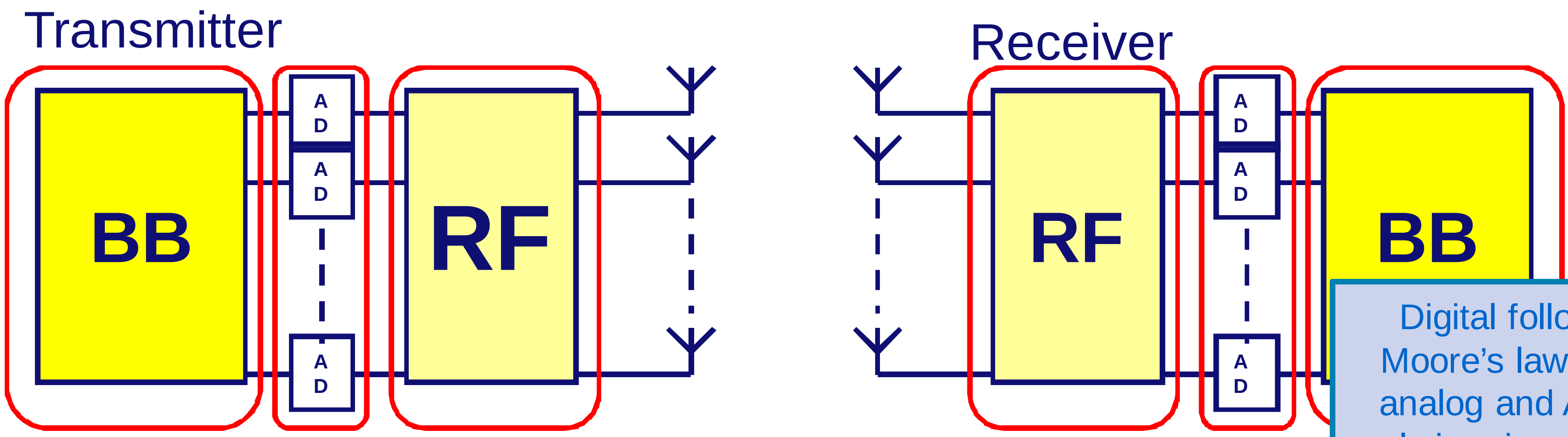






Power trends in the wireless link

Example for cell phones



Digital follows Moore's law, but analog and ADC only imprive slowly

Power per antenna

Current "in the shop" equipment	300mW	300mW	600mW	300mW	300mW	300mW
Current "state of the art" equipment	300mW	300mW	500mW	100mW	300mW	300mW
Expected in five years time due to trends	30mW	120mW	400mW	50mW	120mW	30mW

Still large for cellular radio, but small for sensor networks

Our Focus Now

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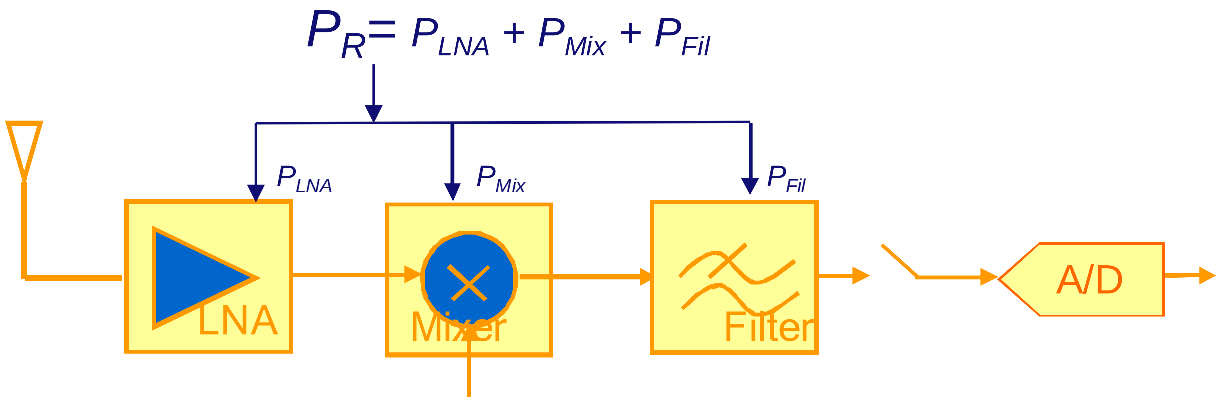
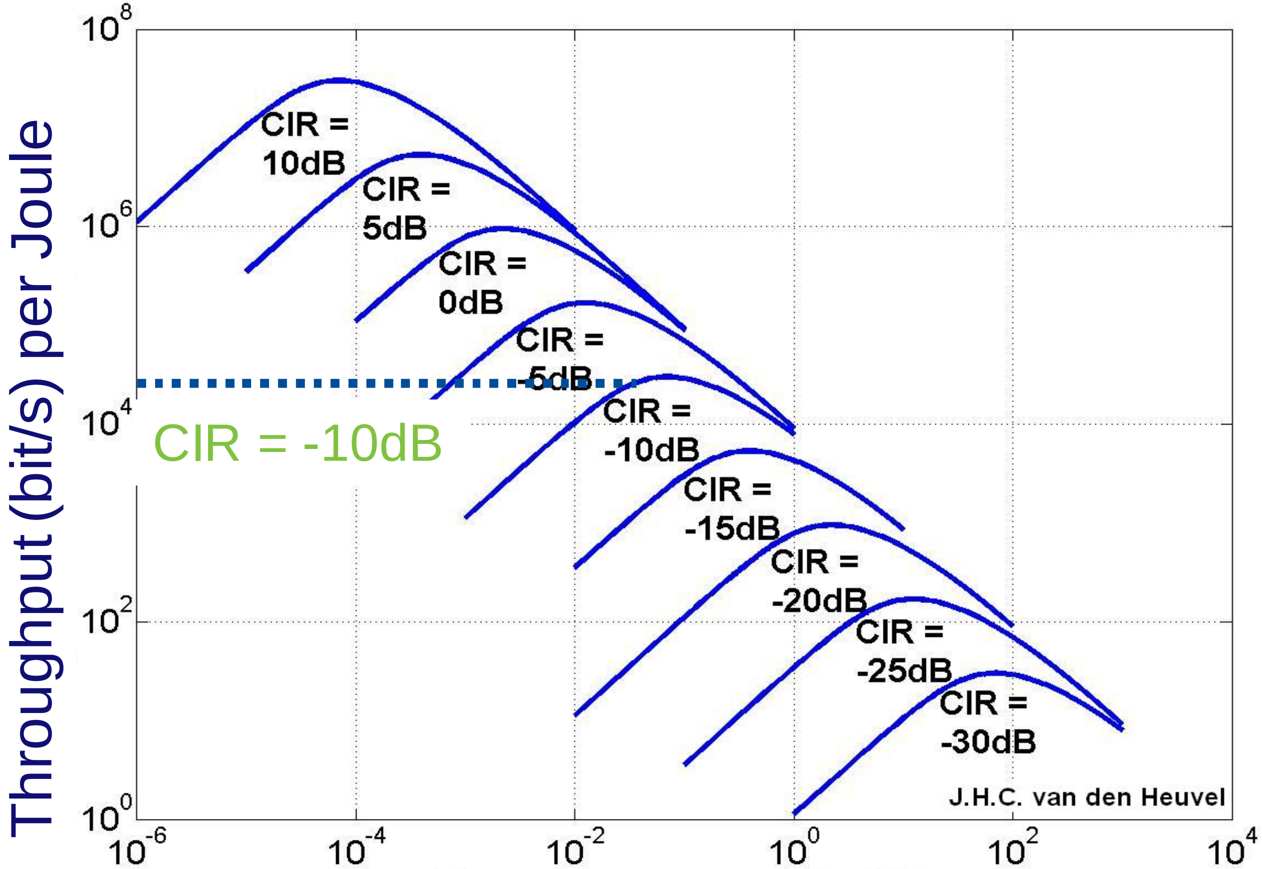
Low power receiver design challenge



What is the best circuit power allocation in order to achieve the highest information throughput (bits) per Joule of energy <u>consumed in the receiver</u> ?

Throughput per Joule that a receiver can achieve while consuming a certain circuit power



Continuous circuit power assigned to receiver, optimally distributed over various stages

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Objectives

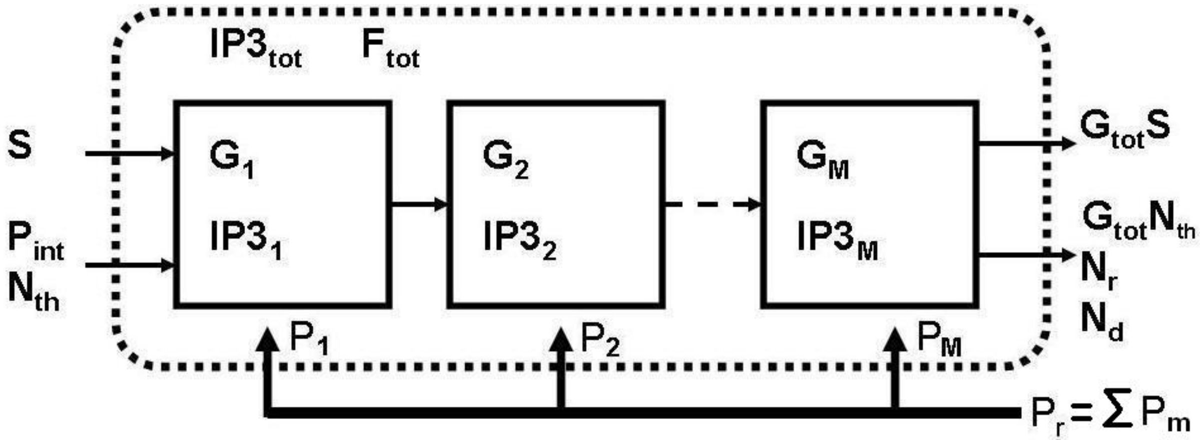
Tradition design paradigm:

- Find the minimum power that achieves the required overall gain, IP3, noise factor
- Typical noise factors and good topologies are common knowledge in RF CMOS design
- Find out what the best gain & IP3 settings per stage are

Our new paradigm:

- Find the optimum throughput *T* per joule of consumed receiver power *Pr*
- In this optimum, the IP3 and gain setting are the best possible choice for that power *Pr*

Maximizing throughput by adjusting receiver IP3, F and G settings



$$\hat{T} = \max T$$

$$T = \log_2\left(1 + \frac{S}{N_{tot}}\right)$$

$$N_{tot} = N_{th} + \frac{N_r}{G_{tot}} + \frac{N_d}{G_{tot}}$$

$$G_{tot} = \prod_{m=1}^{M} G_m$$ **Total power gain**

$$N_{th} = kTB$$ **Thermal noise**

$$N_d = \frac{G_{tot} P_{int}^3}{IP3_{tot}^2}$$ **Distortion noise**

$$N_r = (F_{tot} - 1) N_{th} G_{tot}$$ **Electronics noise**

Disclaimer for information theorists

Our “Capacity” is not Shannon capacity

Our “Capacity” is determined by

- Interference which is out-of-channel, but which sets high linearity requirements
- Limited by known RF front-end design topologies

NB: The throughput may exceed capacity, if optimum signal processing is achieved to cancel out-of-channel interference.

Considering the individual stages of the receiver

Linearity

$$IP3_{tot} = \left(\sum_{m=1}^{M} \frac{\prod_{j=1}^{m-1} G_j}{IP3_m} \right)^{-1}$$

Noise Figure

$$F_{tot} = 1 + \left(\sum_{m=1}^{M} \frac{F_m - 1}{\prod_{j=1}^{m-1} G_j} \right)$$

Circuit power consumption

$$P_m = \frac{f_m G_m IP3_m}{\kappa_m}$$ EFOM

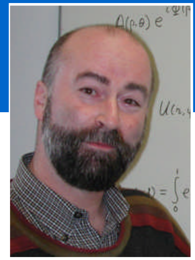
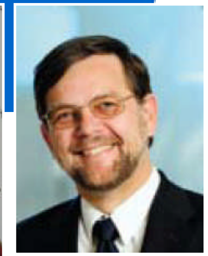
Circuits Library

Choose the circuit from a circuit library which best suits system requirements and has best κ_m

$$P_r = \sum_{m=1}^{M} P_m = \sum_{m=1}^{M} \frac{f_m}{\kappa_m} G_m IP3_m$$

The selection of gain settings and IP3's is considered to be an art.

Formal Solution for Minimizing Power

Derived by Jansen [Baltus, 2004]

Minimum Power Cascade Optimization

$$P_{\min} = \min \sum_{m=1}^{M} P_m = \min_{\substack{G_1,\ldots,G_M \\ IP3_1,\ldots,IP3_M}} \left(\sum_{m=1}^{M} \frac{f_m}{\kappa_m} G_m IP3_m \right)$$

Achieves the lowest-power implementation for a *given* required $IP3_{tot}$, F_1, .., F_M and G_{tot}

Leads to an analytical result for $IP3_{tot} = IP3_{tot}(F_{tot})$

$$P_{\min} = IP3_{tot} \left(\sqrt{F_e} + \sqrt{\frac{F_w}{F_{tot} - F_1}} \right)^2$$

$$F_w = \left(\sum_{m=1}^{M-1} \sqrt[3]{\frac{f_m}{\kappa_m} \left(F_{m+1} - 1 \right)} \right)^3$$

$$F_e = \frac{f_M}{\kappa_M} G_{tot}$$

Maximizing throughput

Maximum Throughput Cascade Optimization:

Use MPCO to express F_{tot} and $\mathrm{IP3}_{tot}$ as a function of power P_r :

$$\hat{T} = \max_{F_{tot}, IP3_{tot}} (T) \quad \leftarrow \quad \hat{N}_{tot} = \min\left(N_{tot}\left(I\hat{P}3_{tot}\left(F_{tot}\right)\right)\right)$$

Optimize F_{tot} and $\mathrm{IP3}_{tot}$ such that total "noise" N_{tot} is minimum for a fixed Pr

$$\frac{dN_{tot}}{dF_{tot}} = 0 \qquad \text{with} \quad IP3_{tot} = P_r\left(\sqrt{F_e} + \sqrt{\frac{F_w}{F_{tot} - F_1}}\right)^{-2}$$

At the optimum throughput….

At the optimum throughput, the noise factors become

$$N_{th} = kTB$$

$$\frac{N_r}{G_{tot}} = (F_1 - 1)N_{th} + \frac{4F_w N_{th}}{\left(-\sqrt{F_e} + \sqrt{F_e + 2^{5/3}\left(F_w N_{th} \frac{P_r^2}{P_{\text{int}}^3}\right)^{1/3}}\right)^2}$$

$$F_w = \left(\sum_{m=1}^{M-1} \sqrt[3]{\frac{f_m}{\kappa_m}(F_{m+1} - 1)}\right)^3$$

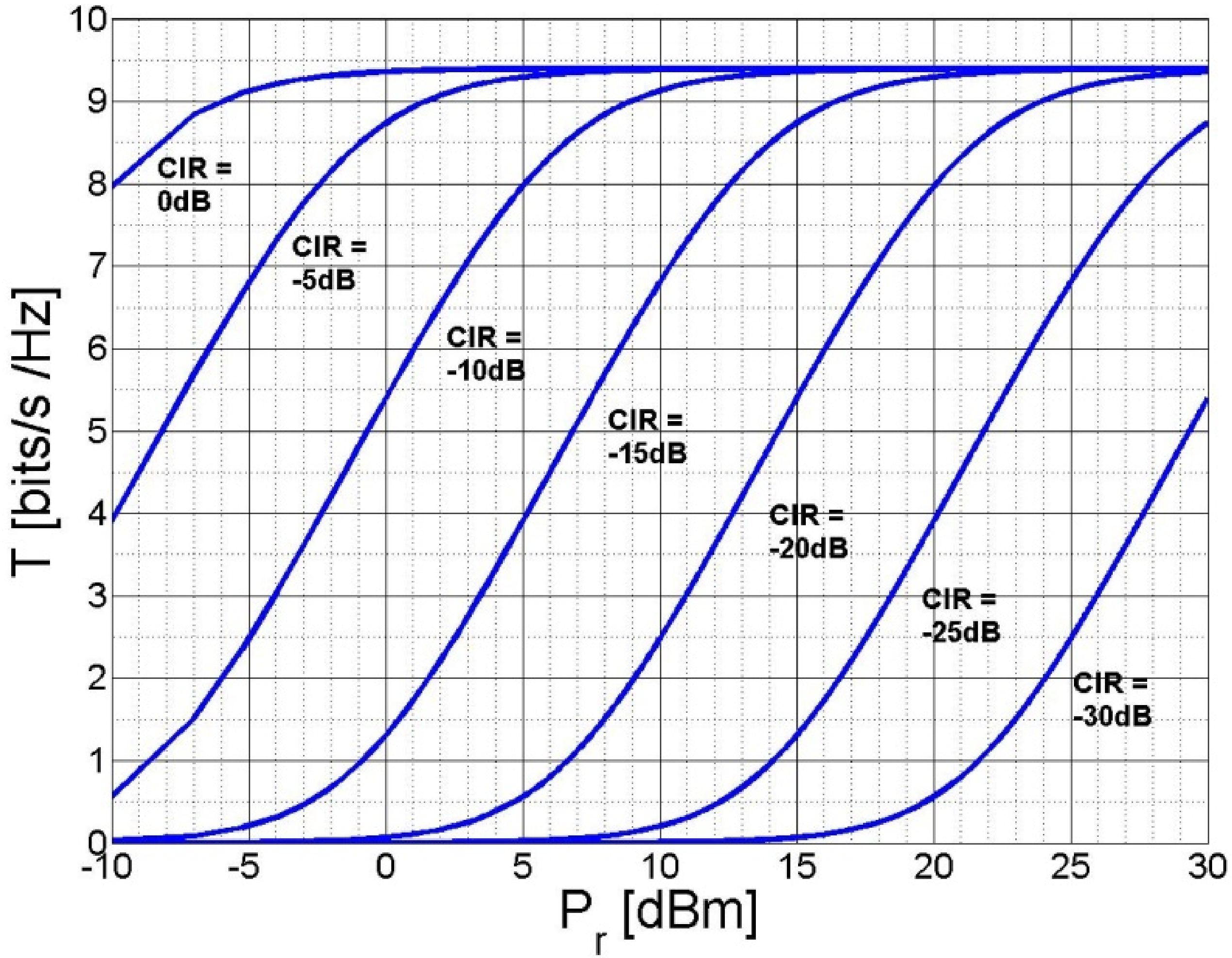
$$F_e = \frac{f_M}{\kappa_M} G_{tot}$$

$$\frac{N_d}{G_{tot}} = \frac{P_{\text{int}}^3}{P_r^2} \frac{1}{16} \left(\sqrt{F_e} + \sqrt{F_e + 2^{5/3}\left(F_w N_{th} \frac{P_r^2}{P_{\text{int}}^3}\right)^{1/3}}\right)^4$$

$$N_{tot} = N_{th} + \frac{N_r}{G_{tot}} + \frac{N_d}{G_{tot}}$$

$$T = \log_2\left(1 + \frac{S}{N_{tot}}\right)$$

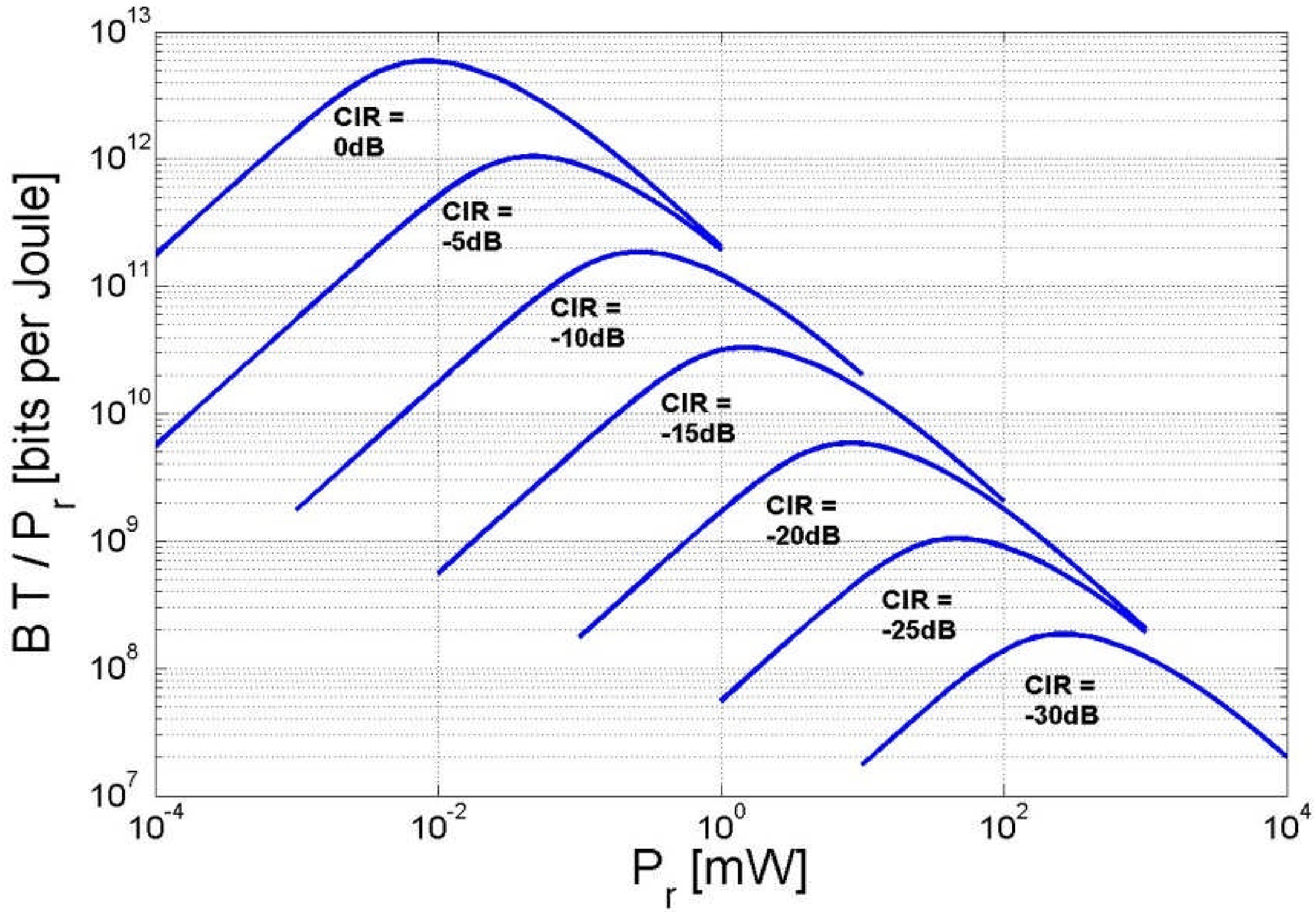
Throughput versus receiver power



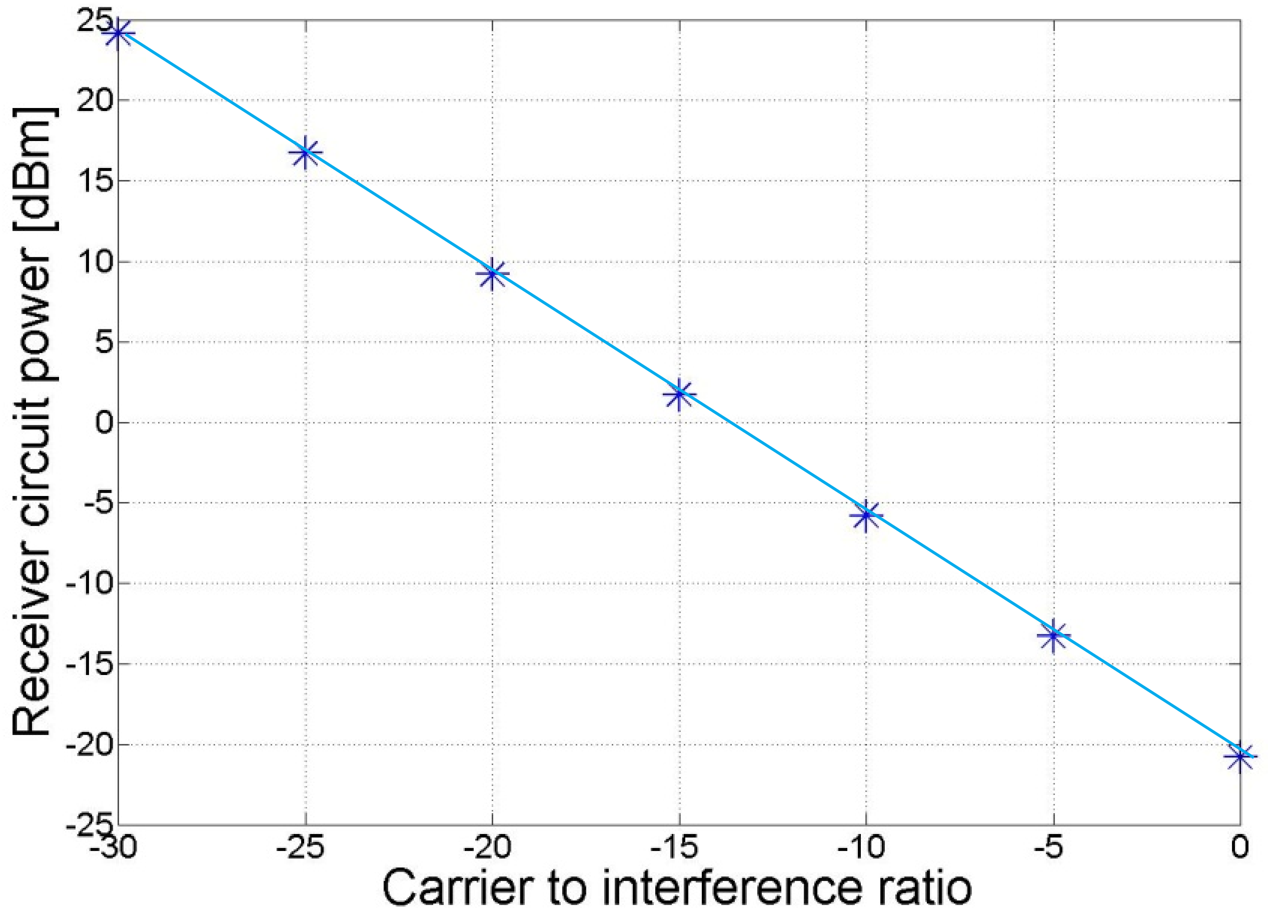
Large P_r: the system is limited by E_b/N_0. Here, 9.4 bit/sec.

Results

Then, optimize *Pr,* such that *T/Pr* is maximized



Optimum receiver battery power versus interference level

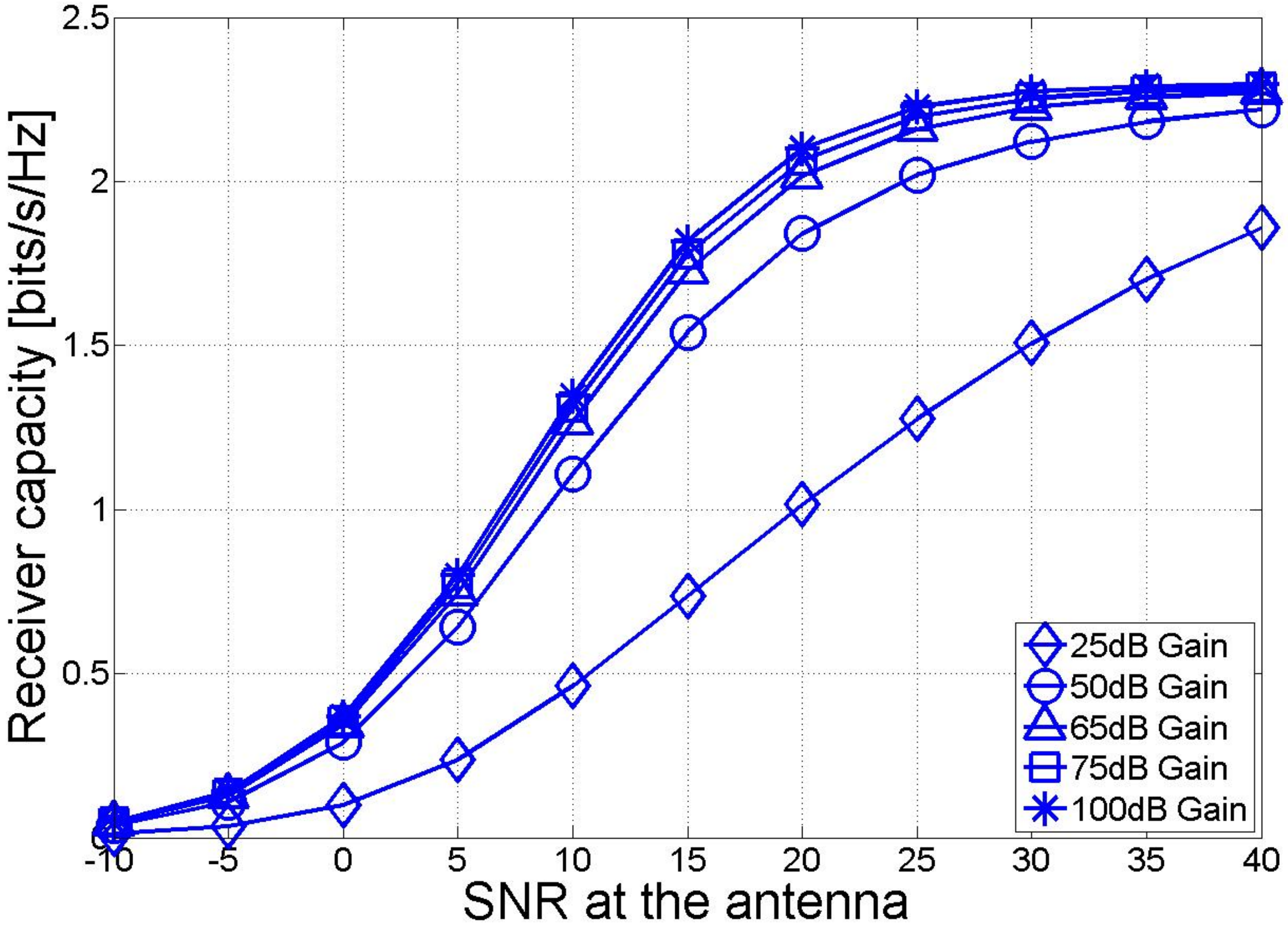


WLAN-like system, SNR = 30 dB.

IC Technology is CMOS C90 90 nm

What bit rate gives the highest throughput ?

For large SNR, the best transmission strategy is 2.29 bit/s



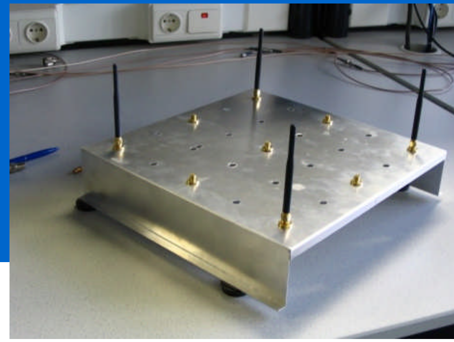
Related work

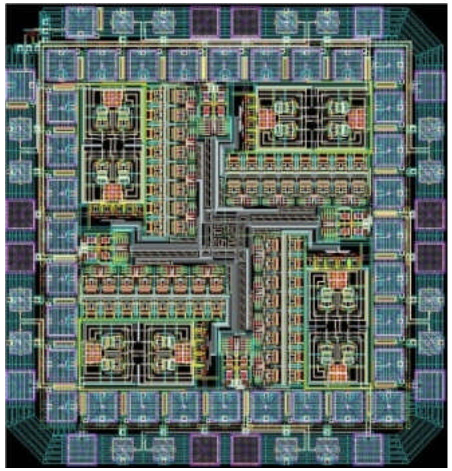
TU/e:

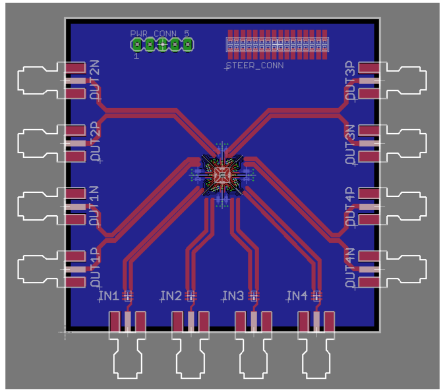
- RF Design of critical elements in adaptive receivers: analog nulling of interferers

UCLA, UC Berkeley:

- Reducing power consumption in Mimo system by nulling interferers







Conclusions

- For sensor networks, listening consumes more power than talking
- There are optimum strategies that minimize receiver circuit power.
- There is an optimum circuit power to be assigned to the receiver, given the amount of interference in neighboring channels
- For large SNR, the best transmission strategy is 2.29 bit/s
- Making the IP3 adaptive is still an IC design challenge

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