

About energy analysis of communication networks

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- 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
- $P_{\text{circuitery}}$: *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).

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):

- $P_{\text{processing}} = a + bR$
- $P_{\text{processing}} = a - b \log(C - R)$

- $P_{\text{manufacturing}}$ seldom taken into account except in [Humar11, 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: $z_n = s_n + w_n$

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

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 $P_{\text{tx}} = E_s W$ (in Watts)

So

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

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

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

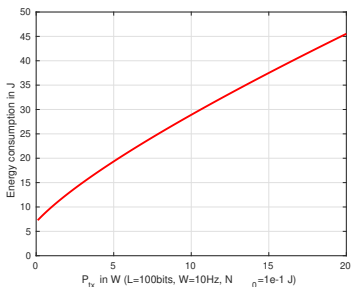
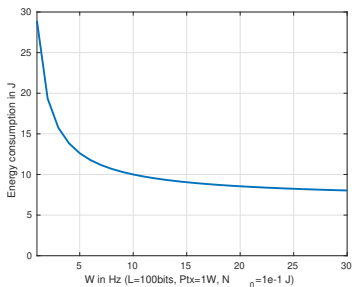
- **Extension to square n_{tx} -MIMO:** additional DoF. Now $n_{\text{tx}} W$

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



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

- DoF (or pre-log term) relevant to decrease transmission energy consumption
 - Done for 5G (compared to 4G) : $n_{\text{tx}} \nearrow$ and $W \nearrow$
 - Data rate increase and also 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_{tx})	4	8	100
Energy per bit (E_{tx}/L)	2.08nJ	0.22 nJ	0.027 nJ

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

Result

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

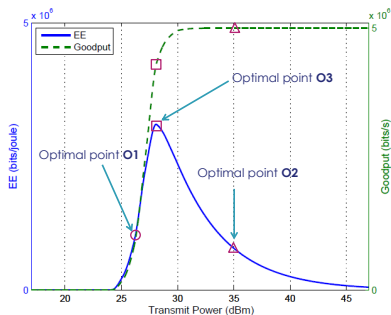
$$\begin{aligned}\mathcal{E}_k &= \frac{\text{\# total amount of data correctly delivered by user } k}{\text{\# total consumed energy by user } k} \\ &= \frac{TC}{TP_{\text{tx}} + TP_{\text{circuitery}}} \\ &= \frac{W \log_2(1 + P_{\text{tx}}/WN_0)}{P_{\text{tx}} + P_{\text{circuitery}}}\end{aligned}$$

where

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

Energy Efficiency operating point

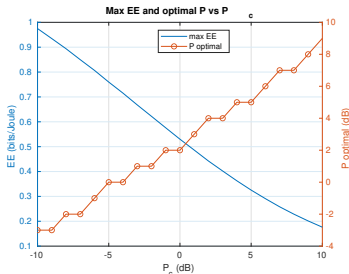
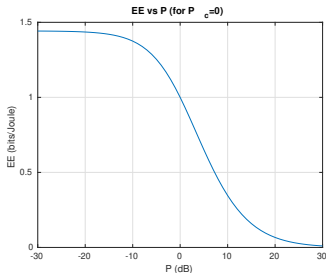
- **O1**: minimum power with data rate constraint (≥ 1 Mbits/s)
- **O2**: maximum data rate with power constraint (≤ 35 dBm)
- **O3**: maximum energy efficiency



Remarks:

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

Energy Efficiency vs P_{tx} or $P_{circuitry}$



EE vs P_{tx} (for $P_{circuitry} = 0$)

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

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

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)

		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

Main breakthrough for 5G (Enhanced Mobile BroadBand-eMNB)

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 $(P_{\text{hardware}}, P_{\text{processing}})$
- Impact of manufacturing power and rebound effect/Jevons' paradox

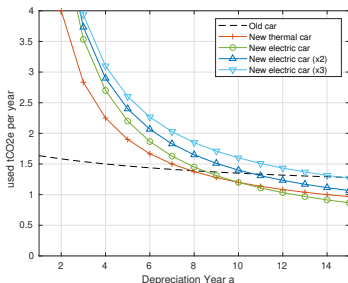
Toy example: energy-saving car

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

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

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 → electrical)



- Warning: rebound effect (if electrical car, do not feel free to drive)
- Target Carbon Fingerprint: 2tCO₂e (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

- $P_{\text{circuitery}}$ circuitry power at both BS and UE with

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

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

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

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 traffic (P_{bt} unitary power)

$$P_{\text{bh}} = K_U R_U P_{\text{bt}}$$

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
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)

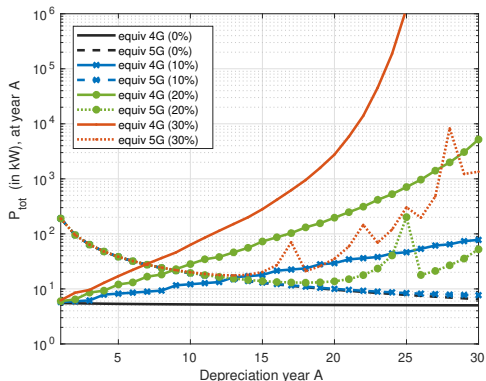
Table: Elementary parameters values

	P_{tx}	P_{fix}	P_{tc}	P_{ce}	P_{cd}	P_{lp}	P_{bh}
$K = 5, R = 10k$	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 traffic increase per year



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- [Xiong12] C. Xiong, G. li, Y. Li, and S. Xu, “When and how should decoding power be considered for achieving high energy efficiency?,” PIMRC, 2012.
- [Zapone16] A. Zappone, E. Björnson, L. Sanguinetti, and E. Jorswieck, “A framework for globally optimal energy-efficient resource allocation in wireless networks,” ICASSP, 2016.
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- [Bjornson15] E. Björnson, L. Sanguinetti, J. Hoydis, and M. Debbah, “Optimal design of energy-efficient multi-user MIMO systems: is massive MIMO the answer?,” *IEEE Trans. on Wireless Com.*, 2015.

- P_{ce} (channel estimation):

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

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

- P_{mc} (precoding application):

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

with L_{bs} flop/W at BS

- P_{mo} (precoding computation):

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