# TSTE85
# Low Power Electronics
# Lecture 11: RF Circuits

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# TSTE85 Course plan

- Introduction
- System level
- Algorithm level
- Architecture level
- Register transfer level
- Logic level
- Circuit level
- Synchronization
- Low power components
- Analog circuits (Guest lecturer: J Jacob Wikner)
- RF circuits (Guest lecturer: Ted Johansson)
- Special techniques

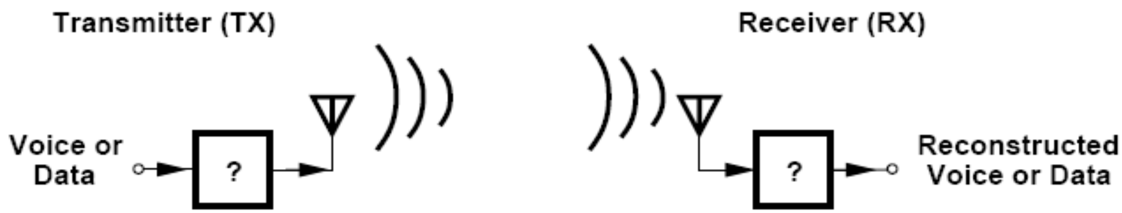
# Outline

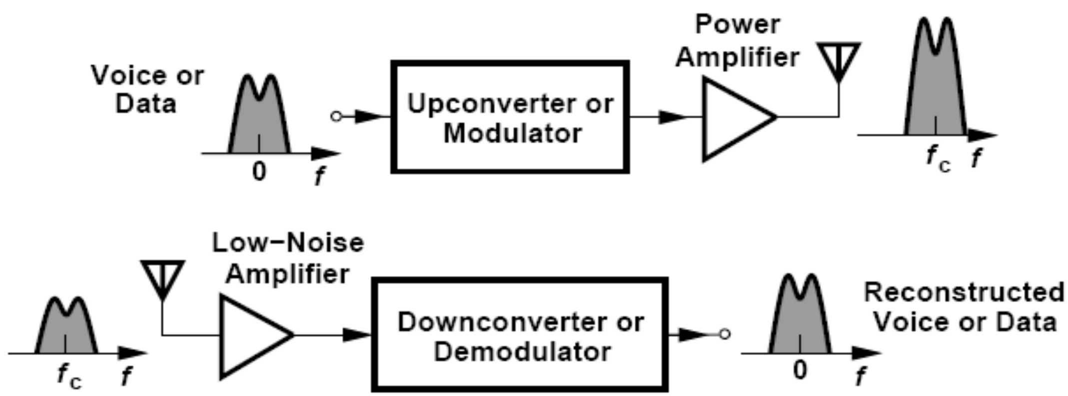
- Introduction: Basics of Radio Electronics
  - Transmitting the signal
  - The channel (link)
  - Receiving the signal
- Paper #1: Low-power radio for BAN
- Paper #2: Wireless power transfer

# The Big Picture: RF Communication

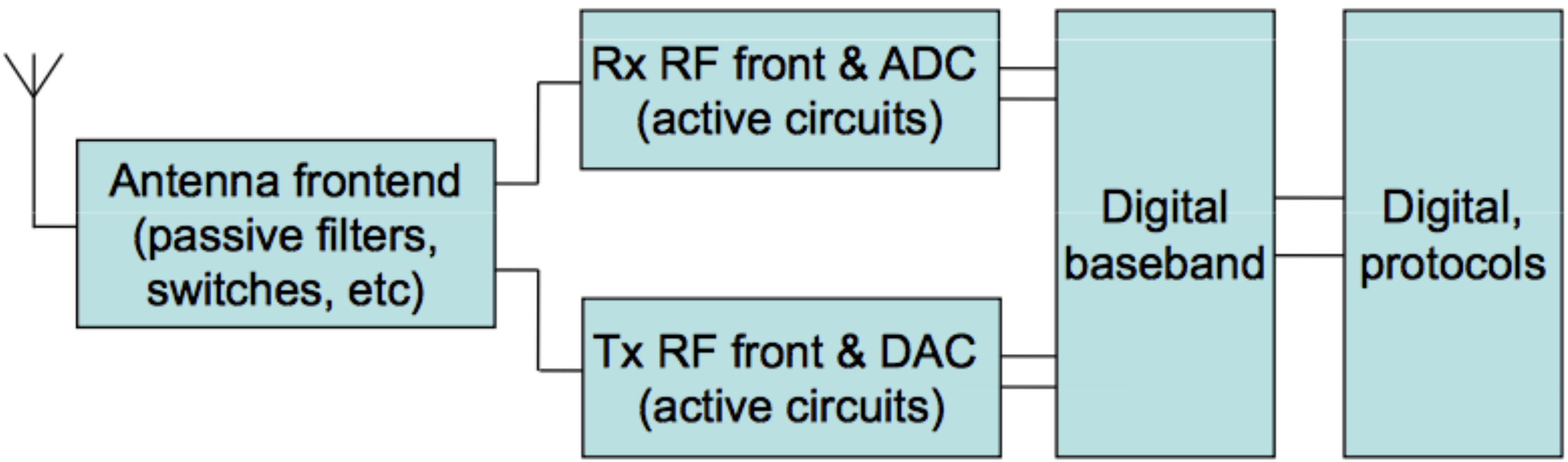
TX: Drive antenna with high power level

RX: Sense small signal (amplify with low noise)

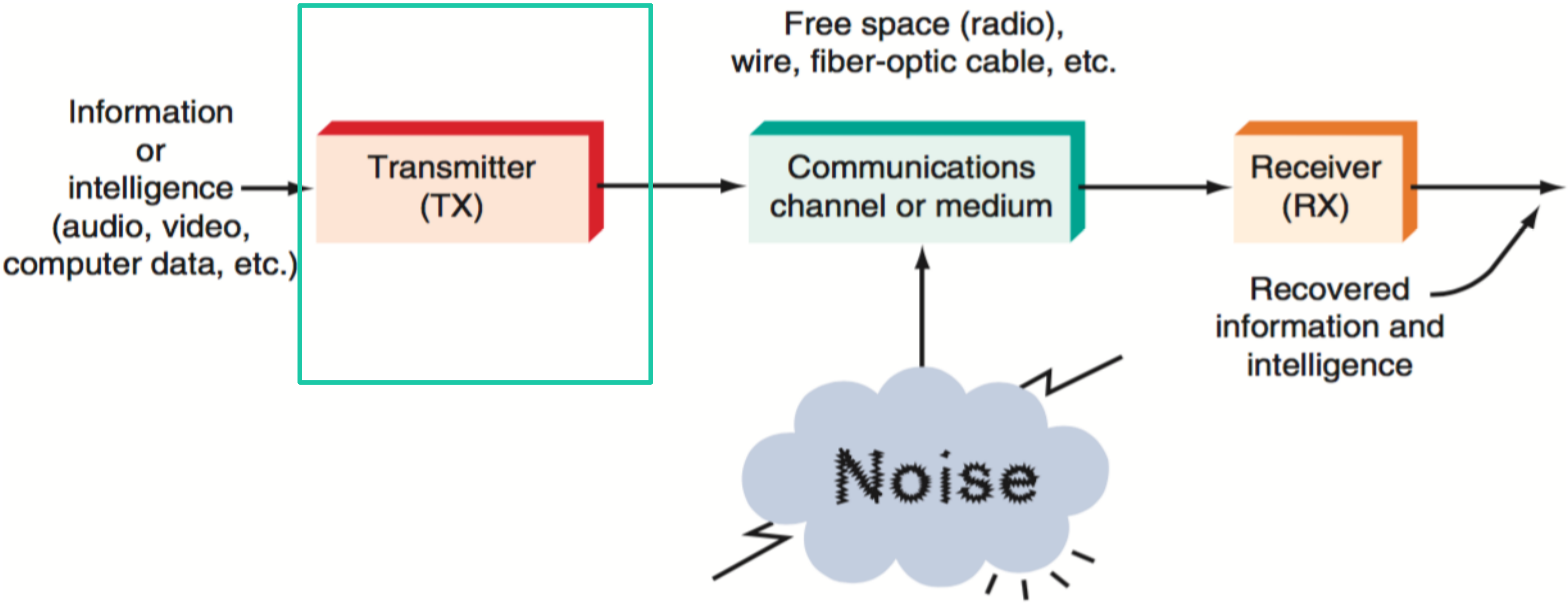


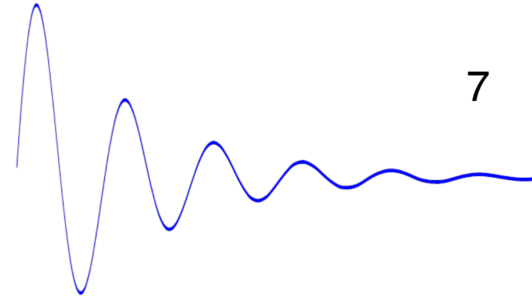
# Generic architecture of a transceiver



# Introduction: transmitting the signal

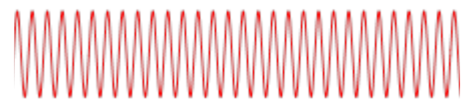


# What is Modulation?

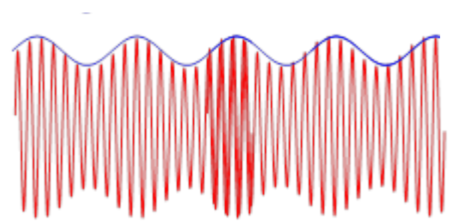


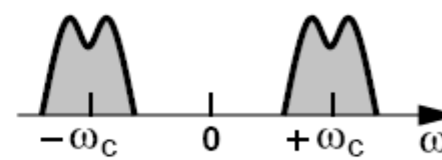
”Information signal” , f < $f_c$

”Radio Frequency signal” , f > $f_c$



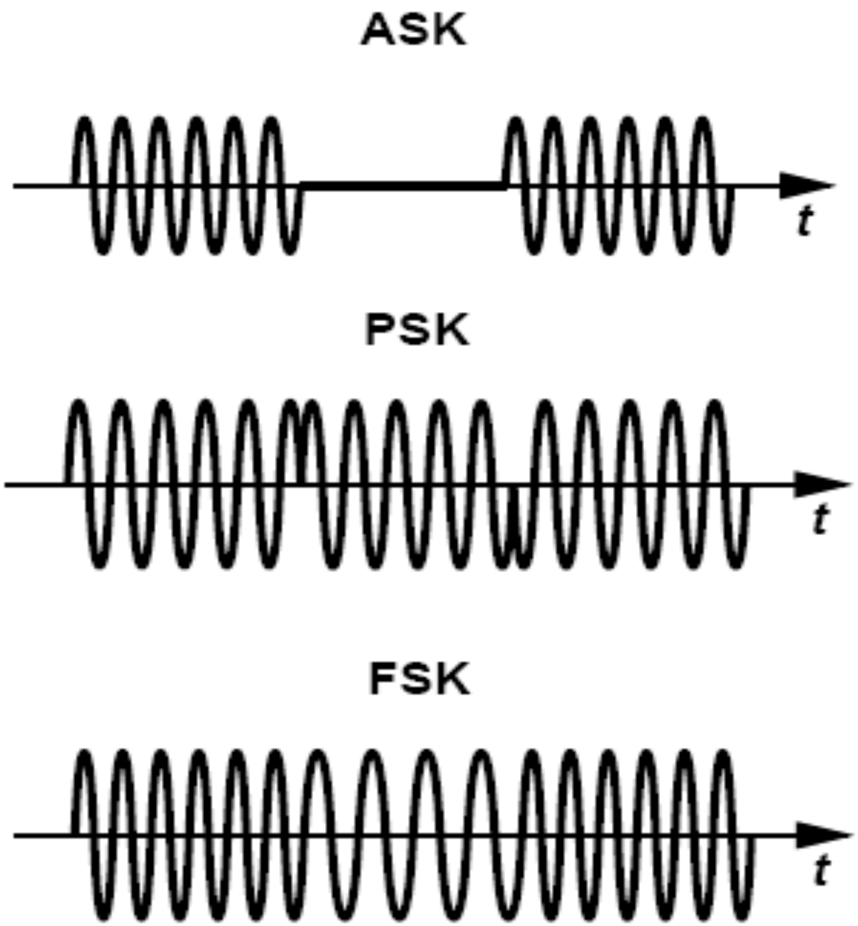
Modulation: carry the information signal on the radio frequency carrier



# Binary Digital Modulation






Binary Amplitude Shift Keying (ASK)

Binary Phase Shift Keying (PSK)

Binary Frequency Shift Keying (FSK)

# Frequency Conversion



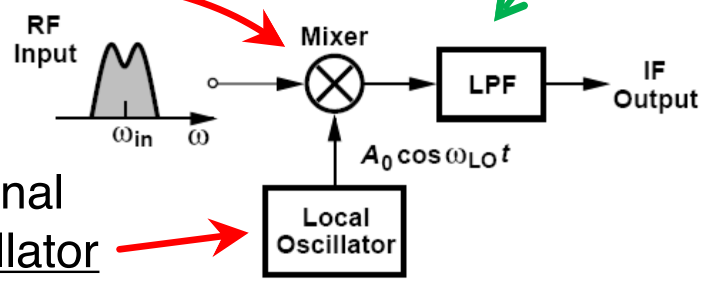
- Frequency of a signal can be shifted by multiplying it with another sinusoidal signal:

$x(t) = A\cos\omega_{in}t, \quad s(t) = \cos\omega_{LO}t$

$x(t) * s(t) = ½A*\cos(\omega_{in} - \omega_{LO}\, t)$ + ~~$½A*\cos(\omega_{in} + \omega_{LO}\, t)$~~

Multiplication is performed by a mixer

Low Pass Filter removes the high frequency signal




The other sinusoidal signal comes from a local oscillator

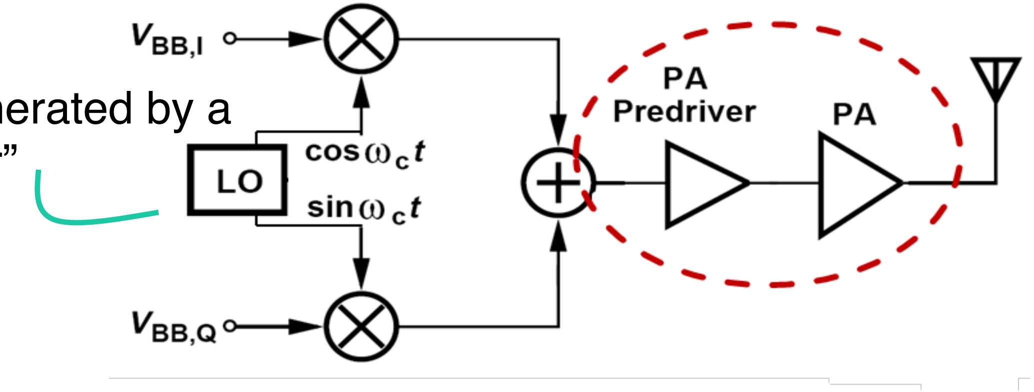
# Direct-Conversion Transmitter

- Most digital modulation schemes could be implemented by quadrature (IQ) modulators
- Power of the signal needs to be amplified so that the signal can reach the receiver

This architecture is called Direct-Conversion Transmitter

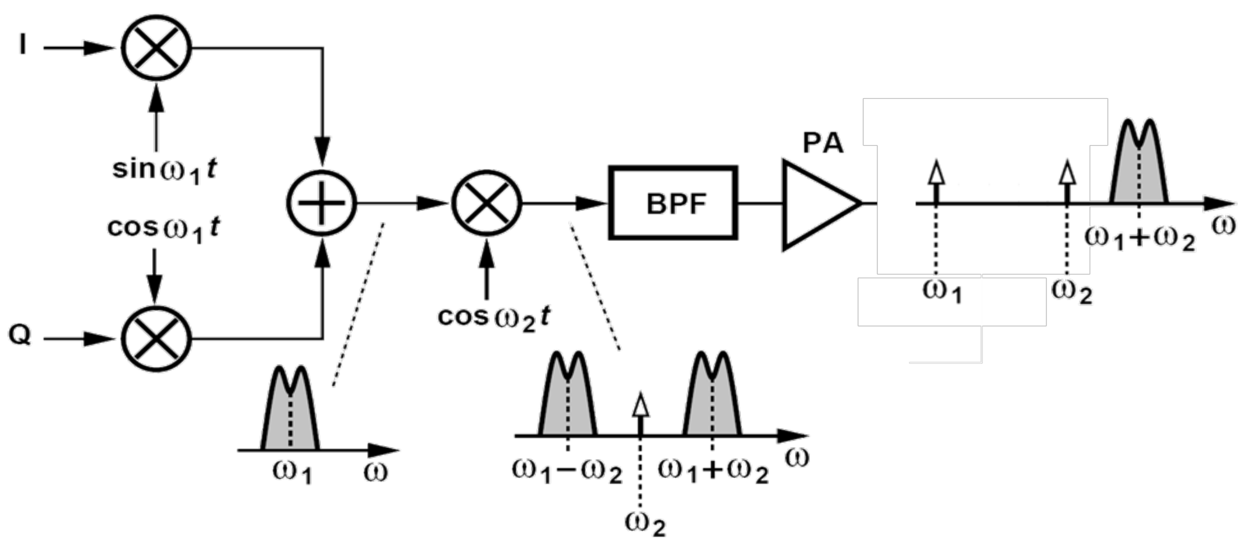
For practical purposes, amplification may be performed in several stages

Carriers are generated by a ”Local Oscillator”



# Two-step Conversion Transmitter

- In this architecture, we intentionally do not choose carrier frequency of the quadrature modulator to be the final transmission frequency, and perform a second frequency up-conversion by $\omega_2$
- We call $\omega_1$ the intermediate frequency (IF)





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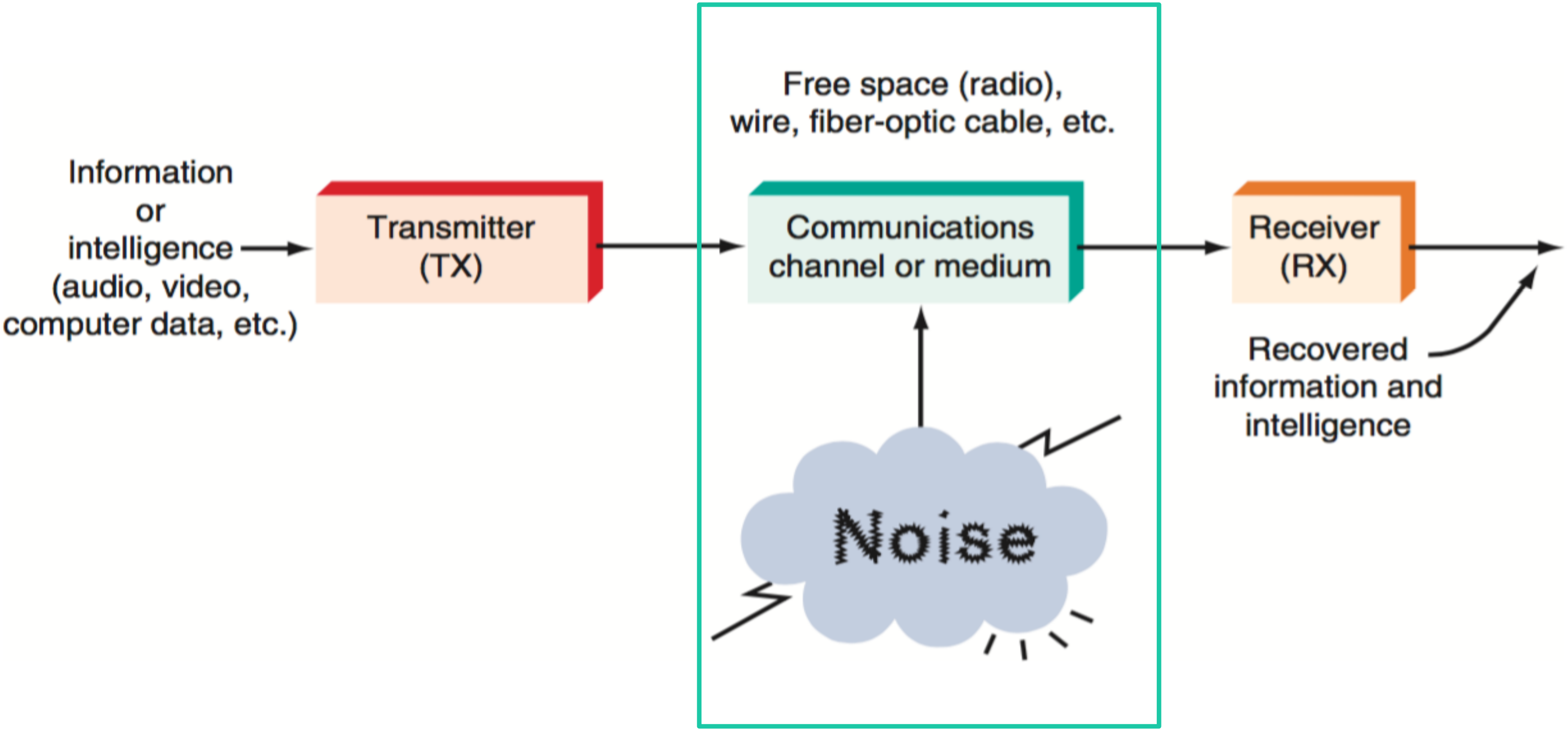
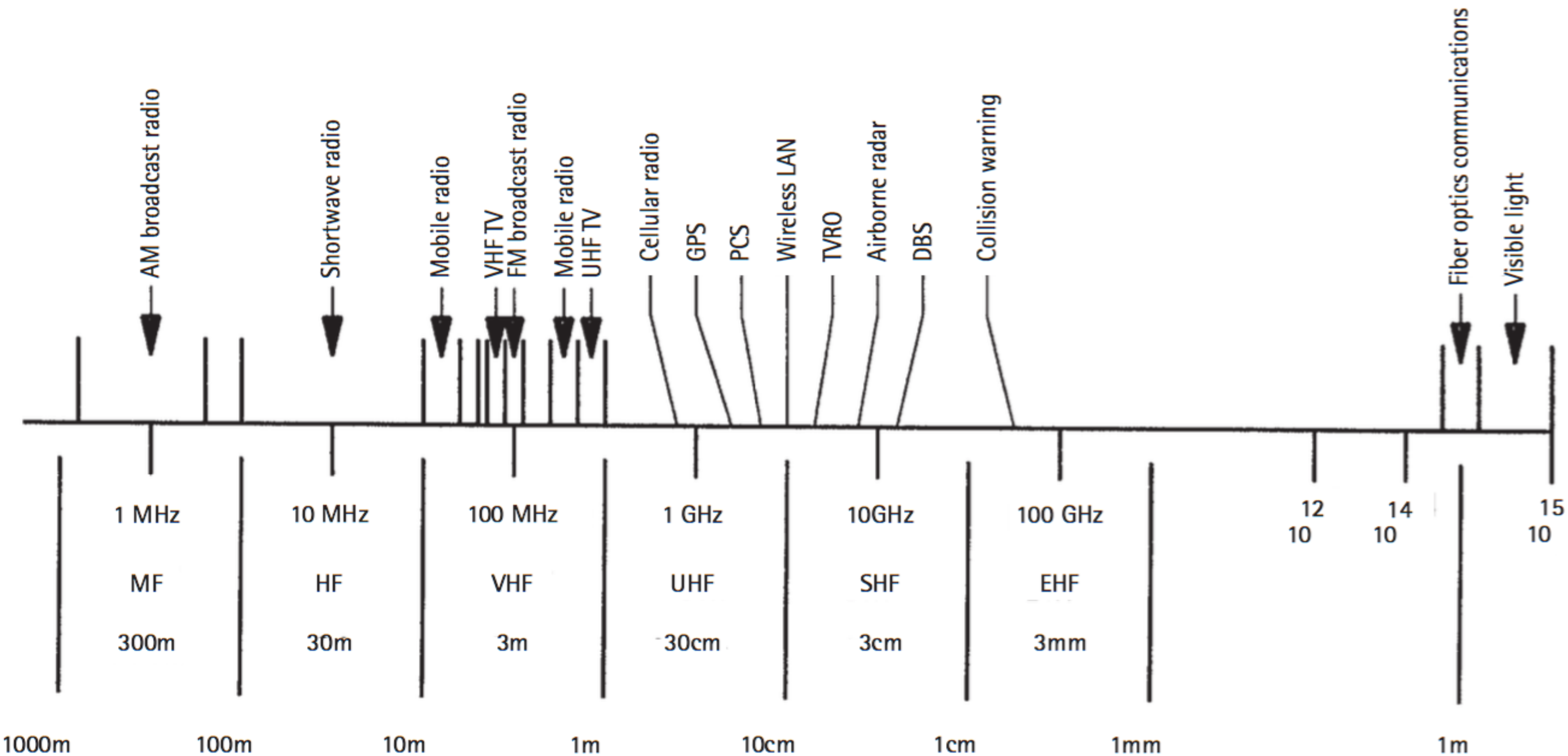
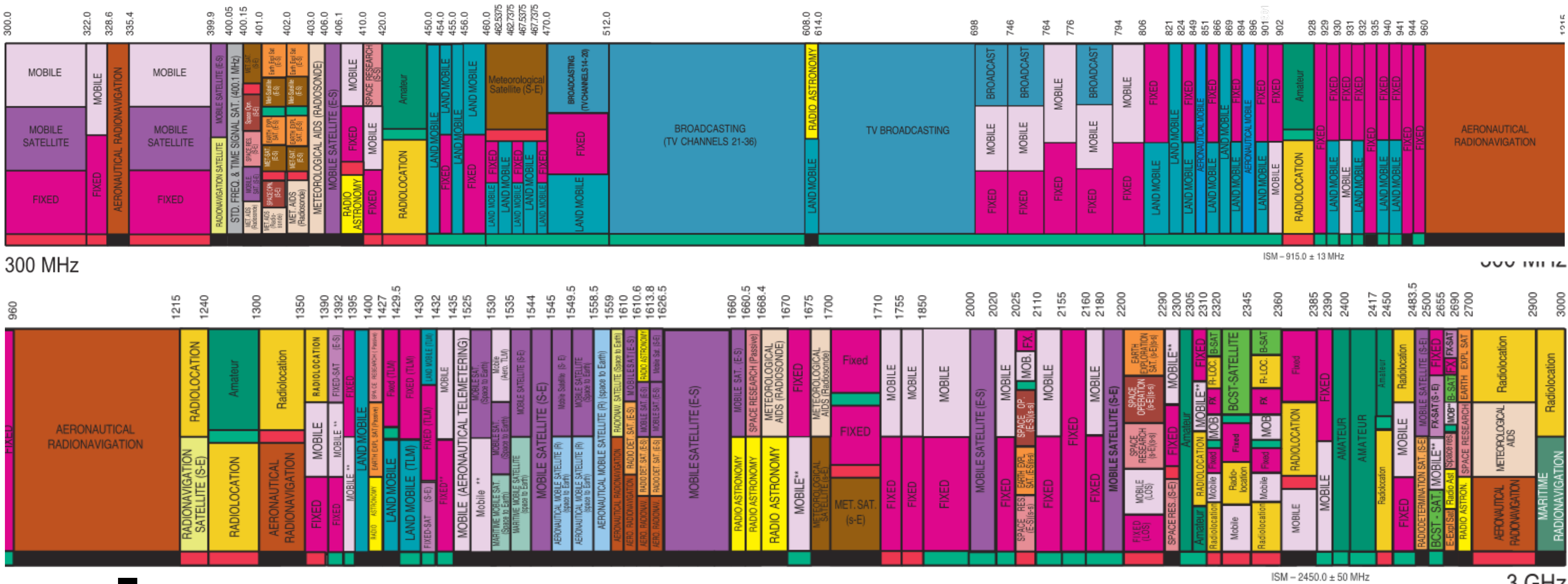
# Introduction: the channel (link)



# The electromagnetic spectrum



# USA frequency allocation
# 0.3 – 3 GHz

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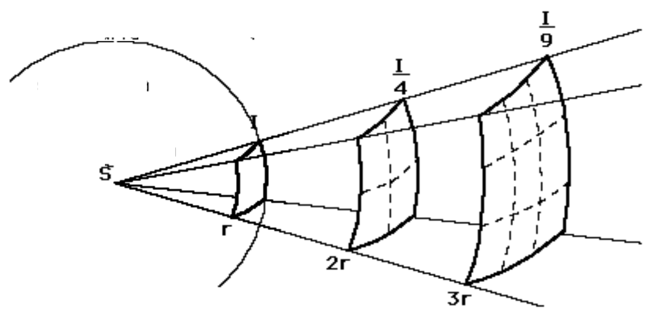
# 3GPP (2.5G, 3G, 4 G) frequency bands



| E-UTRA Operating Band | Uplink (UL) operating band BS receive UE transmit $F_{UL\_low}$ – $F_{UL\_high}$ | Downlink (DL) operating band BS transmit UE receive $F_{DL\_low}$ – $F_{DL\_high}$ | Duplex Mode |
|---|---|---|---|
| 1 | 1920 MHz – 1980 MHz | 2110 MHz – 2170 MHz | FDD |
| 2 | 1850 MHz – 1910 MHz | 1930 MHz – 1990 MHz | FDD |
| 3 | 1710 MHz – 1785 MHz | 1805 MHz – 1880 MHz | FDD |
| 4 | 1710 MHz – 1755 MHz | 2110 MHz – 2155 MHz | FDD |
| 5 | 824 MHz – 849 MHz | 869 MHz – 894MHz | FDD |
| 6 | 830 MHz – 840 MHz | 875 MHz – 885 MHz | FDD |
| 7 | 2500 MHz – 2570 MHz | 2620 MHz – 2690 MHz | FDD |
| 8 | 880 MHz – 915 MHz | 925 MHz – 960 MHz | FDD |
| 9 | 1749.9 MHz – 1784.9 MHz | 1844.9 MHz – 1879.9 MHz | FDD |
| 10 | 1710 MHz – 1770 MHz | 2110 MHz – 2170 MHz | FDD |
| 11 | 1427.9 MHz – 1452.9 MHz | 1475.9 MHz – 1500.9 MHz | FDD |
| 12 | 698 MHz – 716 MHz | 728 MHz – 746 MHz | FDD |
| 13 | 777 MHz – 787 MHz | 746 MHz – 756 MHz | FDD |
| 14 | 788 MHz – 798 MHz | 758 MHz – 768 MHz | FDD |
| … | | | |
| 17 | 704 MHz – 716 MHz | 734 MHz – 746 MHz | FDD |
| … | | | |
| 33 | 1900 MHz – 1920 MHz | 1900 MHz – 1920 MHz | TDD |
| 34 | 2010 MHz – 2025 MHz | 2010 MHz – 2025 MHz | TDD |
| 35 | 1850 MHz – 1910 MHz | 1850 MHz – 1910 MHz | TDD |
| 36 | 1930 MHz – 1990 MHz | 1930 MHz – 1990 MHz | TDD |
| 37 | 1910 MHz – 1930 MHz | 1910 MHz – 1930 MHz | TDD |
| 38 | 2570 MHz – 2620 MHz | 2570 MHz – 2620 MHz | TDD |
| 39 | 1880 MHz – 1920 MHz | 1880 MHz – 1920 MHz | TDD |
| 40 | 2300 MHz – 2400 MHz | 2300 MHz – 2400 MHz | TDD |

# Isotropic Radiation (nondirectional antenna)

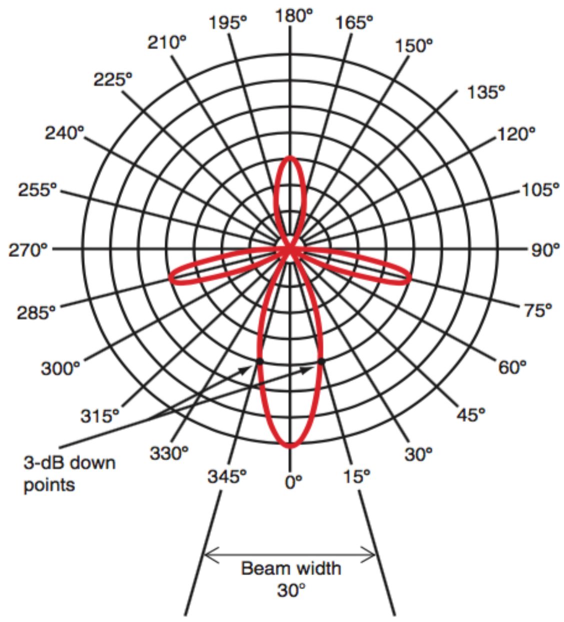
- If energy is emitted from a signal point, it will distribute equally in all directions over a hypothetical sphere.
- Density of power, is defined as the power that the point source emits divided by the area of this sphere:
- transmitted power density = $\dfrac{P_t}{4\pi r^2}$

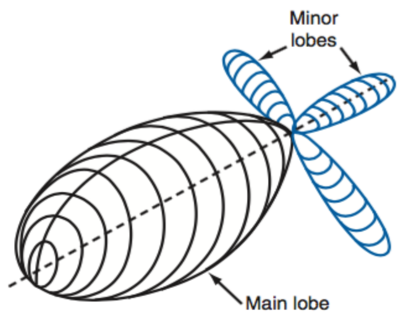



Since area of the sphere with radius *r* is given by $4\pi r^2$, the power density reduces by $r^2$.

# Directional antennas

- Directional antennas provide great efficiency of power transmission because the transmitter power can be focused into a narrow beam directed toward the station of interest.



# Antenna Gain

- The power gain of an antenna can be expressed as the ratio of the power transmitted $P_{trans}$ to the input power of the antenna $P_{in}$.

$$\mathrm{dB} = 10 \log \frac{P_{\mathrm{trans}}}{P_{\mathrm{in}}}$$

- Power gains of 10 or more are easily achieved. This means that a 1-W transmitter can be made to perform as a 10-W transmitter when applied to an antenna with 10 dB of gain.

# Receiver Effective Area

- A receiver uses the antenna to collect parts of the transmitted power which reaches it after transmission
- The amount of received power depends on the receiver antenna effective area:

  Received power =
  (transmitted power density at r) * $A_{RX}$

$$P_r = \frac{P_t}{4\pi r^2} A_{RX}$$

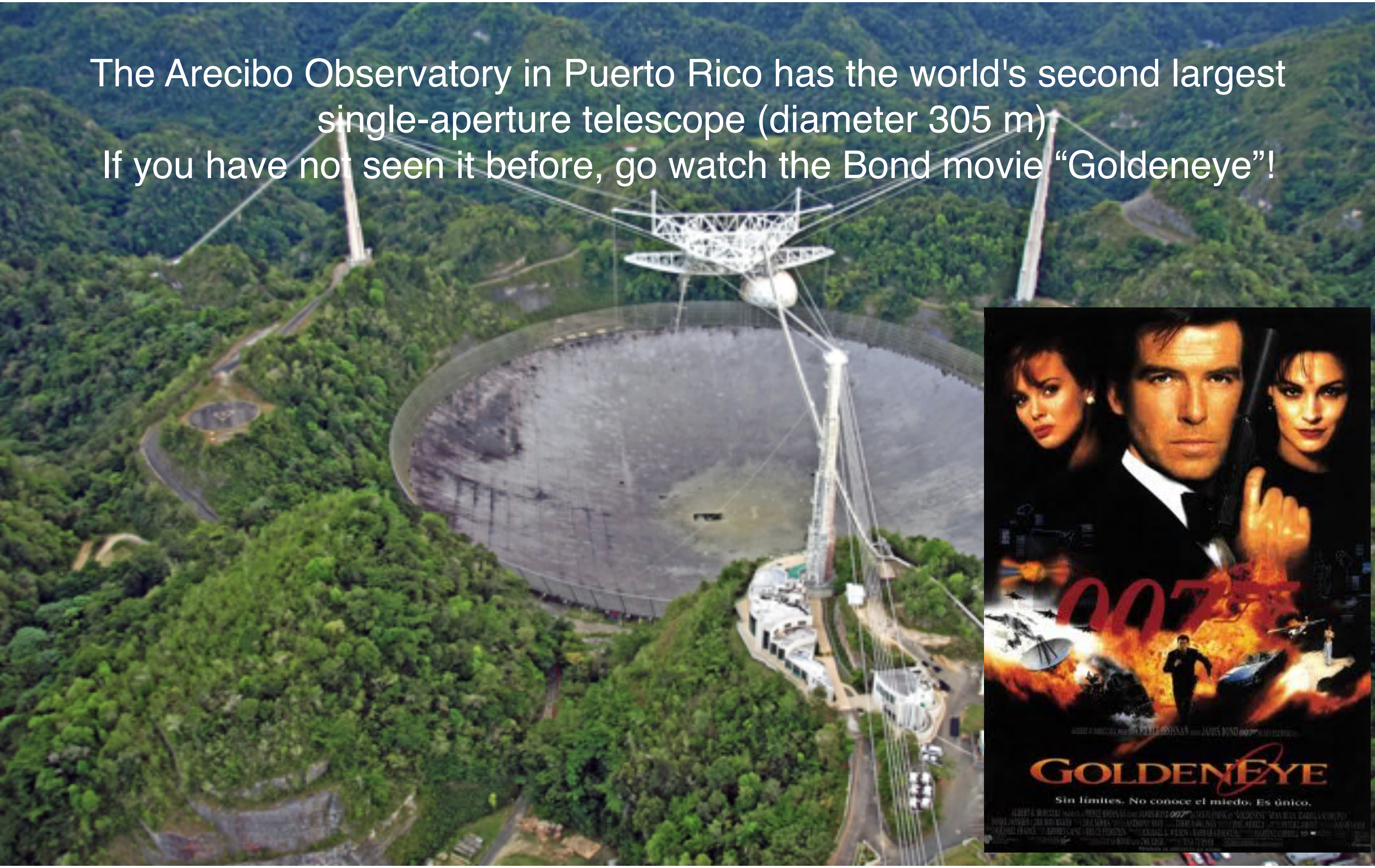
# Antenna Gain

- If the antenna has a larger effective area (e.g. more directional), it collects more power. We can interpret this as antenna gain.

$$A_{RX} = 4\pi \frac{A_{eff}}{\lambda^2}$$

- Antenna gain is therefore dependent on antenna size.
- Size of the antenna should always be stated in comparison to the wavelength.
- What is the largest antenna you have seen?

The Arecibo Observatory in Puerto Rico has the world's second largest single-aperture telescope (diameter 305 m).
If you have not seen it before, go watch the Bond movie “Goldeneye”!



# Friis' Transmission Equation

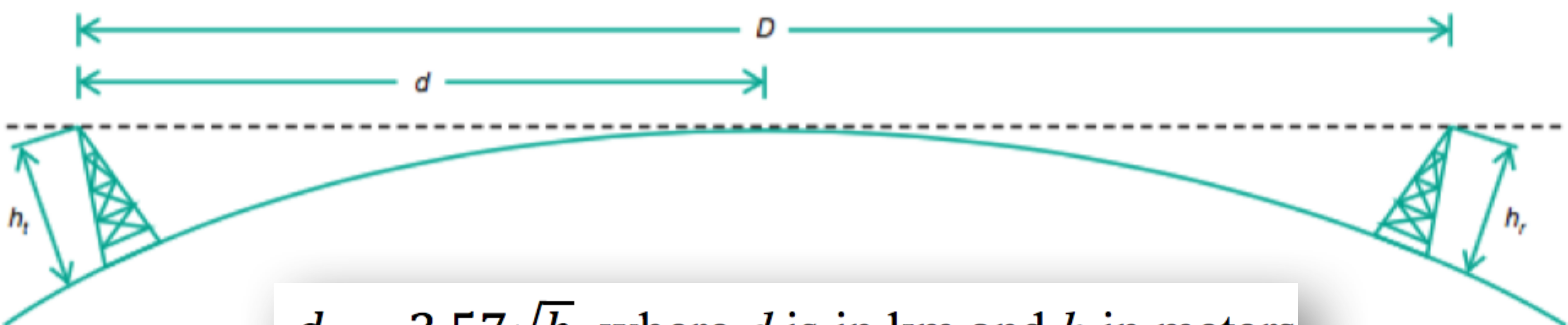
- If we include transmitter and receiver antenna gains, ratio of the received power to transmit power will be given by:

$$P_{receive} = P_{transmit} G_t G_r \left( \frac{\lambda}{4\pi r} \right)^2$$

- Received power
  - decreases with distance,
  - increases by using directive antennas (large),
  - decreases with frequency (smaller), but at the same time, antenna sizes are now larger compared to λ,
  - increases as transmitted power increases.

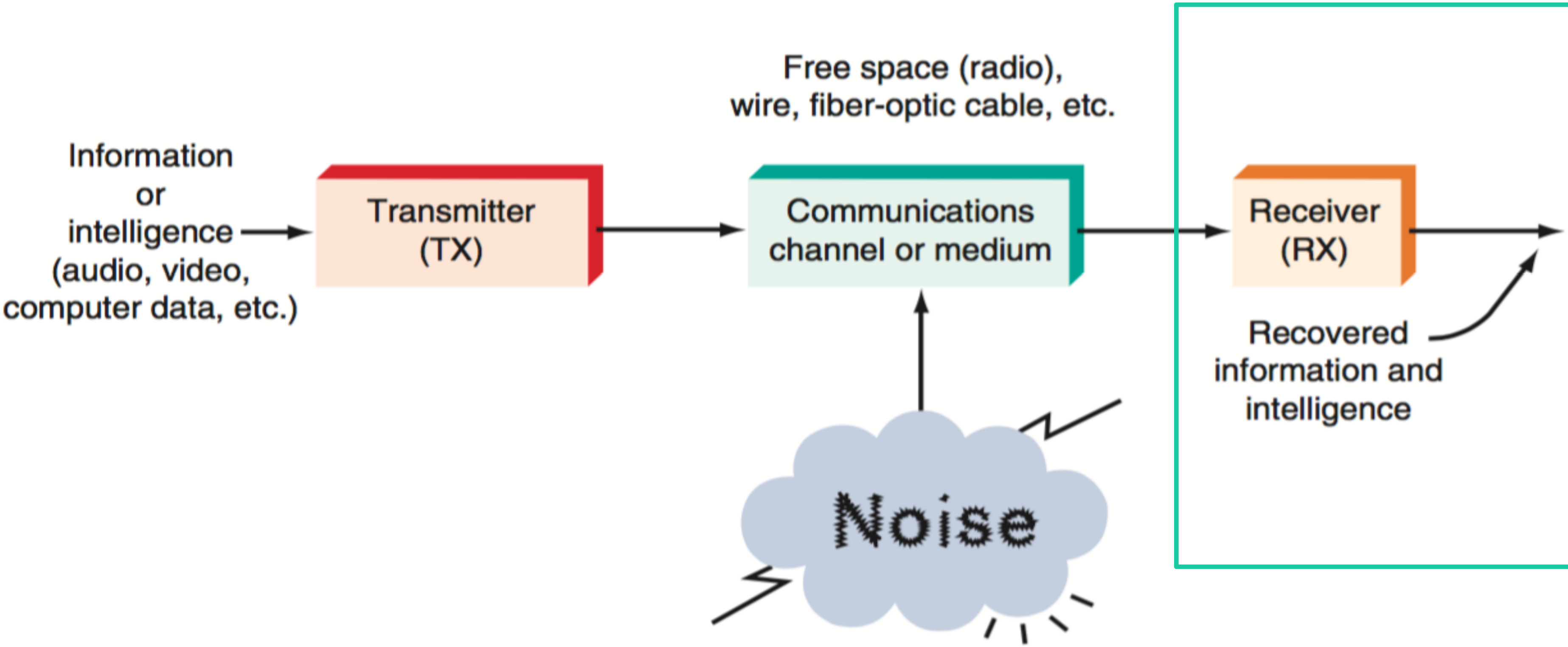
# Propagation of radio waves

- Radio waves can propagate in many different ways:
- < 3 MHz: ground/surface waves, following the curvatures of the earth.
- 3-30 MHz: sky waves (reflections) in the ionosphere.
- > 30 MHz: direct/space waves, ”line-of-sight” (LOS).

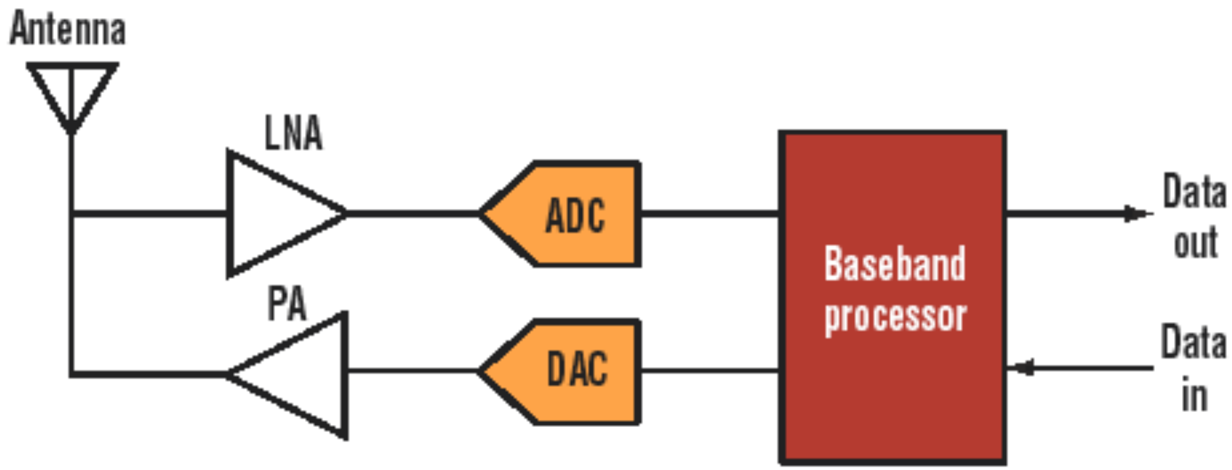



$d = 3.57\sqrt{h}$, where $d$ is in km and $h$ in meters

# Introduction: receiving the signal



# SDR – Software Defined Radio




**1. In the ideal software-defined radio, the antenna connects directly to the LNA and ADC, or the PA and DAC. The processor handles all radio functions, filtering, up/downconversion, modulation/demodulation, and digital baseband.**

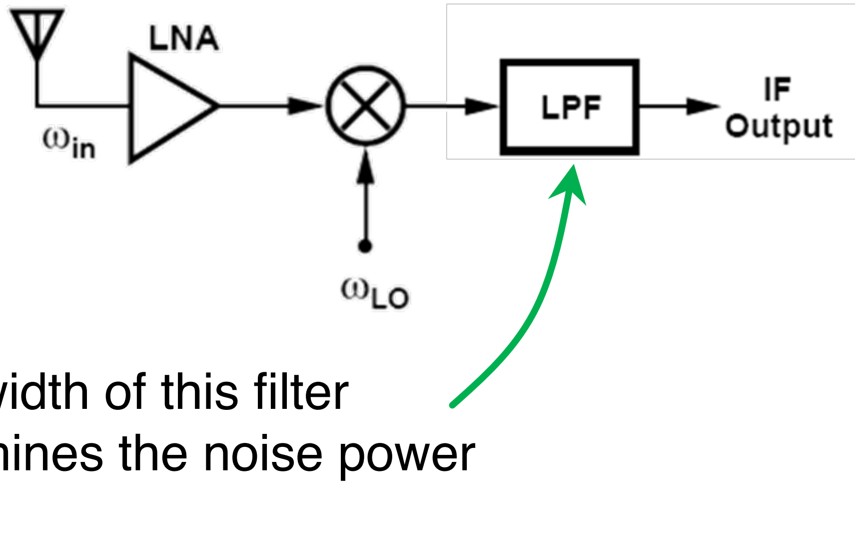
# RX architectures

- Most popular:
  - **Heterodyne** (down-mixing receiver)
  - reliable, flexible frequency plan (with fixed components)
  - low integration level, high power consumption, high requirements on filters, high cost, not suited for multistandard flexibility

  - **Direct conversion** (zero-IF or low-IF, homodyne)
  - popular in terminals because of high integration
  - problems with DC-offset, 1/f-noise, IQ balance
  - not popular in the high-requirements basestation

# Heterodyne Receiver – improved sensitivity

- By down-converting the radio-frequency signal (RF) to a lower intermediate frequency (IF), much better selectivity can be achieved and SNR is improved

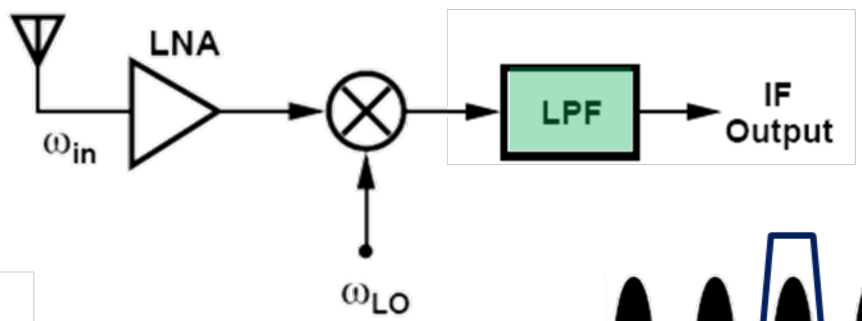


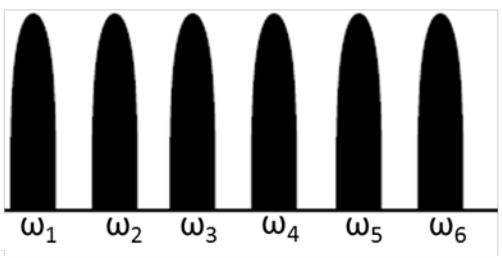

Bandwidth of this filter determines the noise power (kTB)

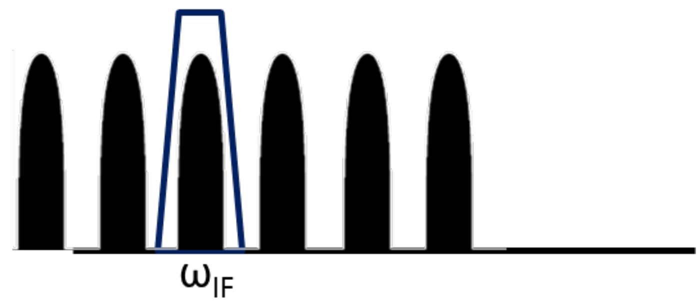
# Heterodyne Receiver – Channel Selection

- By changing $\omega_{LO}$, different $\omega_{in}$ will down-convert to the same IF.

The IF filter is always at a fixed frequency!



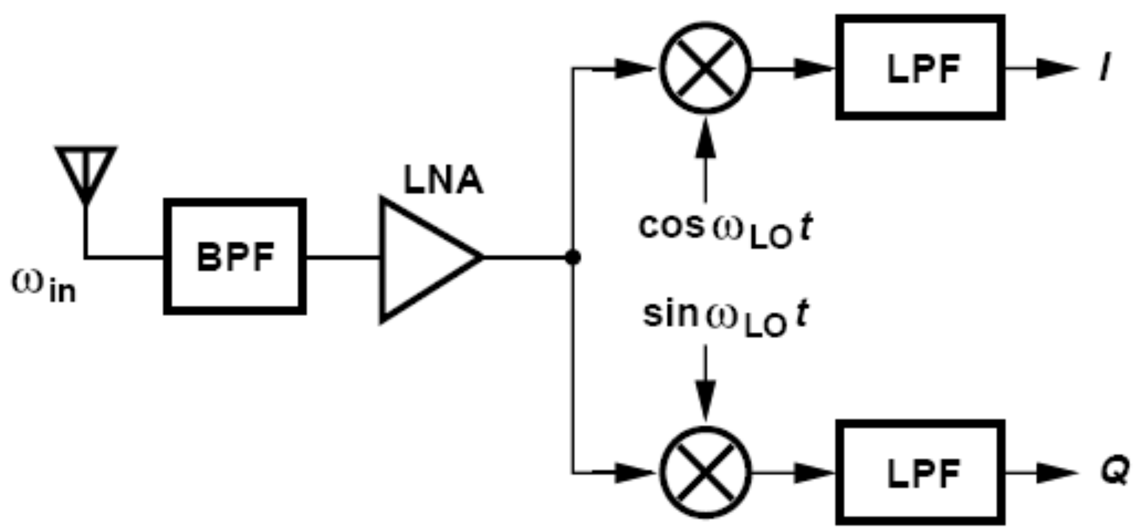




Variable LO frequencies can be made with a synthesizer

$$\omega_{LO1} = \omega_1 - \omega_{IF}$$
$$\omega_{LO2} = \omega_2 - \omega_{IF}$$
$$\omega_{LO3} = \omega_3 - \omega_{IF}$$

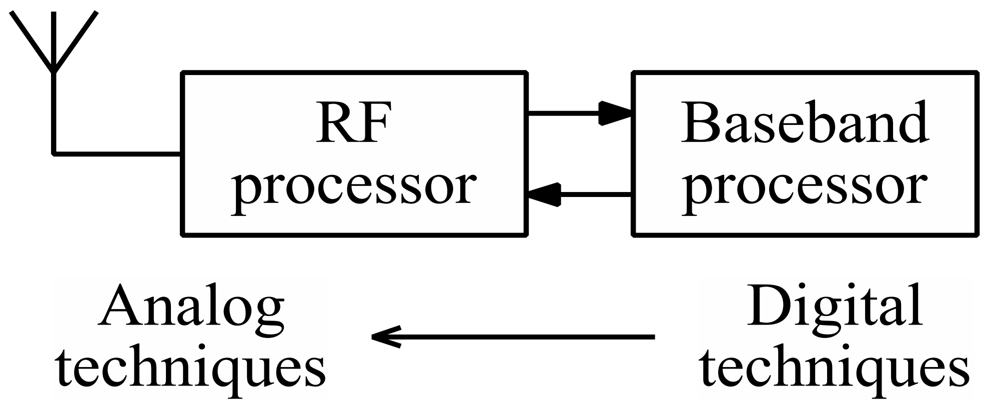
# Direct-Conversion Receiver

- Absence of an image greatly simplifies the design process.
- Channel selection is performed by on-chip low-pass filter.
- Mixing spurs are considerably reduced in number.
- Suitable for ICs, few external components.



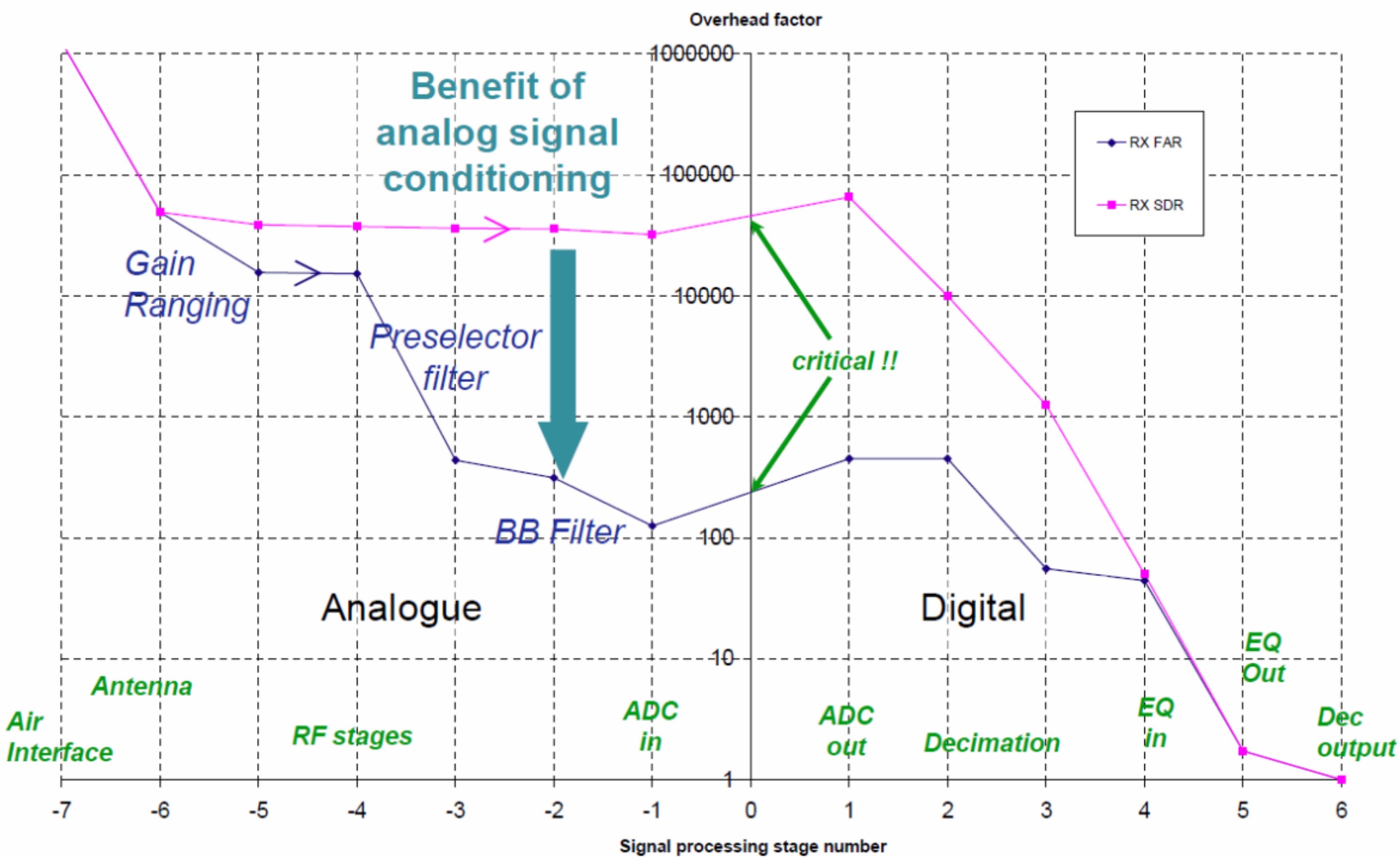
# Analog/digital trade-off

- Digital modulation techniques offer larger bandwidth efficiency.

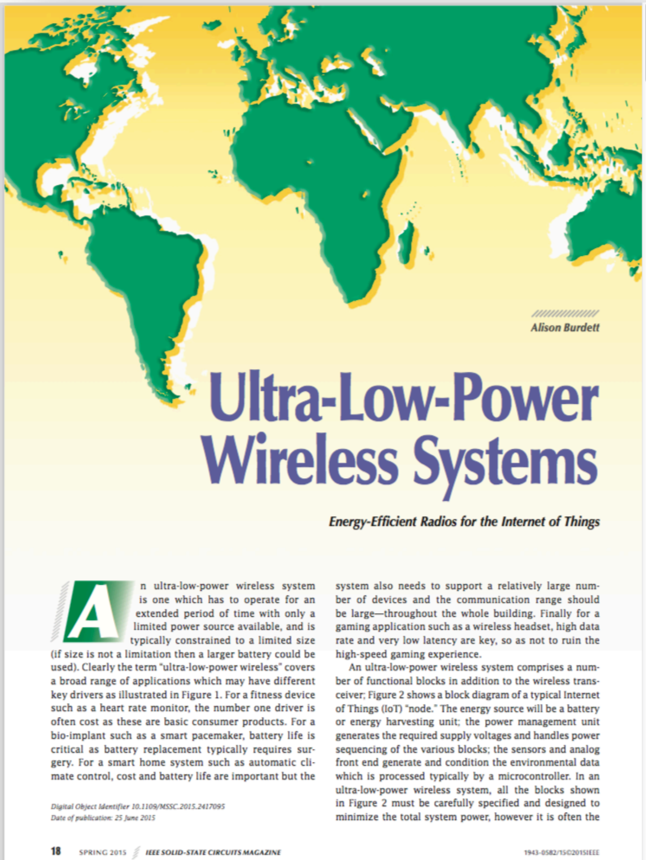



- For slow connections (small amounts of data to be transferred), analog may be better.

# Analog/digital trade-off



# Two papers on low-power RF



Alison Burdett

# Ultra-Low-Power Wireless Systems

*Energy-Efficient Radios for the Internet of Things*

An ultra-low-power wireless system is one which has to operate for an extended period of time with only a limited power source available, and is typically constrained to a limited size (if size is not a limitation then a larger battery could be used). Clearly the term "ultra-low-power wireless" covers a broad range of applications which may have different key drivers as illustrated in Figure 1. For a fitness device such as a heart rate monitor, the number one driver is often cost as these are basic consumer products. For a bio-implant such as a smart pacemaker, battery life is critical as battery replacement typically requires surgery. For a smart home system such as automatic climate control, cost and battery life are important but the system also needs to support a relatively large number of devices and the communication range should be large—throughout the whole building. Finally for a gaming application such as a wireless headset, high data rate and very low latency are key, so as not to ruin the high-speed gaming experience.

An ultra-low-power wireless system comprises a number of functional blocks in addition to the wireless transceiver; Figure 2 shows a block diagram of a typical Internet of Things (IoT) "node." The energy source will be a battery or energy harvesting unit; the power management unit generates the required supply voltages and handles power sequencing of the various blocks; the sensors and analog front end generate and condition the environmental data which is processed typically by a microcontroller. In an ultra-low-power wireless system, all the blocks shown in Figure 2 must be carefully specified and designed to minimize the total system power, however it is often the

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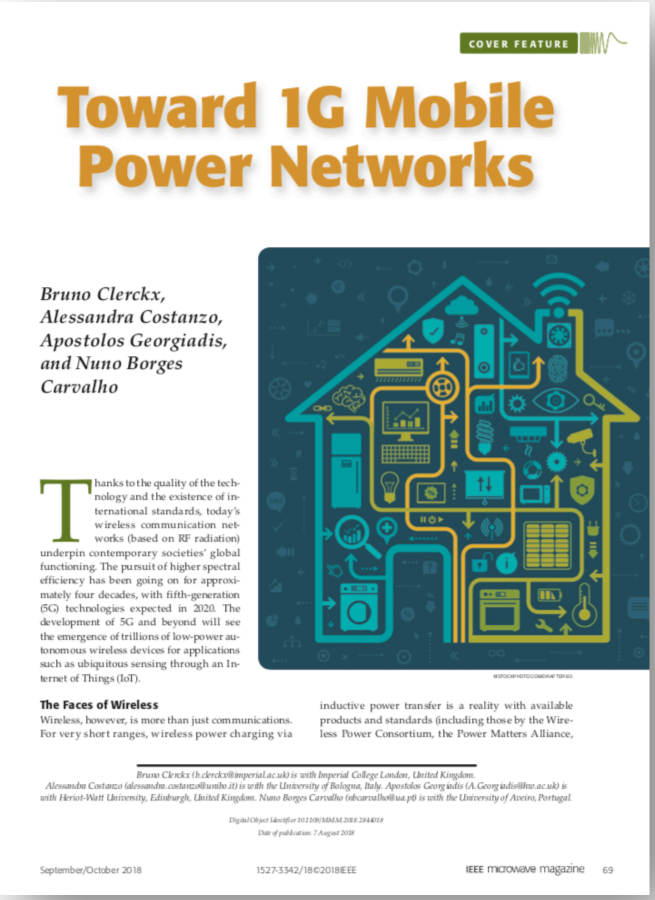

COVER FEATURE

# Toward 1G Mobile Power Networks

*Bruno Clerckx, Alessandra Costanzo, Apostolos Georgiadis, and Nuno Borges Carvalho*

Thanks to the quality of the technology and the existence of international standards, today's wireless communication networks (based on RF radiation) underpin contemporary societies' global functioning. The pursuit of higher spectral efficiency has been going on for approximately four decades, with fifth-generation (5G) technologies expected in 2020. The development of 5G and beyond will see the emergence of trillions of low-power autonomous wireless devices for applications such as ubiquitous sensing through an Internet of Things (IoT).

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## The Faces of Wireless

Wireless, however, is more than just communications. For very short ranges, wireless power charging via inductive power transfer is a reality with available products and standards (including those by the Wireless Power Consortium, the Power Matters Alliance,

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*Date of publication: 7 August 2018*



[A. Burdett, "Ultra-Low-Power Wireless Systems", IEEE Solid-State Circuits Magazine, No. 2, 2015, pp. 18-28.]

[B. Clerckx, A. Costanzo. A. Georgiadis, N. Borges Carvalho, "Toward 1G Mobile Power Networks", IEEE Microwave Magazine, No. 6, 2018. pp. 69-82.]

# Summary of the papers

- Today, low-power (RF) is much concentrated on IoT (internet-of-things) and power harvesting replacing the battery.
- Need of short-range communication (up to 10 m) with limited data speed with really low-power (energy per transferred bit).
- [Burdett] discussed broadly low-power radio design: battery considerations, sleep timer design, receiver and transmitter architectures, current-reuse.
- [Clerckx, et al.] is an overview of the current state-of-the-art of Wireless Power Transfer (WPT) for such devices.

# Burdett: Ultra Low Power (ULP) radio challenges

- Important tradeoffs between power consumption and
  - radiated output power,
  - linearity (distortion),
  - sensitivity (lowest detectable signal),
  - channelization capabilities (other signals),
  - interference sensitivity (robustness in detection with other signals interfering).
- Low-power radio designs often sacrifice one or more of these metrics to obtain low overall power consumption.

# dB (deci Bell)

- In order to make calculations and comparisons easier, RF system designers commonly use logarithmic scale

$$\log(1/x) = -\log x$$
$$\log(x \times y) = \log x + \log y$$
$$(y \times x)_{dB} = 10 \log(x^y)$$

- dB is logarithm base-10 and times 10

$$dB = 10 \log_{10}(X)$$

- Calculations become easier if you can quickly convert any number into its logarithm!

# Power in dBm

- Due to simplicity in calculations, we like to express power in logarithm scale!
- Power is not a ratio, so how can we do this?

- Calculate the ratio of the power to 1 mW and express that in dB! We call this dBm.

- 0 dBm = 1 mW.
- 1 W = X dBm?

$$P_{sig}|_{\mathrm{dBm}} = 10\log\left(\frac{P_{sig}}{1\ \mathrm{mW}}\right)$$

# Ultra Low Power radio

- Definition: output power < 0 dBm (1 mW).
  - cf: GSM mobile phone: 30-32 dBm, 3G/4G: 24 dBm, WLAN 17-23 dBm, Bluetooth BLE 10 dBm, ...
- Power Amplifiers (PAs) do not totally dominate power consumption/efficiency for ULP compared to "normal" transmitters.
- Hence, we may need new architectures for ULP, with stricter power requirements for the other parts of the transmitter than just the PA.
- High-efficiency PAs are still interesting.

# ULP wireless examples

| Importance \ Application | Fitness | Bio-Implant | Smart Home | Gaming |
|---|---|---|---|---|
| Cost | High | Low | High | Medium |
| Battery Life | Medium | High | High | Low |
| Data Rate | Medium | Low/Medium | Low | High |
| Range | Low | Low | High | Medium |
| Latency | Low | Low/Medium | Medium | High |
| # of Nodes | Low | Low | High | Low |

# ULP wireless examples

- WSN: wireless sensor network
  - range < 10 m
  - 2.45 GHz (or other ISM bands)
  - P2P, relays => transmit/receive optimization
  - path loss 60 dB, Pout ~ 0 dBm.
- BAN: body area network
  - range < 2 m
  - path loss 40-80 dB, Pout ~ -10 dBm.

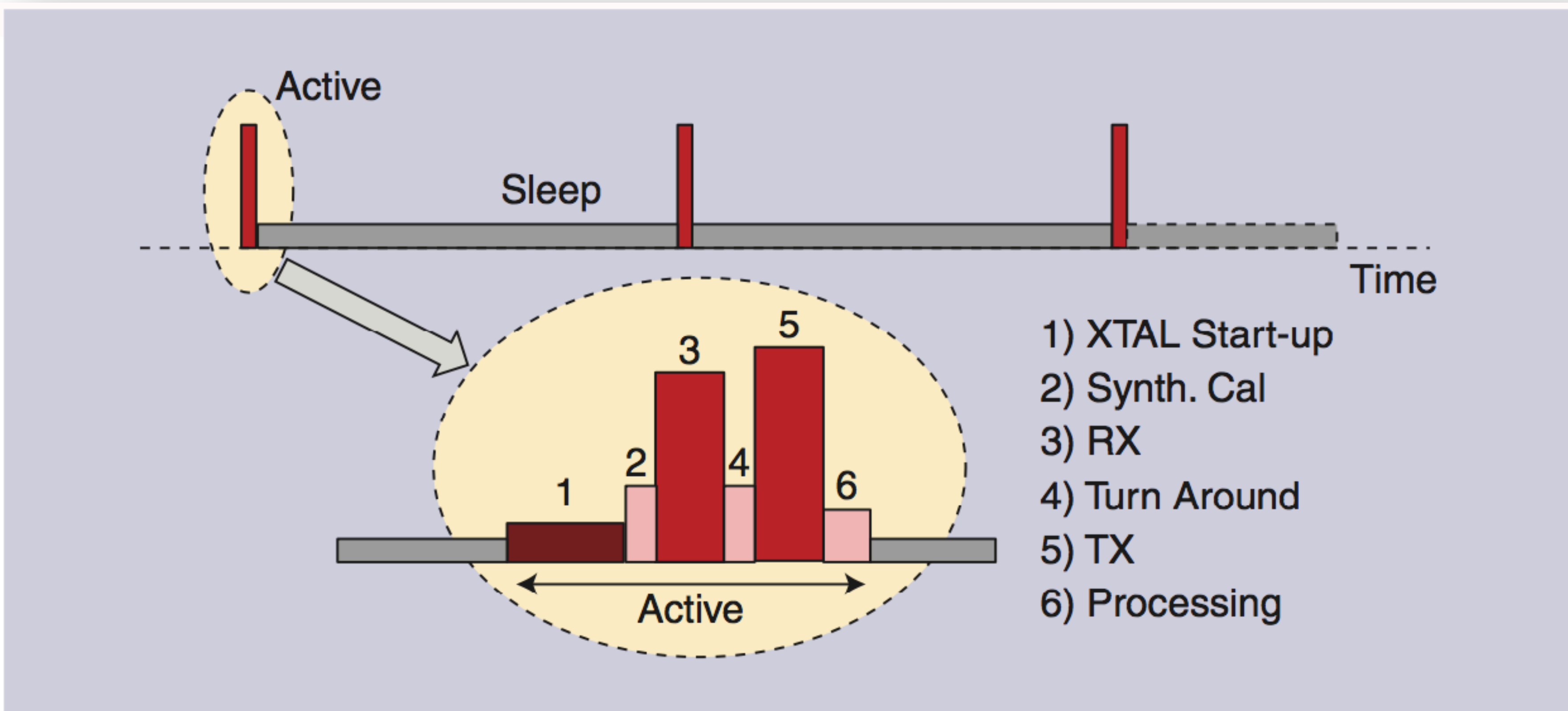
(0 dBm = 1 mW, -10 dBm = 100 µW).

# Small batteries for ULP

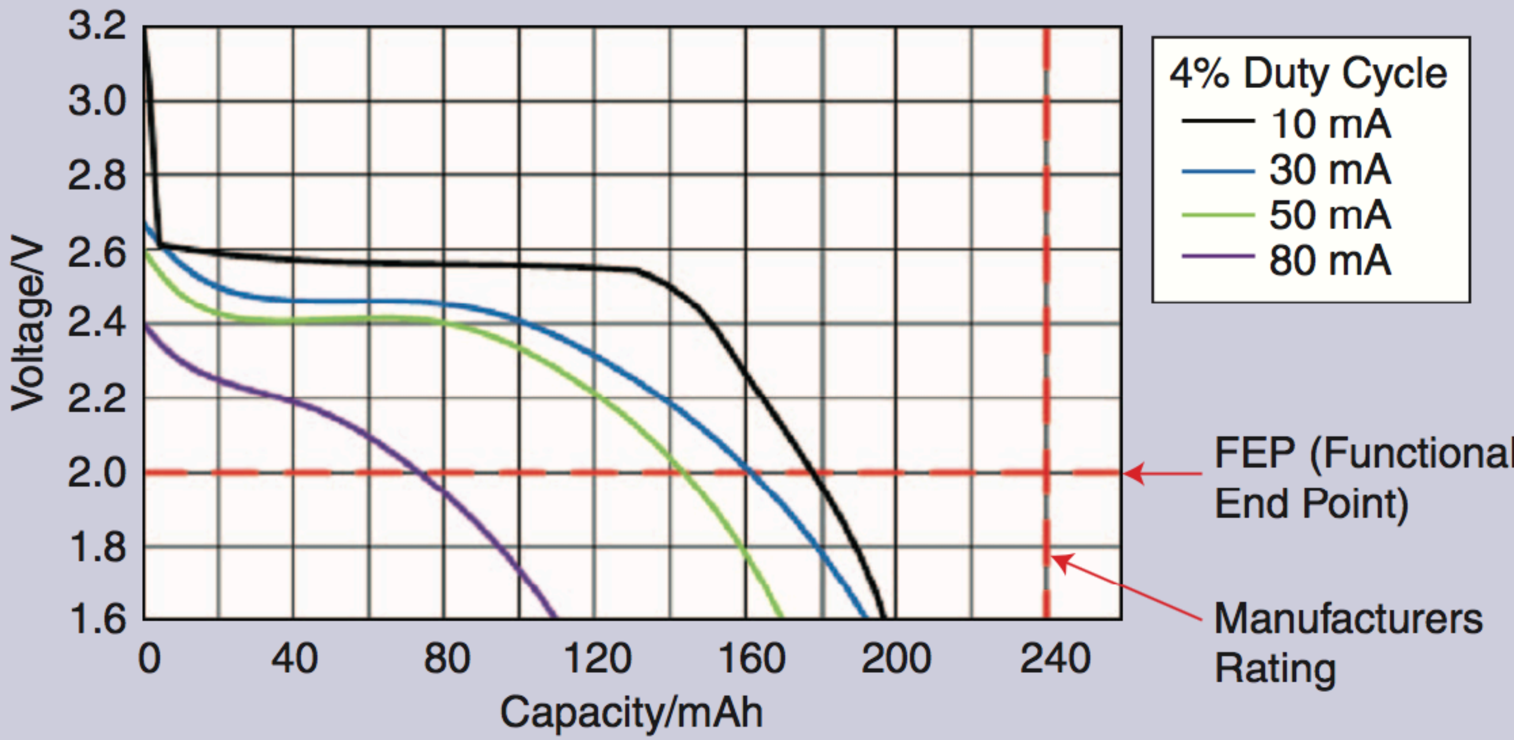


| | CR2032 (Coin) | LR44 (Button) | PR44 (Button) | Thin Film | Super Capacitor |
|---|---|---|---|---|---|
| Technology | $Li/MnO_2$ | $MnO_2$ | $ZnO_2$ | Li Thin Film | Supercap |
| Nominal Voltage | 3.0 V | 1.5 V | 1.4 V | 4.1 V | 2.75 V |
| Capacity | 240 mAh | 153 mAh | 620 mAh | 2 mAh | 0.6 mAh |
| Volume | 1 $cm^3$ | 0.6 $cm^3$ | 0.5 $cm^3$ | 0.25 $cm^3$ | 0.5 $cm^3$ |
| Peak Current | < 15 mA | < 10 mA | < 10 mA | < 5 mA | ~30 A |
| Internal Resistance | 10–40 Ω | 1–5 Ω | 2–8 Ω | ~15 Ω | < 0.02 Ω |
| Self-Discharge | 1%/yr (>10 Years) | 2%/yr (5+ Years) | High (Few Weeks) | 1%/yr (> 10 Years) | 2 uA (Few Days) |

# ULP radio duty cycling (”wake-up radio”)



# Battery discharge with duty cycles

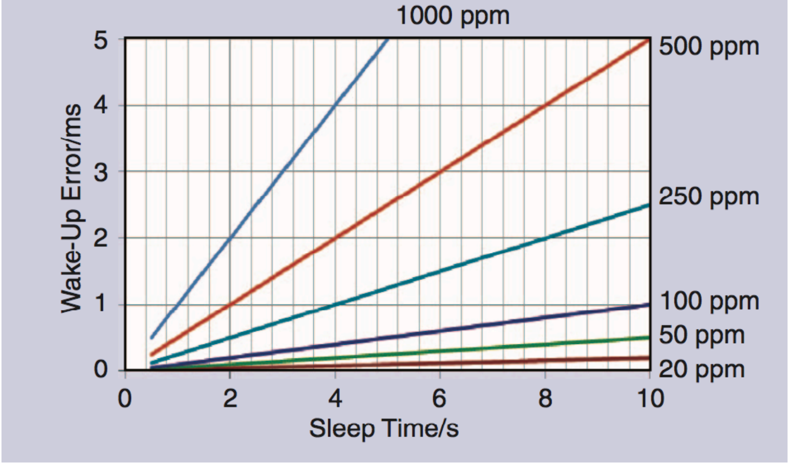


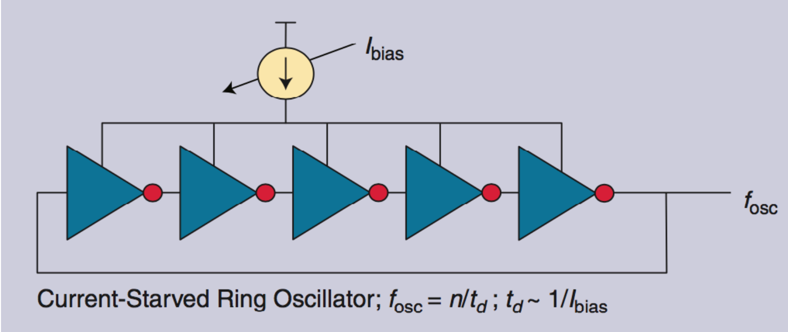

- High Peak Currents Degrade Battery Capacity Even When Duty Cycles Are Short (Sleep Times Are Long)
- Low Average and Peak Currents Are Required

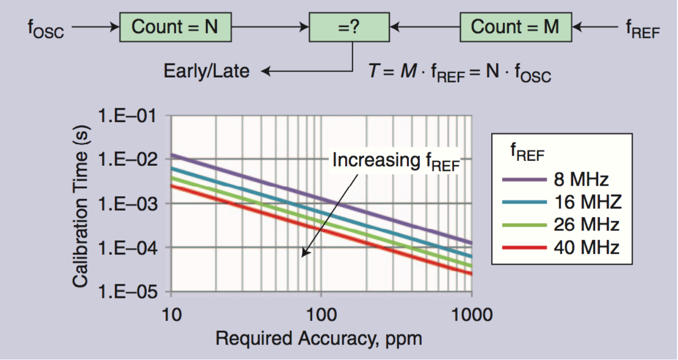
CR2032

# Sleep timer

- Longer sleep time => larger time error when wake-up. (Must be reasonably in sync with the base station.)
- Long sleep time:
    - crystal reference for oscillator
    - fully integrated on-chip timer + calibration



# Operating frequency vs. range

- Friis' transmission equation:

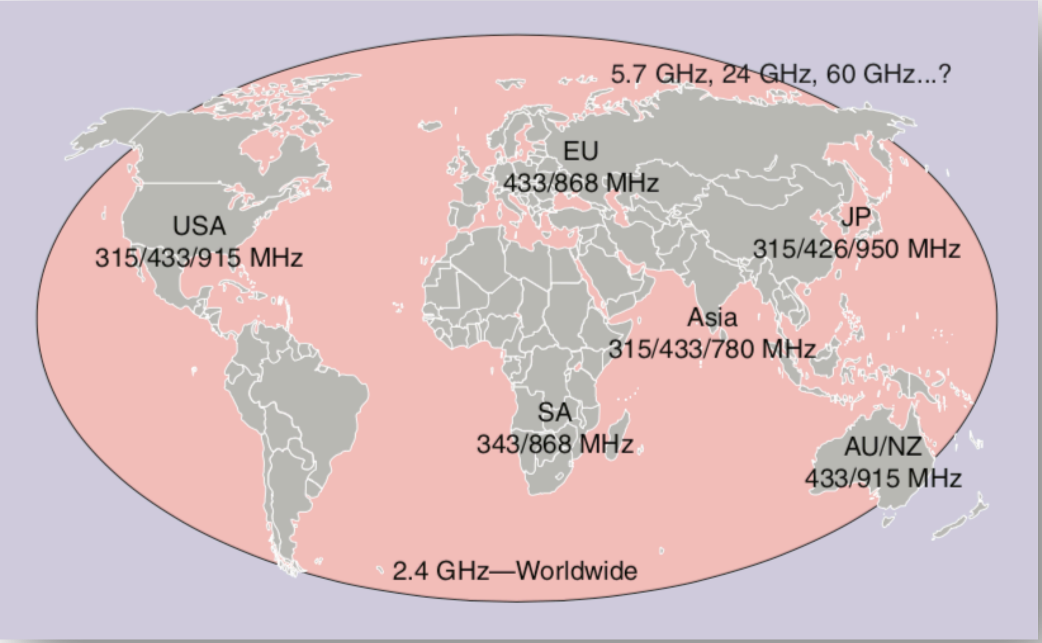
$$20 \log d = Gr(\text{dB}) + Gt(\text{dB}) + Pt(\text{dBm}) - Pr(\text{dBm}) + 20 \log\left(\frac{\lambda}{4\pi}\right)$$

- Example: Gr = Gt = -6 dB, f = 2.4 GHz, d = 50 m.
- => Pt - Pr = 86 dB = ”link budget”
- If the radio receiver requires -76 dBm (Pr), then we must transmit with 10 dBm (Pt).
- 10 dBm = 10 mW, rather high power for ULP.
- If we can e.g. improve the antenna gains, the Pt will decrease correspondingly.
- But usually, the best is to try to improve the receiver sensitivity.

# Operating frequency vs. range

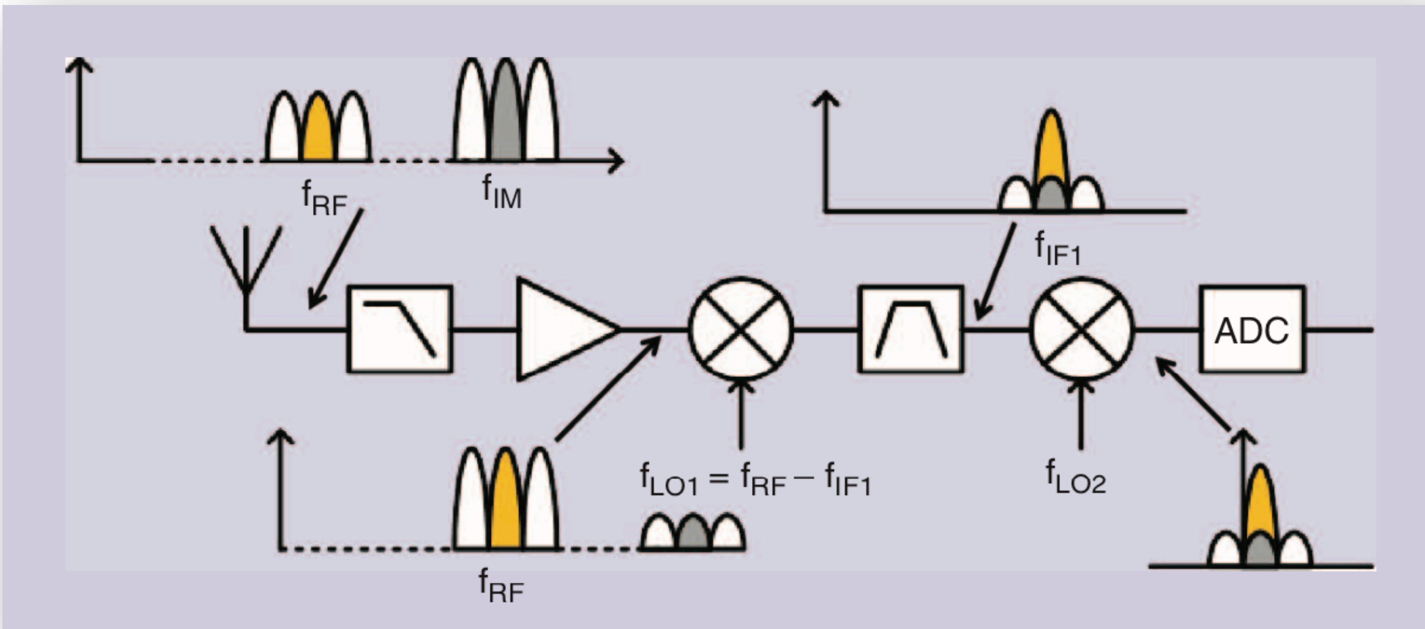
- If you change the frequency, the Pr can be changed: lower frequency => lower Pr possible.
- However, often antenna gains also change => find optimum combination.

- The actual spectrum allocated for short range wireless devices varies with region in the world.
- The 2.4 GHz band is crowded but very popular for ULP radio.



# The ULP receiver

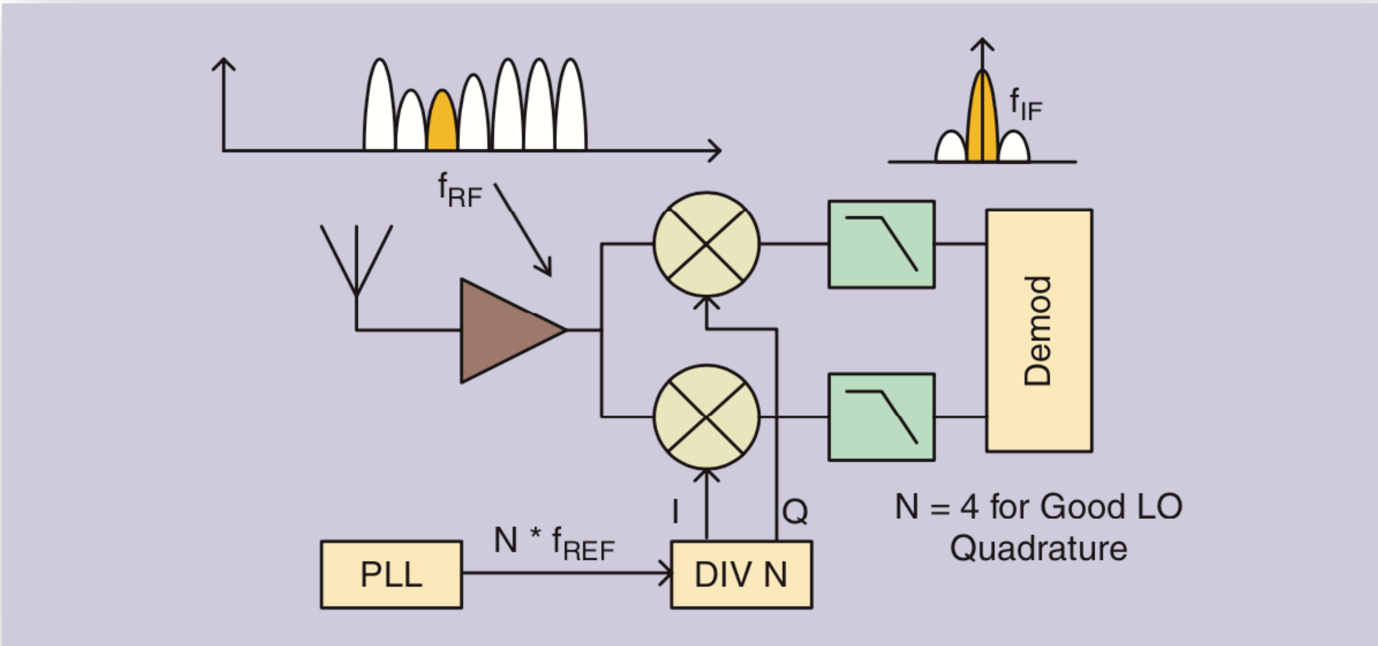
- Heterodyne receiver:




- Two different frequency generators
  => high power consumption.

# The ULP receiver

- Homodyne (direction conversion) receiver:

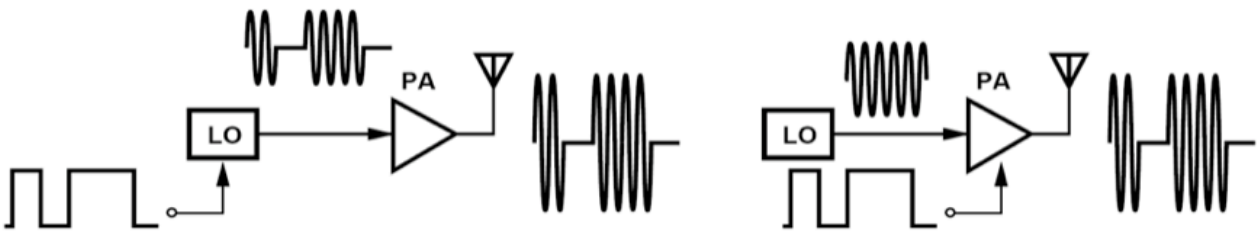



- ”Quadrature LO” => PLL at 2x or 4x RF frequency => high power consumption.

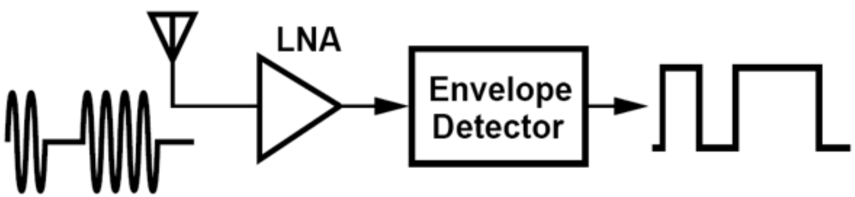
# Modulation scheme for low-power transmissions

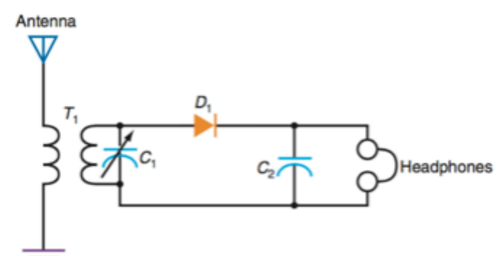
- Reduce the complexity of the modulation scheme => reduces the power => reduces the complexity of the architecture.

- "On-off keying" (OOK) modulation is a special case of ASK where the carrier amplitude is switched between zero and maximum.



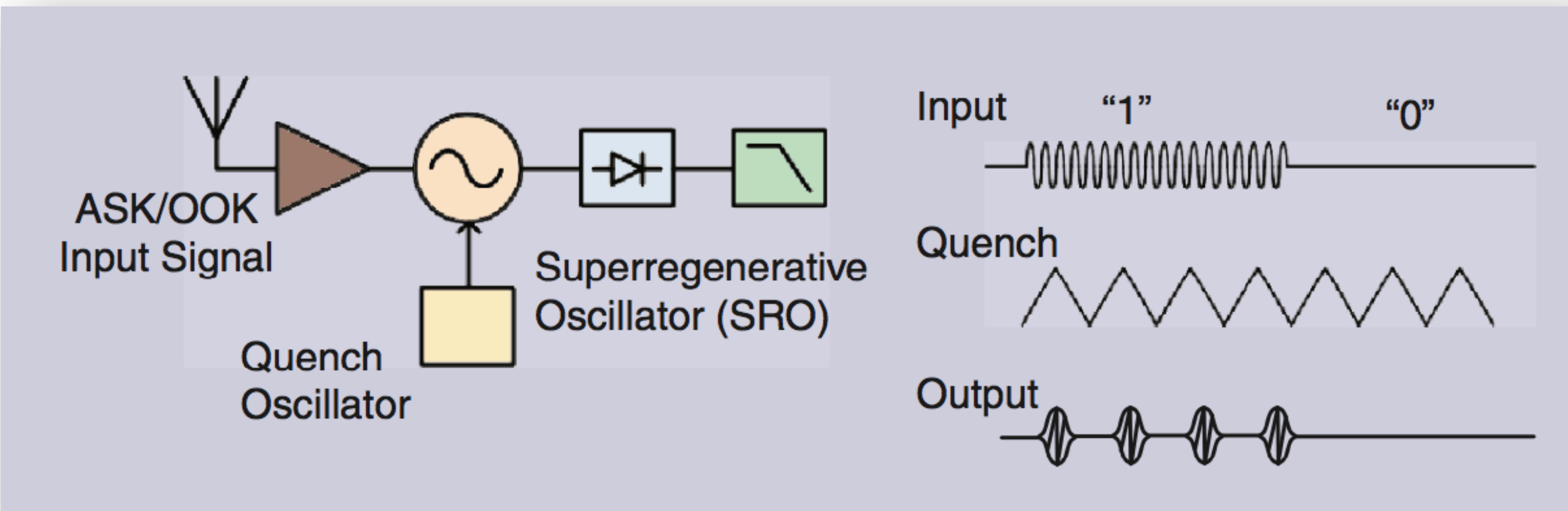

- An LNA followed by an envelope detector can recover the binary data.



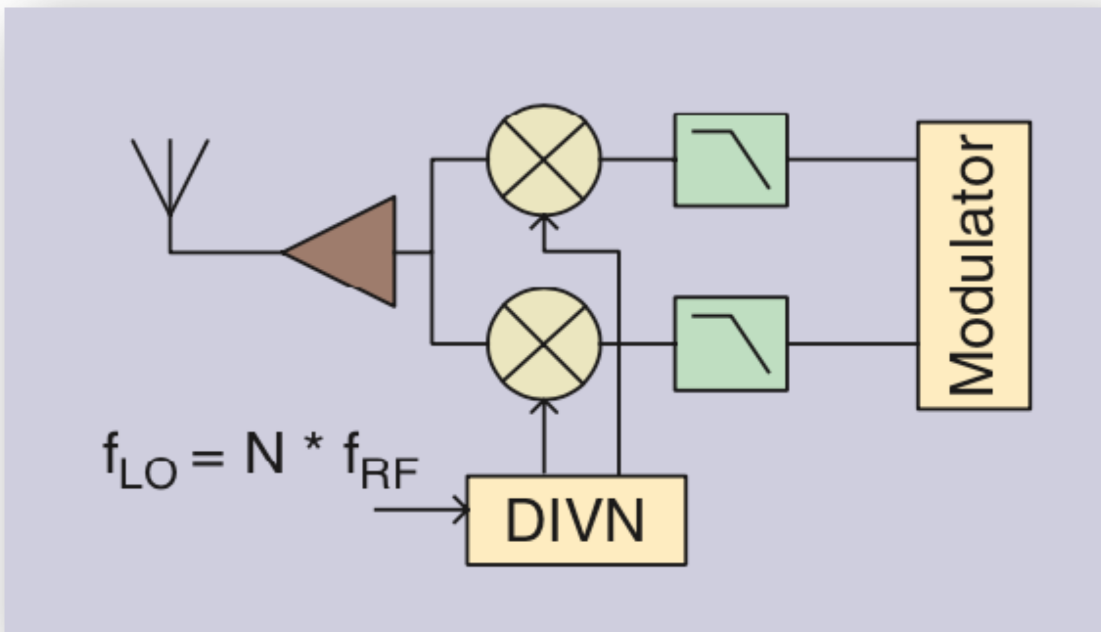
# Receiver for OOK: Super-regenerative

- Concept from the 1920s.
- Oscillator at RF, additional oscillator ”quenches” signal.
- Can be used as OOK receiver.
- Can be realized with very low power for low data rates.



# ULP transmitters

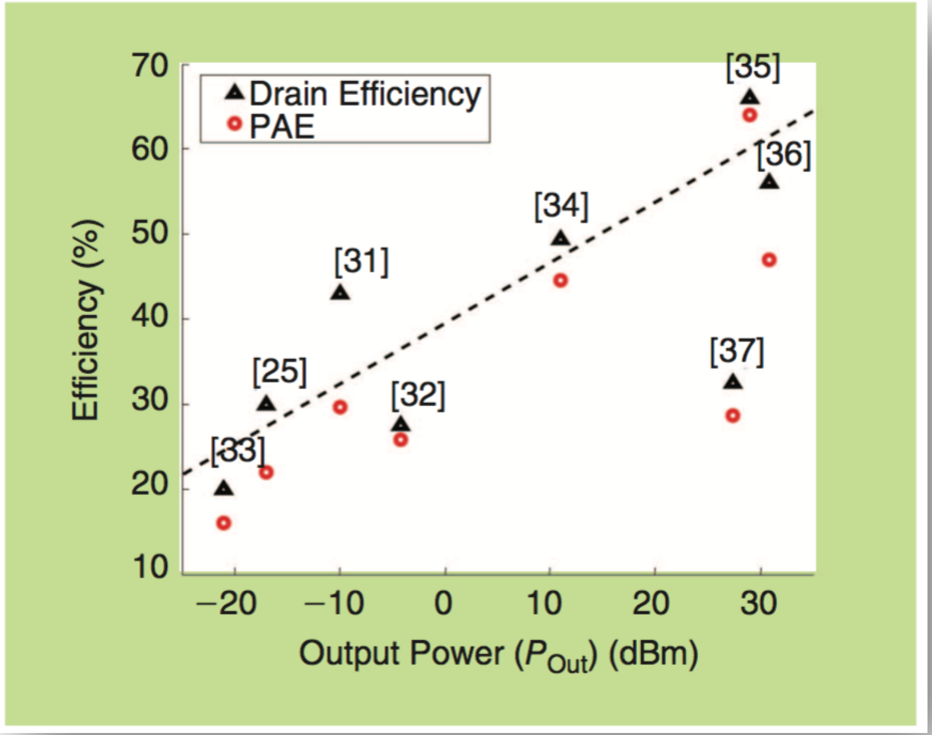
- Direct conversion transmitter is the most common architecture, here with IQ signal.
- However, ”load pulling” from the PA disturbs the VCO.



# Power Amplifiers for ULP

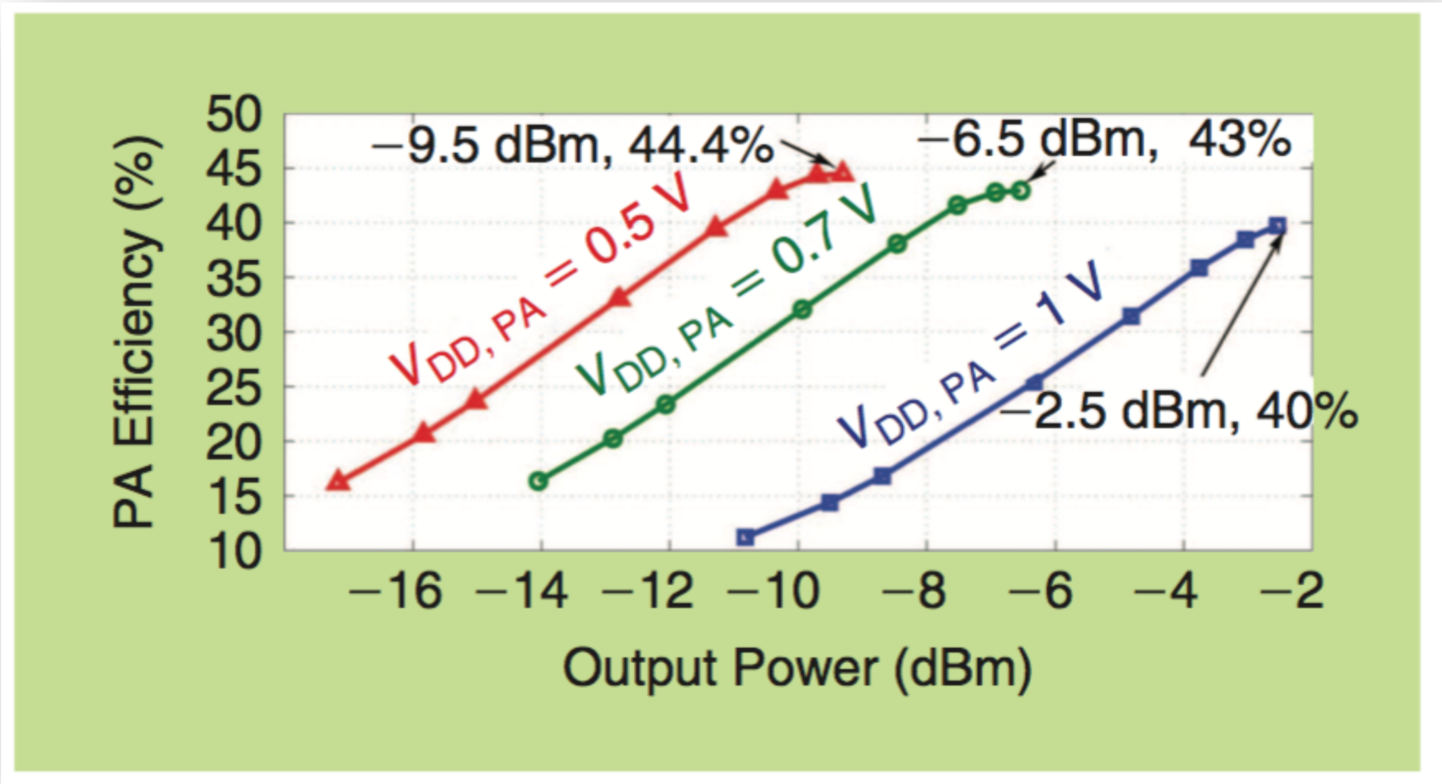
- Does not dominate the TX power (and the whole TRX power) as in mobile communication/wireless networks, but still large part.
- Quite hard to keep up the efficiency (DC -> RF conversion) as the output power is lowered due to parasitic losses.
- PA efficiency becomes dominated by losses at low output power.

(PAE ≈ Drain Eff if gain > 10 dB).



# Lowering the PA supply voltage

- Since $P_{out} = V_{RMS}^2/R_L$, better efficiency at low output power can be achieved by lowering the supply voltage.

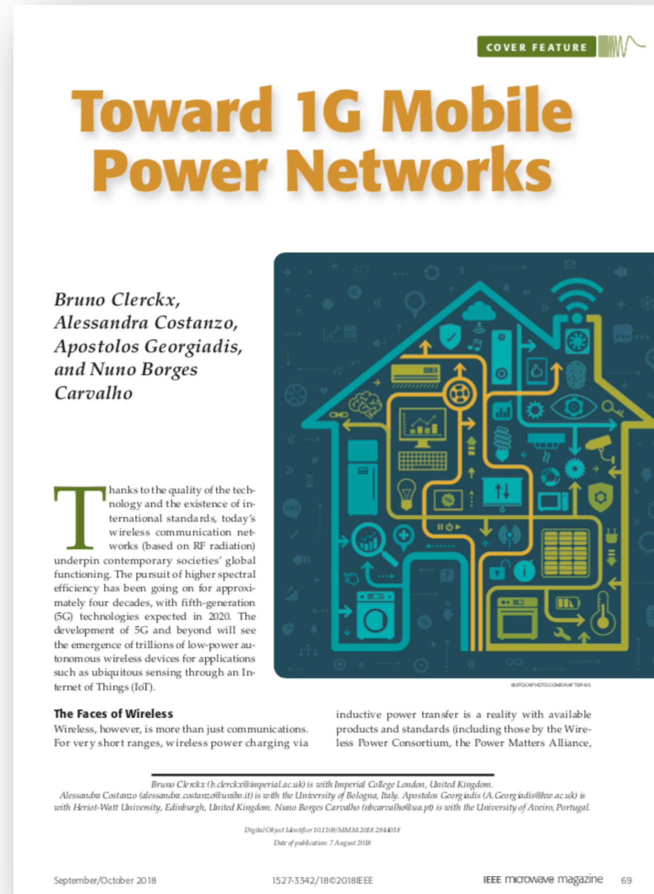


# Burdett: ”Good practice” in ULP radio circuit design

- Reduce maximum frequency.
- Minimize complexity and number of RF components.
- Operate at low supply voltage.
- No overdesign in margins (e.g. for PVT).
- Use high qualitative passive components => lower losses.

# Clerckx, et al.: Mobile Power Networks

- ”Heavy” paper to read, focus on first pages (pp. 69-73).
- New ideas, at least to many in the wireless research community.
- Area that still need much research to prove itself useful.



COVER FEATURE

Toward 1G Mobile Power Networks

*Bruno Clerckx, Alessandra Costanzo, Apostolos Georgiadis, and Nuno Borges Carvalho*

Thanks to the quality of the technology and the existence of international standards, today's wireless communication networks (based on RF radiation) underpin contemporary societies' global functioning. The pursuit of higher spectral efficiency has been going on for approximately four decades, with fifth-generation (5G) technologies expected in 2020. The development of 5G and beyond will see the emergence of trillions of low-power autonomous wireless devices for applications such as ubiquitous sensing through an Internet of Things (IoT).

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The Faces of Wireless

Wireless, however, is more than just communications. For very short ranges, wireless power charging via inductive power transfer is a reality with available products and standards (including those by the Wireless Power Consortium, the Power Matters Alliance,

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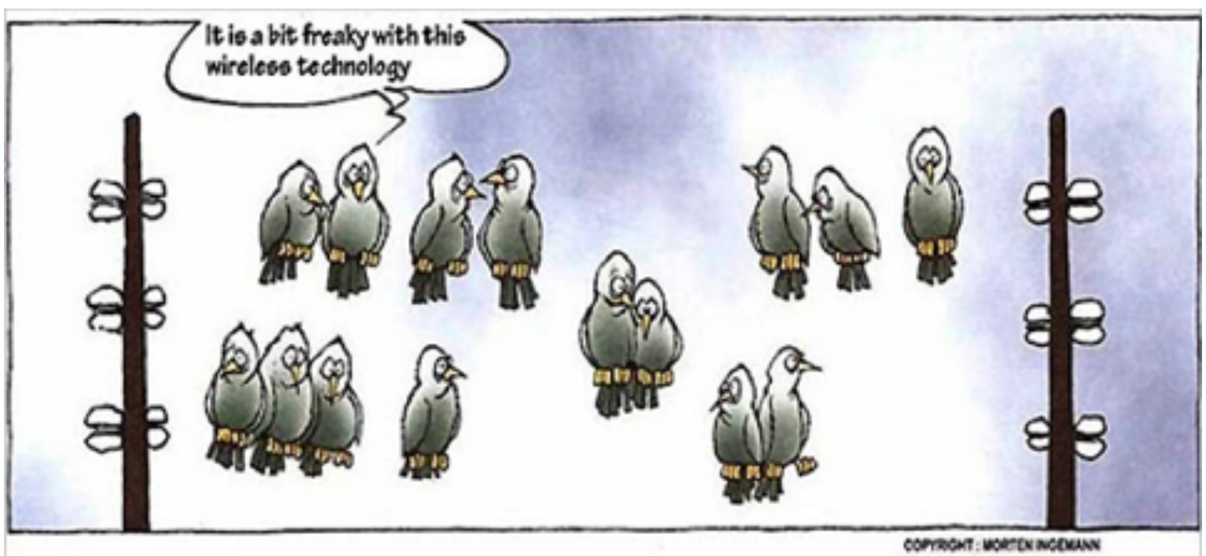
# Wireless

- ”Wireless”:
  - Wireless communication, based on RF radiation
  - Wireless charging, based on inductive power transfer.



# IKEA wireless charging

Standard: ”Qi” (2008), magnetic induction

# Wireless?

- ”Wireless”:
  - Wireless communication, based on RF radiation
  - Wireless charging, based on inductive power transfer.
  - Wireless power transfer via RF (longer range):
    - Wireless Energy Harvesting (WEH), utilizing the wireless communication signals.
    - Wireless power transfer/transmission (WPT), designed for wireless power delivery.

# Wireless power

- Wireless communication is now mature: 5G.
- Power transfer - mobile power and far-field WPT - is still research only, no standards.

- Claimed advantages:
  - ”no wires, no contacts”, ”no batteries”
  - ”ecologically sound” (?)
  - ”reliable energy source (as opposed to ambient energy-harvesting technologies such as solar, thermal and vibration)” (?)

# Wireless power

- Wireless communication and wireless power transfer are currently two independent fields.
- Authors' see merging networks into WIPT - wireless information and power transfer.
- IMHO: too optimistic, many fundamental problems to be solved.

# Requirements

- range: 5 - 100 m (both indoors and outdoors)
- efficiency (end-to-end): a few percent (*my remark:* !)
- ”non-line of sight” support
- mobility support (moving devices, at least up to walking speed)
- ubiquitous (omnipresence) within the network area
- integration between communication and power transfer (WIPT)
- safety and health (comply with regulations)
- energy consumption (make device more power-efficient)

# ULP power requirements, WEH

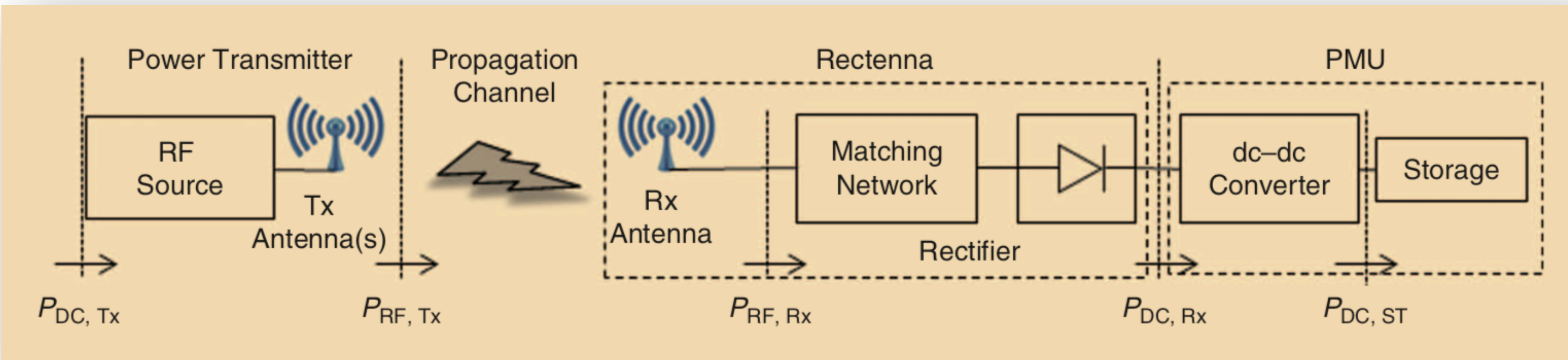
- ULP/sensor standby mode: 20 uW power needed
- Zigbee, Bluetooth: 35 mW
- WiFi: 600 mW in active mode
- low-speed (10-200 kb/s) for sensors and similar
- possible to reach 10-100 uW (digital + RF link) for ULP devices

- Energy harvesting of RF signals (WEH):
  - $10^{-3}$ — $10^{-1}$ uW/cm$^2$ from a GSM900 BS at 25-100 m distance =>
  - receiving antenna: a few cm$^2$ => <1 uW harvested

=> not possible to harvest 10-100 uW.

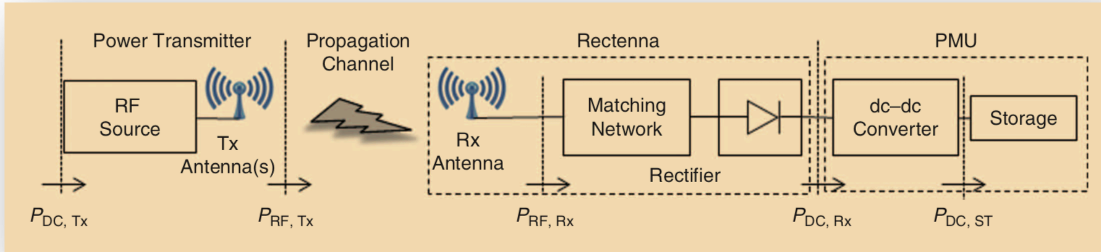
# WPT RF design

- Generic WPT system




$$e = \frac{P_{DC,ST}}{P_{DC,Tx}} = \underbrace{\frac{P_{RF,Tx}}{P_{DC,Tx}}}_{e_1} \underbrace{\frac{P_{RF,Rx}}{P_{RF,Tx}}}_{e_2} \underbrace{\frac{P_{DC,Rx}}{P_{RF,Rx}}}_{e_3} \underbrace{\frac{P_{DC,ST}}{P_{DC,Rx}}}_{e_4}$$

# Efficiency, losses




- DC-to-RF: the power amplifier, very much researched.
- RF-to-RF: the link, must be highly directional (directional antennas, high antenna gain).
- RF-to-DC: much research needed. Varies with the signal type, signal level, matching network, …
- DC-to-DC: much researched.

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