About energy analysis of communication networks

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Outline

- Which kind of energies ?
- Crucial parameters and comparison on their impacts
- Energy Efficiency criterion
  - *Pros and Cons*
  - *Application to file's downloading*
- Application to Massive MIMO (main 5G breakthrough technology)
  - *Practical interest for power transmission*
  - *Power model*
  - *Generation renewal and link to Manufacturing depreciation*
  - *Application to file's downloading with and w/o rebound effect*

Energies ?

- P_{tx}: *power transmission* energy
- $P_{\text{circuitery}}$: *circuitery* energy
  - P_{hardware}: *hardware* circuitery energy (power amplifier, ADC/DAC)
  - $P_{\text{processing}}$: *processing* energy (coding/decoding)
- $P_{\text{manufacturing}}$: *manufacturing* energy related to Life Cycle Analysis (mining, transportation, factory). Requires an economic point of view!

Which energies are taken into account

Often optimize and analyze separately

- P_{tx} in Telecom202a with $P_{\text{processing}} = P_{\text{hardware}} = 0$

- P_{hardware} in Telecom201a

- $P_{\text{processing}}$ rarely taken into account [Grover11, Xiong12]

  Model issue (with R the data rate and C Shannon capacity):
  - $P_{\text{processing}} = a + bR$
  - $P_{\text{processing}} = a - b\log(C - R)$

- $P_{\text{manufacturing}}$ never taken into account except in [Ciblat22]

  Current lecture and lab partly inspired by this paper.

Shannon capacity expression

Reminder

Let R be the data rate. If $R < C$ where C is the Shannon capacity (per channel use-pcu), then it exists a infinite-length code leading to arbitrary small error probability.

Application to Gaussian channel: $z_n = s_n + w_n$

$$C = \log_2 \left(1 + \frac{E_s}{N_0}\right) \text{ (in bpcu)}$$

where $E_s = \mathbb{E}[|s_n|^2]$ (in Joules) and N_0 (in Joules) the level of power spectral density.

Remark: only P_{tx} is taken into account!

Shannon capacity analysis

First, we write the data rate in *bits/s*.

- Let W be the used bandwidth (so send a sample every $1/W$ seconds)
- Then $P_{\rm tx} = E_s W$ (in Watts)

So

$$C = \underbrace{W}_{\substack{\text{Degree of freedom} \\ \text{(DoF/pre-log term)}}} \log_2\left(1 + \underbrace{\frac{P_{\rm tx}}{WN_0}}_{\text{Signal-to-Noise Ratio (SNR)}}\right) \text{(in bits/s)}$$

Analysis:

- E_s constant: linear increasing function wrt W.
- $P_{\rm tx}$ constant: increasing function wrt W but asymptotic limit. But asymptotically in $P_{\rm tx}$ (i.e., for $P_{\rm tx}$ large enough), we get

$$C \propto W \log_2(P_{\rm tx}).$$

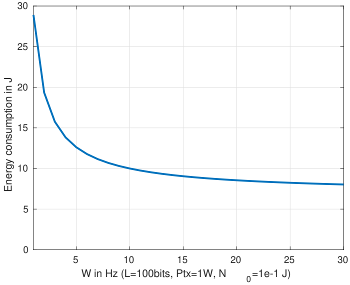
- **Extension to square $n_{\rm tx}$-MIMO:** additional DoF. Now $n_{\rm tx} W$.

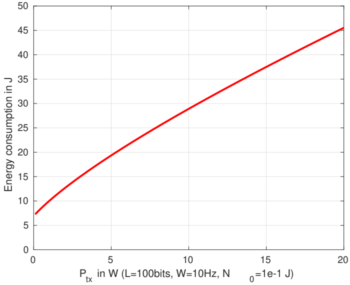
Example: file transmission

- Sending a file of L bits
- Analysis of relevance of increasing W or P_{tx} in terms of energy transmission consumption

$$E_{\text{tx,file}} = \frac{LP_{\text{tx}}}{W \log_2 \left(1 + \frac{P_{\text{tx}}}{WN_0}\right)}$$

Numerical illustrations





$E_{\mathrm{tx,file}}$ vs W (left) and P_{tx} (right)

- DoF (or pre-log term) relevant to decrease transmission energy consumption
  - Done for 5G (compared to 4G) : $n_{\mathrm{tx}} \nearrow$ and $W \nearrow$
  - Data rate increase and <u>also</u> J/bit decrease
  - Warning: only transmission power consumption !
- Irrelevant to increase power (or in-log term) for decreasing energy consumption

Numerical illustrations (cont'd)

	4G	**5G sMIMO**	**5G mMIMO**
Bandwidth (W)	20MHz	100MHz	100MHz
Antennes ($n_{\rm tx}$)	4	8	100
Energy per bit ($E_{\rm tx}/L$)	2.87nJ	0.31nJ	0.027 nJ

with $P_{\rm tx} = 10$W and $N_0 = -170$dBm/Hz.

Result

According to the transmit power, 5G may be until 100 times more efficient than 4G for each transmit bit (as commonly heard or advocated by ETSI)

Energy efficiency criterion

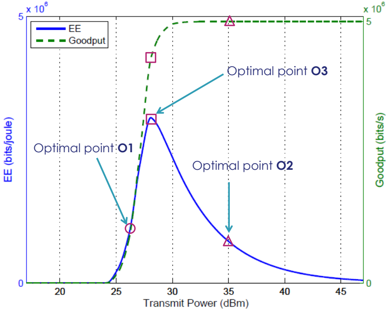
$$
\begin{aligned}
\mathcal{E}_k &= \frac{\#\ \text{total amount of data correctly delivered by user } k}{\#\ \text{total consumed energy by user } k} \\
&= \frac{TC}{TP_{\text{tx}} + TP_{\text{circuitery}}} \\
&= \frac{W \log_2(1 + P_{\text{tx}}/WN_0)}{P_{\text{tx}} + P_{\text{circuitery}}}
\end{aligned}
$$

where

- T duration of transmission
- $P_{\text{circuitery}}$ consumed power due to circuitery
  - here : amplifier, ADC/DAC, processing ($P_{\text{hardware}} + P_{\text{processing}}$) but no manufacturing
  - usually assumed constant wrt P_{tx} [Zapone16]

Energy Efficiency operating point

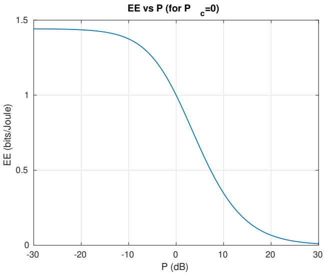
- **O1**: minimum power with data rate constraint ($\geq$ 1Mbits/s)
- **O2**: maximum data rate with power constraint ($\leq$ 35dBm)
- **O3**: maximum energy efficiency



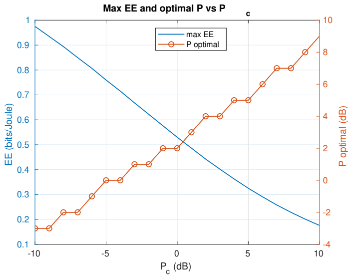
Remarks:

- we do not control the operating point
- consumed energy = transmit power + circuitery power

Energy Efficiency vs P_{tx} or $P_{\text{circuitery}}$



EE vs P_{tx} *(*$P_{\text{circuitery}} = 0$*)*



Max EE (-) and best P_{tx} *(o) vs* $P_{\text{circuitery}}$

- EE makes sense iff $P_{\text{circuitery}} \neq 0$
- EE operating point strongly depends on $P_{\text{circuitery}}$
  - If $P_{\text{circuitery}}$ is large (not efficient), then EE leads to high P_{tx}, and more Green House Gas (GHG)
  - If $P_{\text{circuitery}}$ is low (very efficient), then EE leads to low P_{tx}, and to lowtech (low rate, for instance)

- Q_r remaining battery (%),
- T_t time to transmit the messages (s),
- N_p number of transmitted messages,
- and Data rate (Mbits/s)

		Q_r	T_t (s)	N_p	Data rate
10^7 sent messages	EE	96	297	10^7	4.3
	MTO	85	256	10^7	5
	MPO	89	1 280	10^7	1
Full battery use	EE	0	8 327	2.8×10^8	4.3
	MTO	0	1 800	7×10^7	5
	MPO	0	12 180	9.5×10^7	1

Massive MIMO

Main breakthrough for 5G (Enhanced Mobile BoadBand-eMMB)

Goal

- After how many years, is it useful to replace 4G with 5G (by taking into account all kinds of energies)?
- Tradeoff between P_{tx} and $(P_{\mathrm{hardware}}, P_{\mathrm{processing}})$
- Impact of manufacturing power and rebound effect/Jevons' paradox

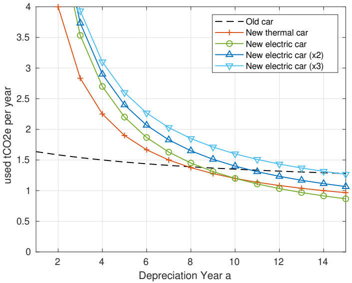
Toy example: energy-saving car

- utilization (per year): $u \to u' = pu$
- manufacturing: f' with a depreciation years and f for old (10-year) car.

$$\text{Energy consumption per year} = \begin{cases} u + \frac{f}{10+a} & \text{old car} \\ pu + \frac{f'}{a} & \text{new car} \end{cases}$$

Toy example illustration

- 1tCO2e for a year of use (10,000km)
- 7tCO2 for manufacturing thermal one or 10 for electrical one
- p : 0.5 (incremental gain) ou 0.2 (thermal $\rightarrow$ electrical)



- Warning: rebound effect (if electrical car, do not feel free to drive)
- Target Carbon Footprint: 2tCO2e per year (car with 10.000km a year still too much!)

Massive MIMO: power model

- K users
- Required Data Rate per user: R.
- N antennas on BS (so $(N-1)$ users can served simultaneously)
- K_u active users with rate R_u at each timeslot

$$P_{\text{tot}} = P_{\text{tx}} + P_{\text{circuitery}} + P_{\text{manufacturing}}$$

where

- [Bjornson15]
$$P_{\text{tx}} = \frac{WN_0}{\eta} \frac{2^{R_u/W} - 1}{N - K_u} \mathcal{D} K_u$$
with η amplifier efficiency and $\mathcal{D}$ depends on propagation model
- $P_{\text{circuitery}}$ circuitery power at both BS and UE with
$$P_{\text{circuitery}} = \underbrace{P_{\text{fix}} + P_{\text{tc}}}_{\text{hardware}} + \underbrace{P_{\text{ce}} + P_{\text{cd}} + P_{\text{lp}}}_{\text{processing}} + P_{\text{bh}}$$
- $P_{\text{manufacturing}} = NP_{\text{m,bs}} + KP_{\text{m,ue}}$ with A the depreciation year, and
$$P_{\text{m},\cdot} = E_{\text{m},\cdot}/(365 \times 24 \times 3600 \times A).$$

Massive MIMO: power model (cont'd)

- P_{fix} sleep power (cooling system for instance)
- P_{tc} hardware power (amplifier, oscillator, ...)

$$P_{\text{tc}} = NP_{\text{bs}} + P_{\text{lo}} + KP_{\text{ue}}$$

- P_{ce} channel estimation power
- P_{cd} coding and decoding power

$$P_{\text{cd}} = K_u R_u (P_{\text{cod}} + P_{\text{dec}})$$

  with P_{cod} and P_{dec} unitary coding and decoding powers
- P_{lp} signal processing power (linear precoding, for instance)

$$P_{\text{lp}} = P_{\text{mc}} + P_{\text{mo}}$$

  with P_{mc} precoding application and P_{mo} precoding computation
- P_{bh} core network power dedicated to this trafic (P_{bt} unitary power)

$$P_{\text{bh}} = K_u R_u P_{\text{bt}}.$$

Massive MIMO: some values

W	20 MHz	$E_{\mathrm{m,bs}}$	60 GJ
N_0	-140 dBm/Hz	$E_{\mathrm{m,ue}}$	0.175 GJ
η	0.39	P_{fix}	18 W
U	1800	P_{bs}	1 W
τ	1	P_{lo}	2 W
L_{ue}	5 Gflops/W	P_{ue}	0.1 W
L_{bs}	12.8 Gflops/W	P_{cod}	0.1 W/(Gb/s)
d_0	$10^{-3.53}$	P_{dec}	0.8 W/(Gb/s)
κ	3.76	P_{bt}	0.25 W/(Gb/s)

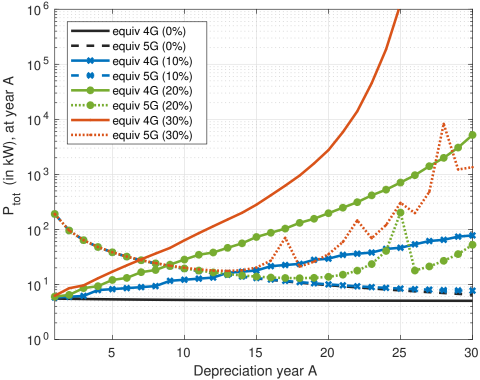
Table: Elementary parameters values

	P_{tx}	P_{fix}	P_{tc}	P_{ce}	P_{cd}	P_{lp}	P_{bh}
$K = 5, R = 10\mathrm{k}$	13	18	22.5	10^{-4}	10^{-5}	0.3	10^{-5}
$K = 50, R = 10\mathrm{M}$	1660	18	1491	0.02	0.5	235	0.15

Table: Involved Power values (in Watts)

Numerical illustrations

- 4G-like: 4 antennas carried out for 10 years
- 5G-like: 100 antennas
- Percentage corresponds to trafic increase per year



References

[Grover11] P. Gover, K. Woyach, and A. Sahai, “Towards a communication-theoretic understanding of system-level power consumption”, *IEEE Jnl of Selected Areas in Com*, vol. 29, no. 8, pp. 1744-1755, August 2011.

[Xiong12] C. Xiong, G. li, Y. Li, and S. Xu, “When and how should decoding power be considered for achieving high energy efficiency?”, PIMRC symposium, 2012

[Zapone16] A. Zappone, E. Björnson, L. Sanguinetti, and E. Jorswieck, “A framework for globally optimal energy-efficient resource allocation in wireless networks”, ICASSP symposium, 2016

[Ciblat22] P Ciblat, “A propos du MIMO massif dans un contexte de sobriété numérique”, Gretsi symposium, 2022

[Bjornson15] E. Björnson, L. Sanguinetti, J. Hoydis, and M. Debbah, “Optimal design of energy-efficient multi-user MIMO systems: ismassive MIMO the answer?”, *IEEE Trans. on Wireless Com.*, vol. 14, no. 6, pp. 3059-3024, June 2015

Appendix

- P_{ce} (channel estimation):

$$P_{\text{ce}} = \frac{W}{U}\frac{4\tau K_u^2}{L_{\text{ue}}}$$

  with U the coherence time of the channel, τ training sequence ratio, and L_{ue} flop/W at UE

- P_{mc} (precoding application):

$$P_{\text{mc}} = W\left(1 - \frac{\tau K_u}{U}\right)\frac{2NK_u}{L_{\text{bs}}}$$

  with L_{bs} flop/W at BS

- P_{mo} (precoding computation):

$$P_{\text{mo}} = \frac{W}{U}\left(\frac{K_u^3}{3L_{\text{bs}}} + \frac{3NK_u^2 + NK_u}{L_{\text{bs}}}\right)$$