Fundamentals of Energy Efficiency in Dual Band Wireless Links Using Sleep Modes

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Research Questions

From an energy efficiency (bit/J) perspective: How should a base station be configured?

Paper A

How much Transmit Power, Bandwidth, Antennas Should a BS use?

Paper B

How to to use a FR1 band together with sleep modes and a high frequency band?

Paper A: Fundamentals of Energy-Efficient Wireless Links: Optimal Ratios and Scaling Behaviors. Anders Enqvist, Özlem Tuğfe Demir, Cicek Cavdar and Emil Björnson Presented at IEEE Vehicular Technology Conference (VTC) 2024 Singapore.

Paper B: Energy-Efficient Dual-Band Communication: How to Allocate Traffic to Sub-THz Carriers? Anders Enqvist, Emil Björnson and Cicek Cavdar, Submitted to ICCSPA Conference 2026 Madrid.

Paper A: Fundamentals of Energy-Efficient Wireless Links: Optimal Ratios and Scaling Behaviors

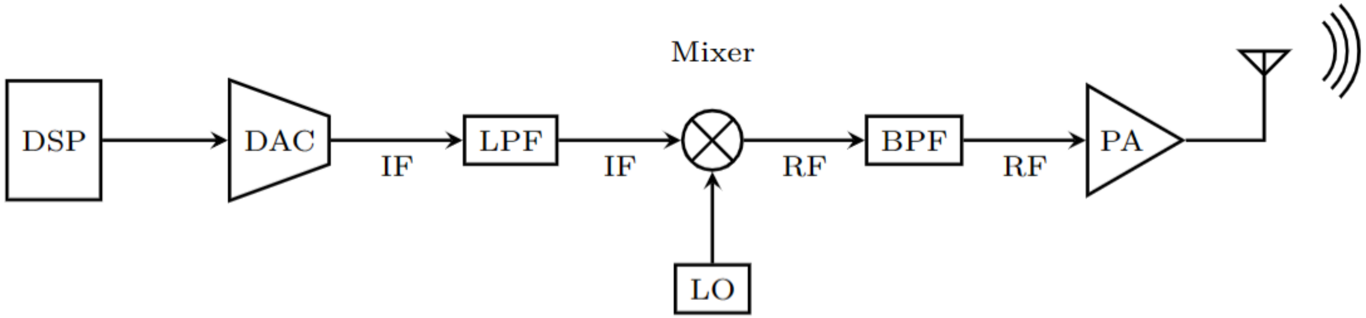
Anders Enqvist, Özlem Tuğfe Demir, Cicek Cavdar and Emil Björnson Presented at IEEE Vehicular Technology Conference (VTC) 2024 Singapore.

Motivation

- How should the BS be configured to maximize the energy efficiency in the downlink?
- We discover new relationships between power, bandwidth and the number of antennas at the optimum point
- We propose a new optimization algorithm which converges to the optimum EE-point

Power Consumption Model

- Power amplifier efficiency factor κ
- Constant circuit power μ
- Per Transceiver chain circuit power D_0
- Sample processing power ν



Parameter	Value
Passive circuit power: μ	100 mW
Transceiver chain power consumption: D_0	20 mW
Sample processing power consumption: ν	10^{-10} J/sample
Power amplifier efficiency: κ	0.4
Computational efficiency: η	10^{-11} J/bit
Maximum bandwidth: $B_{\max}$	10 GHz
Maximum power: $P_{\max}$	40 dBm
Maximum number of transmit antennas: $M_{\max}$	512
Receiver noise power spectral density: N_0	−174 dBm/Hz
Channel gain: β	−110 dB

$$\mathrm{PC} = P/\kappa + \mu + (D_0 + \nu B)M + \eta B \log_2\left(1 + \frac{MP\beta}{BN_0}\right)$$

$$\mathrm{EE} = \frac{B \log_2\left(1 + \frac{MP\beta}{BN_0}\right)}{P/\kappa + \mu + (D_0 + \nu B)M + \eta B \log_2\left(1 + \frac{MP\beta}{BN_0}\right)}$$

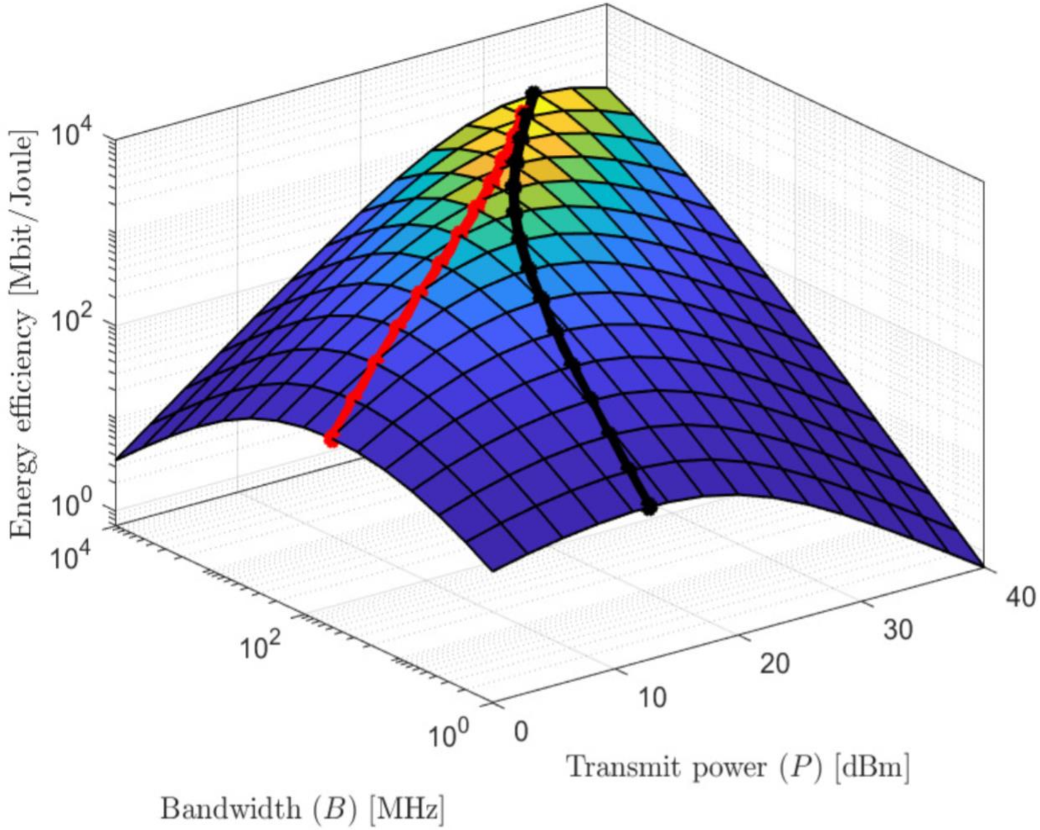
Optimal ratio: Power per antenna

- The input transmit power is equal to the passive power consumption in the transceiver chains for all the antennas plus the power dissipated in the ADC / DAC

Theorem 2. *If the solution* $(P_{\text{opt}}, M_{\text{opt}})$ *that maximizes the EE in* (5) *for a given value of* B *satisfies* $P_{\text{opt}} \leq P_{\max}$ *and* $M_{\text{opt}} \leq M_{\max}$*, then the following relation holds:*

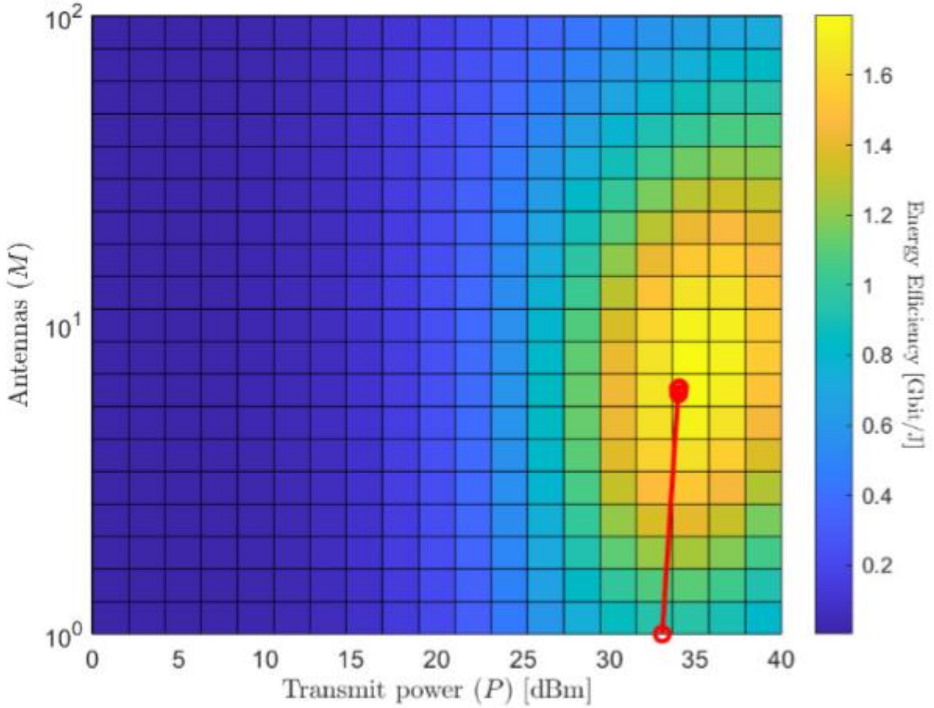
$$\frac{P_{\text{opt}}}{\kappa} = (D_0 + \nu B) M_{\text{opt}}$$

- We also prove that the solution will always be at maximum power or bandwidth



Optimization Algorithm 1

- An alternating optimization algorithm for power, bandwidth and antenna number is developed to maximize EE(P,B,M)



$$\mathrm{EE} = \frac{B\log_2\left(1+\frac{MP\beta}{BN_0}\right)}{P/\kappa + \mu + (D_0+\nu B)M + \eta B\log_2\left(1+\frac{MP\beta}{BN_0}\right)}$$

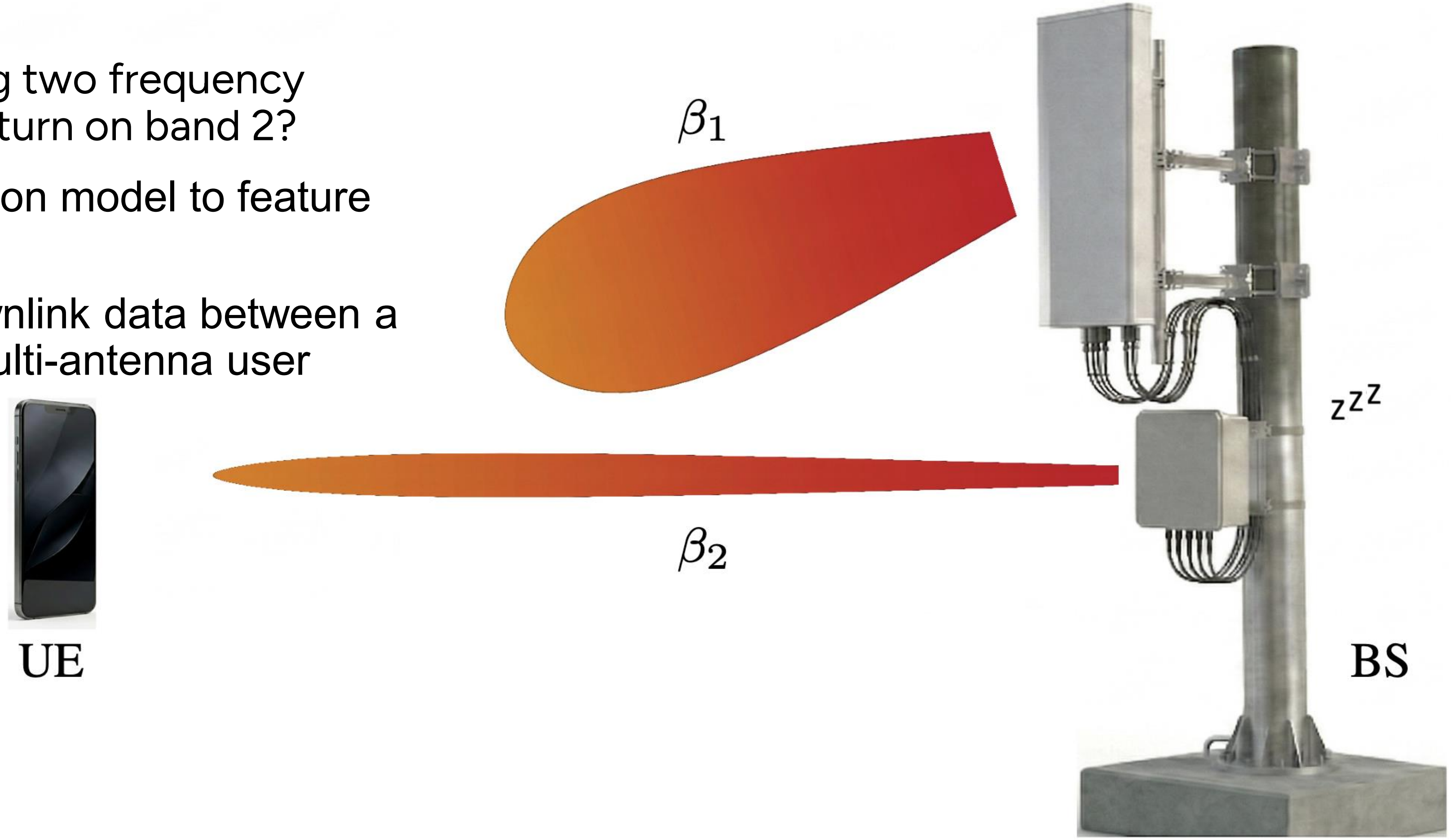
while $\mathrm{EE}_i - \mathrm{EE}_{i-1} > \delta$ **do**
  use Lemma 1: calculate P and $\mathrm{EE}(P, B_{\max})$
  if $(P \geq P_{\max})$ **then**
    $P = P_{\max}$
  end if
  use Lemma 2: calculate B and $\mathrm{EE}(P_{\max}, B)$
  if $(B \geq B_{\max})$ **then**
    $B = B_{\max}$
  end if
  if $\mathrm{EE}(P_{\max}, B) \geq \mathrm{EE}(P, B_{\max})$ **then**
    $P = P_{\max}$
  else
    $B = B_{\max}$
  end if
  use Lemma 3: update M for these values of P and B
  if $(M \geq M_{\max})$ **then**
    $M = M_{\max}$
  end if
  update $i = i + 1$
  update $\mathrm{EE_i}(P, B, M)$
end while

Paper B: Energy-Efficient Dual-Band Communication: How to Allocate Traffic to Sub-THz Carriers?

Anders Enqvist, Emil Björnson and Cicek Cavdar. Submitted to Madrid 2026

Motivation

- **Objective:** Maximize EE under a rate constraint by introducing Sleep Modes.
- In case of a base station utilizing two frequency bands, when is it EE-optimal to turn on band 2?
- We extend the power consumption model to feature sleep modes
- we consider how to transfer downlink data between a dual-band base station and a multi-antenna user equipment to maximize EE.



Dual band sleep modes

-
- Active Rate in each band $R_i = B_i \log_2 \left(1 + \frac{P_i M_i N_i \beta_i}{B_i N_0}\right)$ bit/s
- Power consumption in each band $P_{a,i} = \frac{P_i}{\kappa_i} + \mu_i + (D_{0,i} + \nu_i B_i) M_i$
- Deep Sleep power consumption in each band $P_{s,i} = \mu_i.$
- Average power consumption in each band $P_{\text{avg},i} = \alpha_i P_{a,i} + (1 - \alpha_i) P_{s,i}$
- For a needed rate, how should the total EE be maximized? $\text{EE}_{\text{dual}} = \frac{\alpha_1 B_1 \log_2 (1 + c_1 P_1^2) + \alpha_2 B_2 \log_2 (1 + c_2 P_2^2)}{\alpha_1 \frac{2P_1}{\kappa_1} + \alpha_2 \frac{2P_2}{\kappa_2} + \mu_1 + \mu_2}$

Problem Solution Regions 1 and 2

- Region 1: up to $R \leq R_1^*$ only use FR1 and sleep part of the time

$$\mathrm{EE}_{1,\mathrm{opt}} \neq \mathrm{EE}_{2,\mathrm{opt}}$$

$$\mathrm{EE}_{1,\mathrm{opt}} > \mathrm{EE}_{2,\mathrm{opt}}$$

- Band 1 is more EE than Band 2

$$R_i^* = B_i \log_2\left(1 + \frac{P_i^* M_i^* N_i \beta_i}{B_i N_0}\right) = B_i \log_2(u^*)$$

$$u^* = \frac{-2}{W_0\left(-2e^{-2}\right)} \approx 4.9216$$

$$P_i^* = \sqrt{\frac{u^* - 1}{c_i}}$$

$$M_i^* = \frac{P_i^*}{\kappa_i(D_{0,i} + \nu B_i)}$$

$$c_i = \frac{N_i \beta_i}{\kappa_i(D_{0,i} + \nu_i B_i) B_i N_0}$$

$$\alpha_i = R/R_i^*$$

- Region 2: Only use FR1 only without sleeping. There is an exponential increase in power consumption to meet rate requirement

$$P_1(R_1) = \sqrt{c_1^{-1}(2^{R_1/B_1} - 1)} \qquad R_1^* \leq R \leq R_{bp}$$

- By equating the derivatives $\frac{dP_{\mathrm{avg},1}}{dR_1} = \frac{dP_{\mathrm{avg},2}}{dR_2}$ we obtain a breakpoint activation point for Band 2

$$R_{bp} = B_1 \log_2(1 + c_1 P_{1,bp}^2)$$

$$P_{1,bp} = \left(\frac{\kappa_1 B_1 \sqrt{u^* - 1}}{\kappa_2 B_2 \sqrt{c_2} \ln(u^*)}\right) + \sqrt{\left(\frac{\kappa_1 B_1 \sqrt{u^* - 1}}{\kappa_2 B_2 \sqrt{c_2} \ln(u^*)}\right)^2 - \frac{1}{c_1}}$$

$$\mathrm{EE}_{\mathrm{dual}} = \frac{\alpha_1 B_1 \log_2\left(1 + c_1 P_1^2\right) + \alpha_2 B_2 \log_2\left(1 + c_2 P_2^2\right)}{\alpha_1 \frac{2P_1}{\kappa_1} + \alpha_2 \frac{2P_2}{\kappa_2} + \mu_1 + \mu_2}$$

Ideal Problem Solution Regions 3 and 4

- Region 3: Keep Band 1 at constant power and rate. Increase power consumption linearly with rate by activating Band 2 at a higher time fraction (alpha)

$$R_{bp} < R \leq R_{\text{sat}}.$$

$$\alpha_2(R) = \frac{R_2}{B_2 \log_2(u^*)}$$

$$P_{\text{avg}}(R) = \left(\frac{2P_{1,\text{bp}}}{\kappa_1} + \mu_1\right) + \left(\alpha_2(R)\frac{2P_2^*}{\kappa_2} + \mu_2\right)$$

$$R_{\text{sat}} = R_{\text{bp}} + B_2 \log_2(u^*)$$

- Region 4: Don't sleep and there is an exponential increase in power consumption to meet rate requirement

$$R > R_{\text{sat}}$$

- Need to solve these non-linear equations

$$\begin{cases} \frac{1+c_1 P_1^2}{\kappa_1 B_1 c_1 P_1} = \frac{1+c_2 P_2^2}{\kappa_2 B_2 c_2 P_2} \\ B_1 \log_2(1 + c_1 P_1^2) + B_2 \log_2(1 + c_2 P_2^2) = R. \end{cases}$$

- Power Consumption increases exponentially.
- In the large rate limit we have

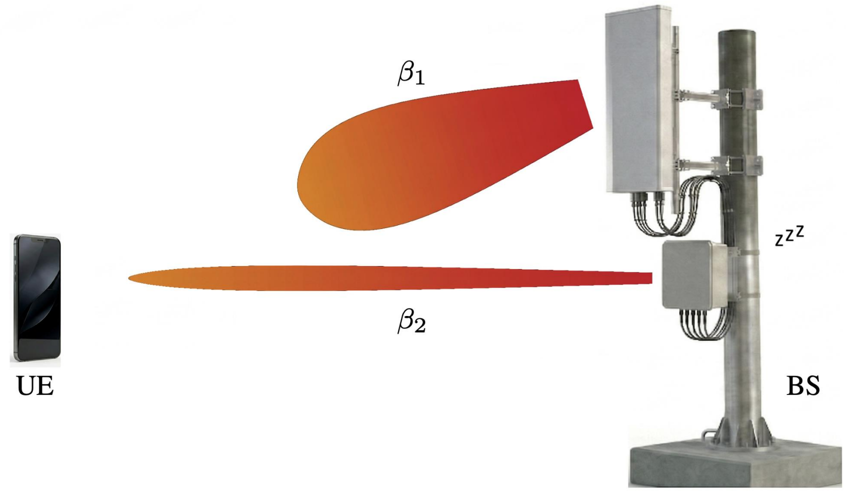
$$\lim_{R\to\infty} \frac{P_1(R)}{P_2(R)} = \frac{\kappa_1 B_1}{\kappa_2 B_2}$$

$$\text{EE}_{\text{dual}} = \frac{\alpha_1 B_1 \log_2\left(1 + c_1 P_1^2\right) + \alpha_2 B_2 \log_2\left(1 + c_2 P_2^2\right)}{\alpha_1 \frac{2P_1}{\kappa_1} + \alpha_2 \frac{2P_2}{\kappa_2} + \mu_1 + \mu_2}$$

Numerical Results

Simulation Parameters

Parameter	**Value** (FR1, FR2)
Passive circuit power μ_1, μ_2	1000 mW, 1000 mW
Transceiver chain power: $D_{0,1}$ $D_{0,2}$	100 mW, 10 mW
Sample processing energy: ν_1, ν_2	$10^{-10}, 10^{-11}$ J/sample
Power amplifier efficiency: κ_1, κ_2	0.4, 0.05
Carrier bandwidths B_1, B_2	100 MHz, 400 MHz
Maximum power: $P_{\max,1}, P_{\max,2}$	40 dBm, 20 dBm
Maximum transmit antennas: $M_{\max,1}, M_{\max,2}$	32, 2048
Receiver noise power spectral density: N_0	−174 dBm/Hz
Channel gain (FR1, FR2): β_1, β_2	−126 dB, −153 dB
Receive antennas N_1, N_2	4, 64



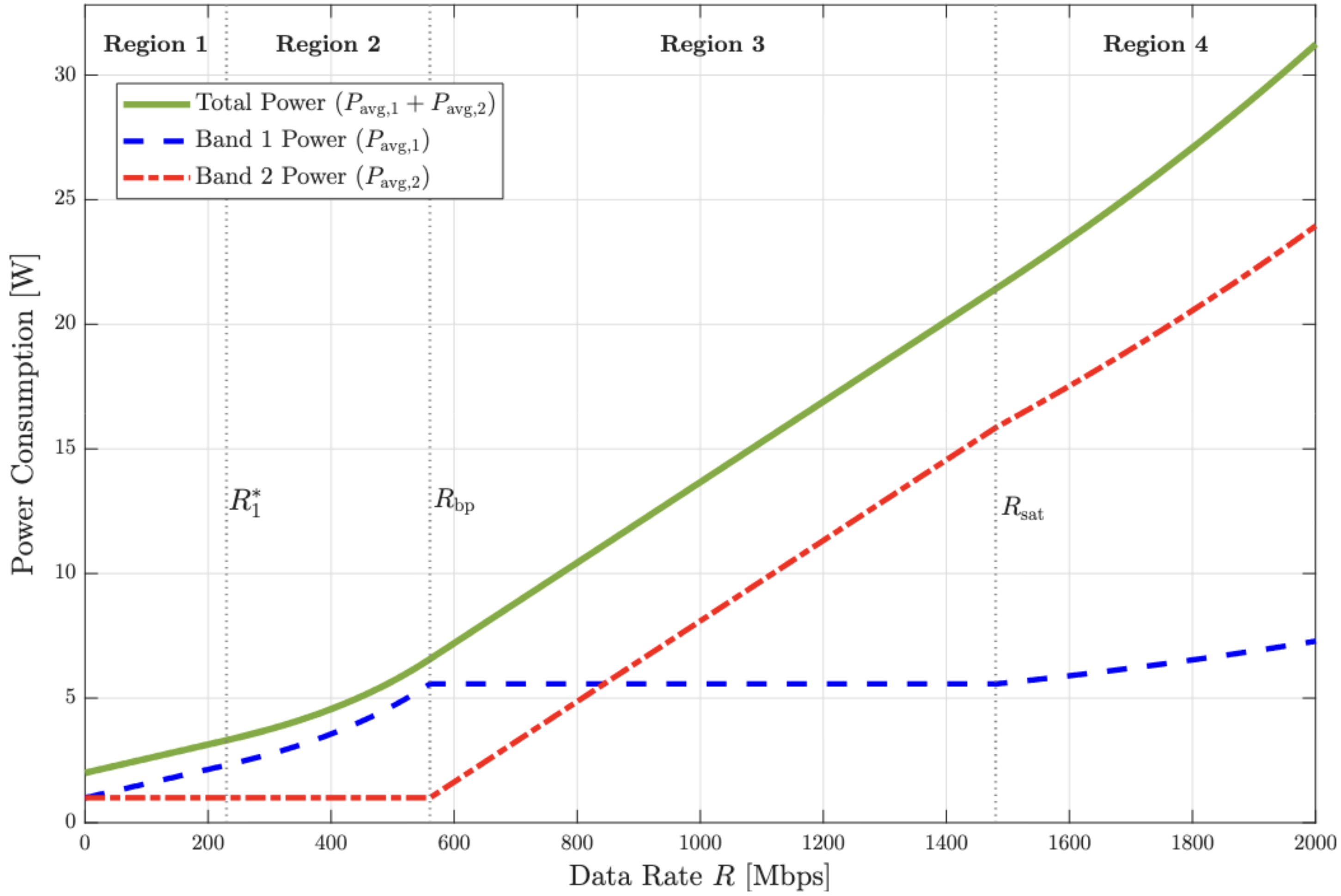
Combined PC

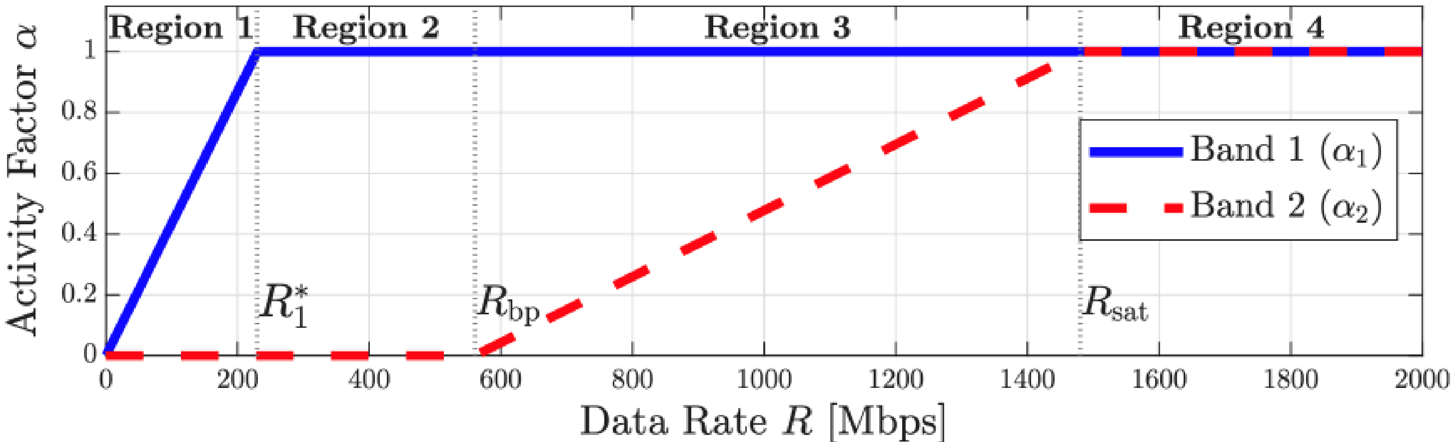
- PC of FR1 in blue
- PC of band 2 in red
- Combined FR1 and band 2 PC in green
- Combined PC in green grows first linearly in region 1, then exponentially in region 2 and linearly again in region 3 and exponentially in region 4

$$\underset{\alpha_1,\alpha_2,P_1,P_2,M_1,M_2}{\text{minimize}} \quad \sum_{i=1}^{2} P_{\text{avg},i}$$

$$\text{subject to} \quad \sum_{i=1}^{2} \alpha_i R_i = R$$

$$0 \leq P_i,\ 0 \leq M_i,\ 0 \leq \alpha_i \leq 1$$





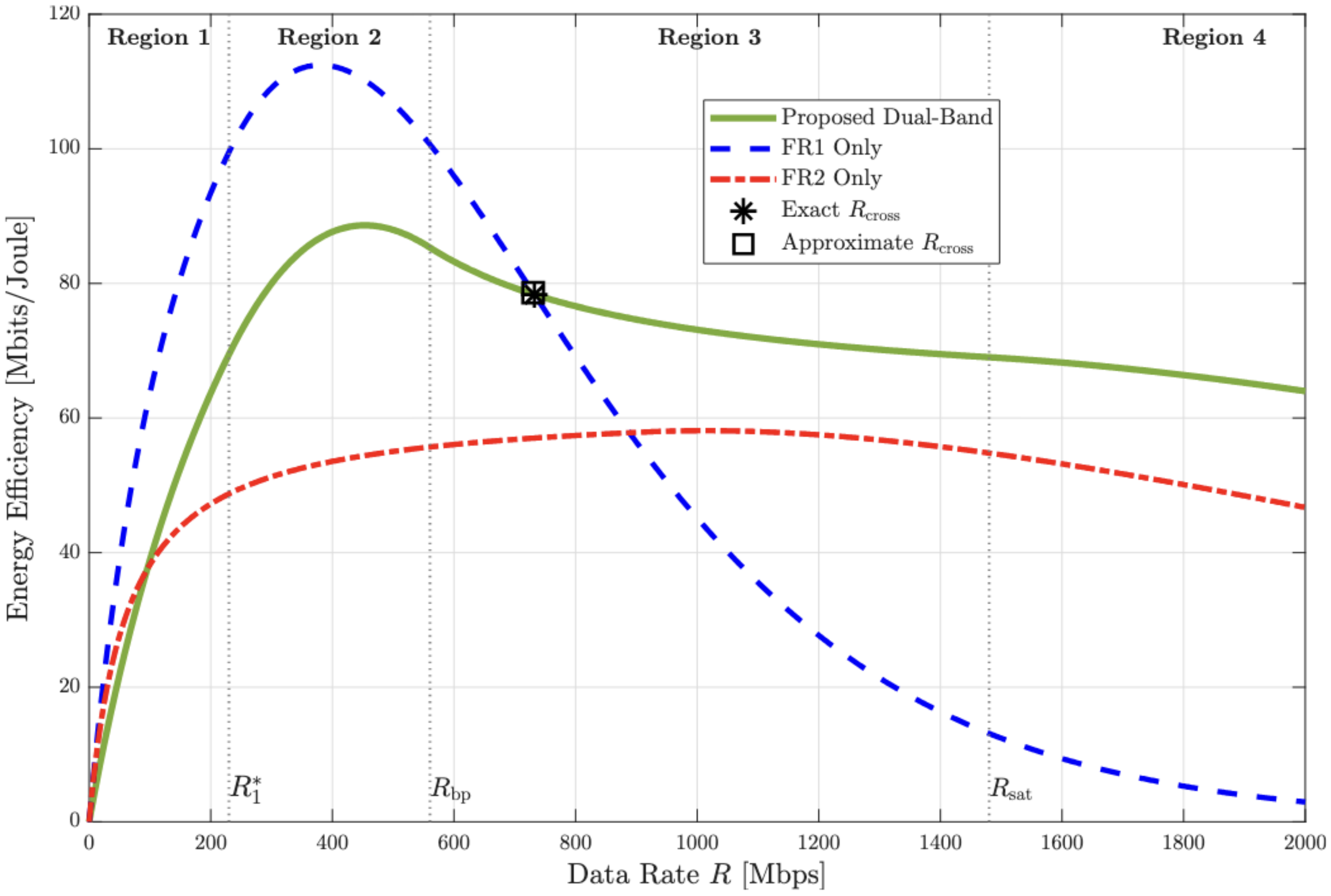
EE in dual band BS

- EE of using only FR1 in blue
- EE of using only FR2 in red
- Combined FR1 and FR2 EE in green

$$R_{cross} \approx -C\left(\frac{\kappa_2 R_2^*}{2P_2^*}\right) - \frac{2B_1}{\ln 2} W_{-1}(Z)$$

$$C = \frac{2P_{1,bp}}{\kappa_1} + \mu_2 - \left(\frac{2P_2^*}{\kappa_2 R_2^*}\right) R_{bp}$$

$$Z = -\frac{\kappa_2 R_2^* \ln 2}{2P_2^* B_1 \kappa_1 \sqrt{c_1}} \exp\left(-\frac{C\kappa_2 R_2^* \ln 2}{4P_2^* B_1}\right)$$



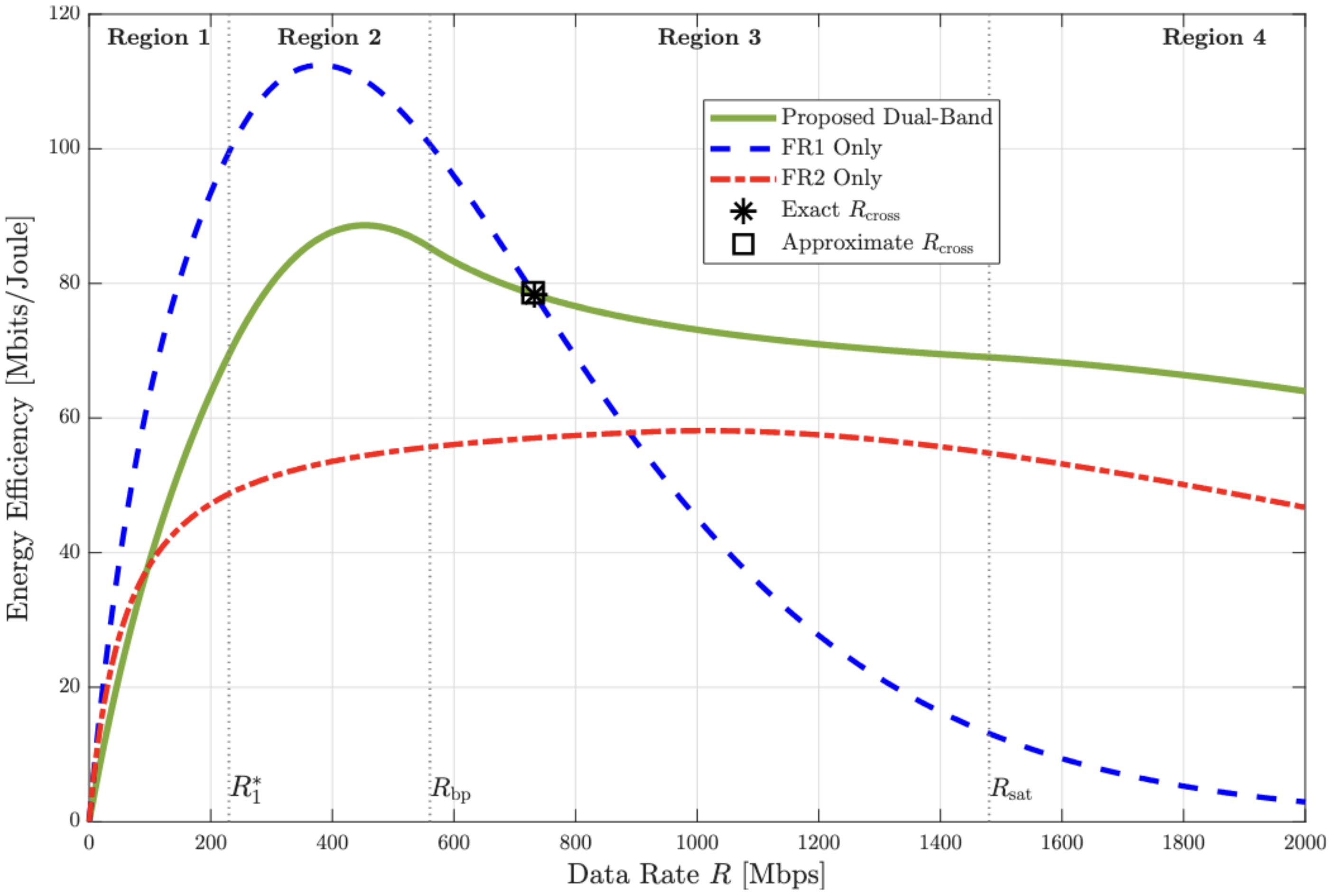
EE in dual band BS

- If Band 2 is already active, start allocating bits to it after Rbp
- If Band 2 is not turned on then activate Band 2 at crossover rate and allocate Rcross – Rbp bits to it (most EE way to operate a BS)

$$R_{cross} \approx -C\left(\frac{\kappa_2 R_2^*}{2P_2^*}\right) - \frac{2B_1}{\ln 2} W_{-1}(Z)$$

$$C = \frac{2P_{1,bp}}{\kappa_1} + \mu_2 - \left(\frac{2P_2^*}{\kappa_2 R_2^*}\right) R_{bp}$$

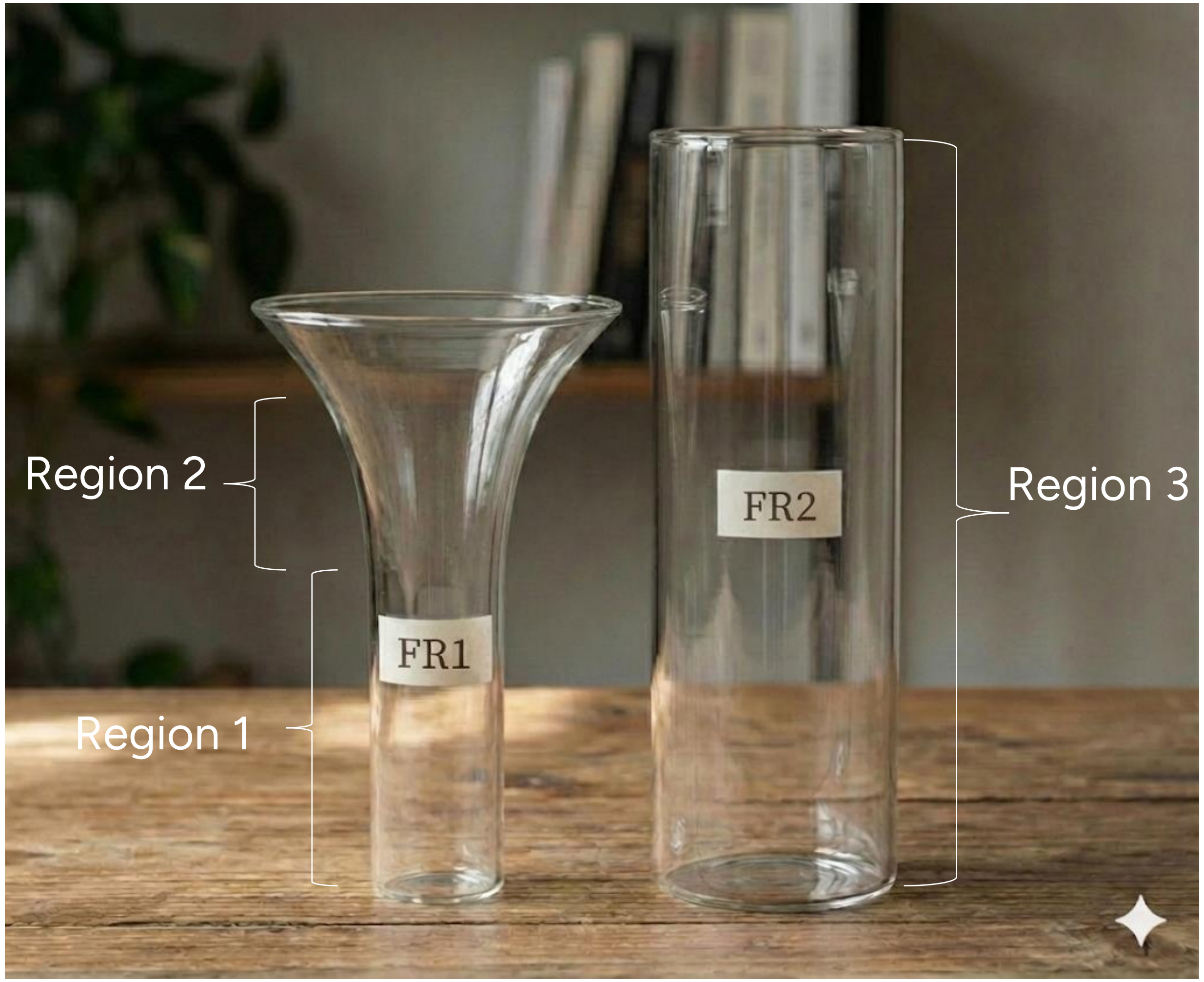
$$Z = -\frac{\kappa_2 R_2^* \ln 2}{2P_2^* B_1 \kappa_1 \sqrt{c_1}} \exp\left(-\frac{C\kappa_2 R_2^* \ln 2}{4P_2^* B_1}\right)$$



$$\mathrm{EE_{dual}} = \frac{\alpha_1 B_1 \log_2\left(1 + c_1 P_1^2\right) + \alpha_2 B_2 \log_2\left(1 + c_2 P_2^2\right)}{\alpha_1 \frac{2P_1}{\kappa_1} + \alpha_2 \frac{2P_2}{\kappa_2} + \mu_1 + \mu_2}$$

Modified Waterfilling

- Problem can be likened to how one should pour water into these two vases to maximize the sum of the height of the water.
- First allocate water to FR1, then allocate water to FR2



Region	Rate Range R	FR1 Status	FR2 Status	Total PC Scaling
1	$0 < R < R_1^*$	Partially Active ($\alpha_1 < 1$)	Off ($\alpha_2 = 0$)	Linear (FR1 duty-cycled)
2	$R_1^* < R < R_{\text{bp}}$	Fully active ($\alpha_1 = 1$)	Off ($\alpha_2 = 0$)	Exponential (FR1 saturated)
3	$R_{\text{bp}} < R < R_{\text{sat}}$	Fully active ($\alpha_1 = 1$)	Partially Active ($\alpha_2 < 1$)	Linear (FR2 duty-cycled)
4	$R > R_{\text{sat}}$	Fully active ($\alpha_1 = 1$)	Fully active ($\alpha_2 = 1$)	Exponential (Both saturated)

Movie Time


FR
FR
FR
FR

Summary

- We developed an optimization algorithm which converges to the optimum EE-point

- It is EE-optimal to alternate transmitting at the optimum point with using sleep modes
- the PC can scale linearly with the transmitted rate

- If Band 2 is not turned on then activate Band 2 at crossover rate Rcross and allocate (Rcross – Rbp) bits to it
- If Band 2 is already active, start allocating traffic to it for residual rates higher than Rbp

Thank you!

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