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

- *P*_{tx}: *power transmission* energy
- *P*_{circuitery}: *circuitery* energy
 - *P*_{hardware}: *hardware* circuitery energy (power amplifier, ADC/DAC)
 - *P*_{processing}: *processing* energy (coding/decoding)
- *P*_{manufacturing}: *manufacturing* energy related to Life Cycle Analysis (mining, transportation, factory).

Which energies are taken into account

Often optimize and analyze separately

- P_{tx} in Telecom202a with $P_{processing} = P_{hardware} = 0$
- P_{hardware} in Telecom201a
- *P*_{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*_{manufacturing} never taken into account except in [Ciblat22]
 Current lecture and lab partly inspired by this paper.

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: $z_n = s_n + w_n$

$$C = \log_2\left(1 + \frac{E_s}{N_0}\right)$$
 (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 $P_{tx} = E_s W$ (in Watts)

So



Analysis:

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

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

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

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

$$m{E}_{ ext{tx,file}} = rac{L m{P}_{ ext{tx}}}{m{W} \log_2 \left(1 + rac{m{P}_{ ext{tx}}}{m{W} N_0}
ight)}$$

Numerical illustrations



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

- DoF (or pre-log term) relevant to decrease transmission energy consumption
 - Done for 5G (compared to 4G) : $n_{tx} \nearrow$ 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

	4G	5G sMIMO	5G mMIMO
Bandwidth (W)	20MHz	100MHz	100MHz
Antennes (n _{tx})	4	8	100
Energy per bit (E_{tx}/L)	2.87nJ	0.31nJ	0.027 nJ

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

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

$$\mathcal{E}_{k} = \frac{\# \text{ total amount of data correctly delivered by user } k}{\# \text{ total consumed energy by user } k}$$
$$= \frac{TC}{TP_{\text{tx}} + TP_{\text{circuitery}}}$$
$$= \frac{W \log_{2}(1 + P_{\text{tx}}/WN_{0})}{P_{\text{tx}} + P_{\text{circuitery}}}$$

where

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

Energy Efficiency operating point

- O1: minimum power with data rate constraint (> 1Mbits/s)
- O2: maximum data rate with power constraint (< 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 $P_{circuitery}$



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

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

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

Energy Efficiency: example

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

		Qr	T_t (s)	Np	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	8327	$2.8 imes 10^{8}$	4.3
	MTO	0	1 800	7 × 10 ⁷	5
	MPO	0	12 180	$9.5 imes 10^{7}$	1

Massive MIMO

Main breakthrough for 5G (Enhanced Mobile BroadBand-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*_{hardware}, *P*_{processing})
- Impact of manufacturing power and rebound effect/Jevons' paradox

Toy example: energy-saving car

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

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]

$$P_{\rm tx} = \frac{WN_0}{\eta} \frac{2^{R_u/W} - 1}{N - K_u} \mathcal{D}K_u$$

with η amplifier efficiency and D depends on propagation model • $P_{\text{circuitery}}$ circuitery power at both BS and UE with

$$P_{\text{circuitery}} = \underbrace{P_{\text{fix}} + P_{\text{tc}}}_{\text{hardware}} + \underbrace{P_{\text{ce}} + P_{\text{cd}} + P_{\text{lp}}}_{\text{processing}} + P_{\text{bh}}$$

$$P_{\text{manufacturing}} = NP_{\text{m,bs}} + KP_{\text{m,ue}} \text{ with } A \text{ the depreciation year, and}$$

$$P_{\text{m,.}} = E_{\text{m,.}} / (365 \times 24 \times 3600 \times A).$$

Massive MIMO: power model (cont'd)

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

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

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

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

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

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

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

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

Massive MIMO: some values

W	20 MHz	E _{m,bs}	60 GJ
N ₀	-140 dBm/Hz	E _{m,ue}	0.175 GJ
η	0.39	P _{fix}	18 W
U	1800	P _{bs}	1 W
τ	1	P _{lo}	2 W
Lue	5 Gflops/W	P_{ue}	0.1 W
L _{bs}	12.8 Gflops/W	$P_{\rm cod}$	0.1 W/(Gb/s)
d_0	10 ^{-3.53}	$P_{\rm dec}$	0.8 W/(Gb/s)
κ	3.76	P _{bt}	0.25 W/(Gb/s)

Table: Elementary parameters values

	P _{tx}	P _{fix}	$P_{\rm tc}$	P _{ce}	$P_{\rm cd}$	$P_{\rm lp}$	$P_{\rm bh}$
K = 5, R = 10k	13	18	22.5	10 ⁻⁴	10 ⁻⁵	0.3	10 ⁻⁵
K = 50, R = 10M	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



[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.

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Appendix

• *P*_{ce} (channel estimation):

$$P_{\rm ce} = rac{W}{U} rac{4 au K_u^2}{L_{
m ue}}$$

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

• *P*_{mc} (precoding application):

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

with L_{bs} flop/W at BS

• *P*_{mo} (precoding computation):

$$\mathcal{P}_{\mathrm{mo}} = rac{W}{U} \left(rac{\mathcal{K}_{u}^{3}}{3L_{\mathrm{bs}}} + rac{3N\mathcal{K}_{u}^{2} + N\mathcal{K}_{u}}{L_{\mathrm{bs}}}
ight)$$