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Optimal Energy-Delay Tradeoff for Mobile Edge Generation (MEG)

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Background: What is LAM?

Large generative model (LAM) is reshaping the way to develop AI in all industries

Human-computer dialogue by ChatGPT

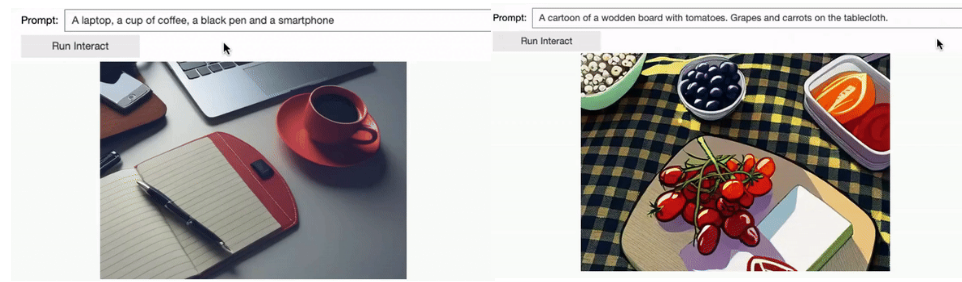


Image Generation & Editing by Nvidia

Key Concept & Advantage

- **LGM: large-scale** neural networks (NNs) with **human-like AI-generated contents (AIGC)** capabilities
- Built to **understand & create multimodal contents** across text, images, audios/music, videos, point clouds, etc. like human **experts**
- Innovatively support **smart human-computer dialogue/interaction**, infeasible in the past

Background: LAM vs. Conventional AI

Popular LAMs

Large language models (LLMs)

ChatGPT, deepseek, Meta Llama 3 …

Multi-modal visual generative model

Stable Diffusion, DALL·E, SORA …

LAM

- Generative AI (GAI) paradigm
- Model scale: billions/trillions of parameters
- Use case: AIGC/AI-generated everything (AIGX)
- Multimodal: text, image, video, audio …
- Inference latency: high (even for generating a single image/video)

Conventional AI Models

- Discriminative AI (DAI) paradigm
- Model scale: <100 millions parameters
- Use case: classification & regression
- Multimodal: lack of support
- Inference latency: low, millisecond-level/batch

Why Mobile Edge Generation (MEG)

Current AIGC: Centralized Generation

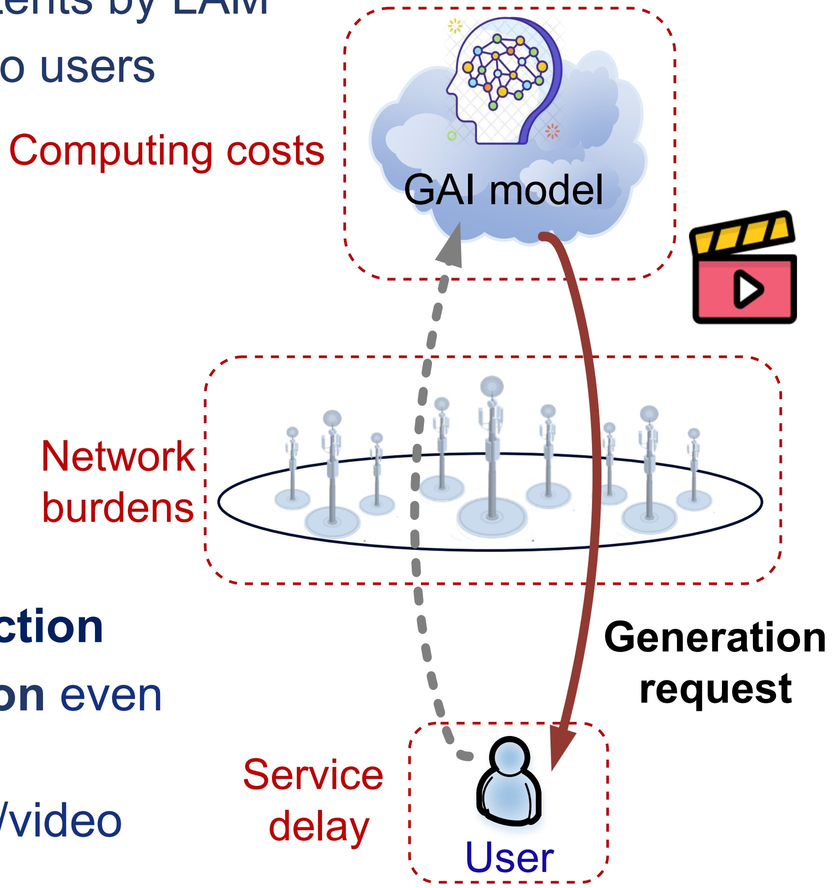
- **Upload:** Users upload request (e.g., prompt) & local data
- **Generate:** Cloud/edge server generates contents by LAM
- **Download:** Transmit large-volume contents to users

Limitations

- Large **communication** overheads for AIGC downloads
- High **delay** for massive user scenarios
- Huge **computing** and storage costs for LAM
- Privacy leakage risks

Cannot offer intensive human-machine interaction

- **Example: DeepSeek experiences congestion** even for text generation
- **Resource scarcity** is more serious for image/video generation



(Centralized Generation)

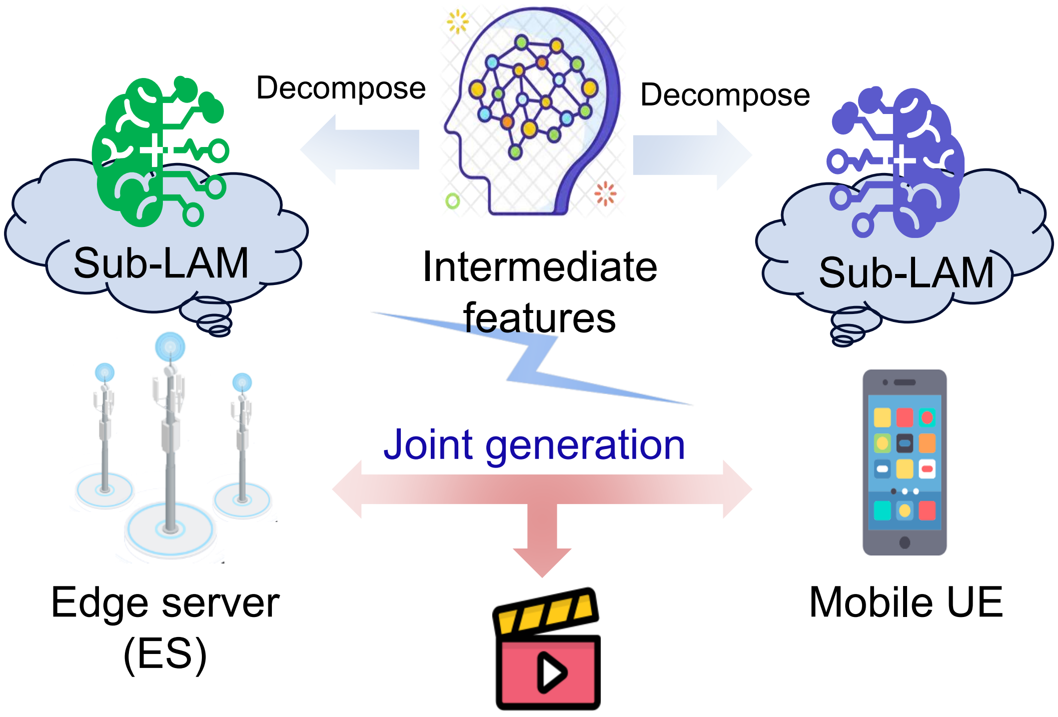
Motivation of Mobile Edge Generation (MEG)

Key idea of MEG

- Decompose LAM into distributed sub-models on different edge devices (ESs, UEs)
- 6G-connected ES-UE co-generation

Advantage

- Transmit low-dimension features, rather than large-volume generated contents
- Affordable computing complexity for mobile devices
- Enhance privacy and data security by feature coding
- Customized local LAM according to user preference



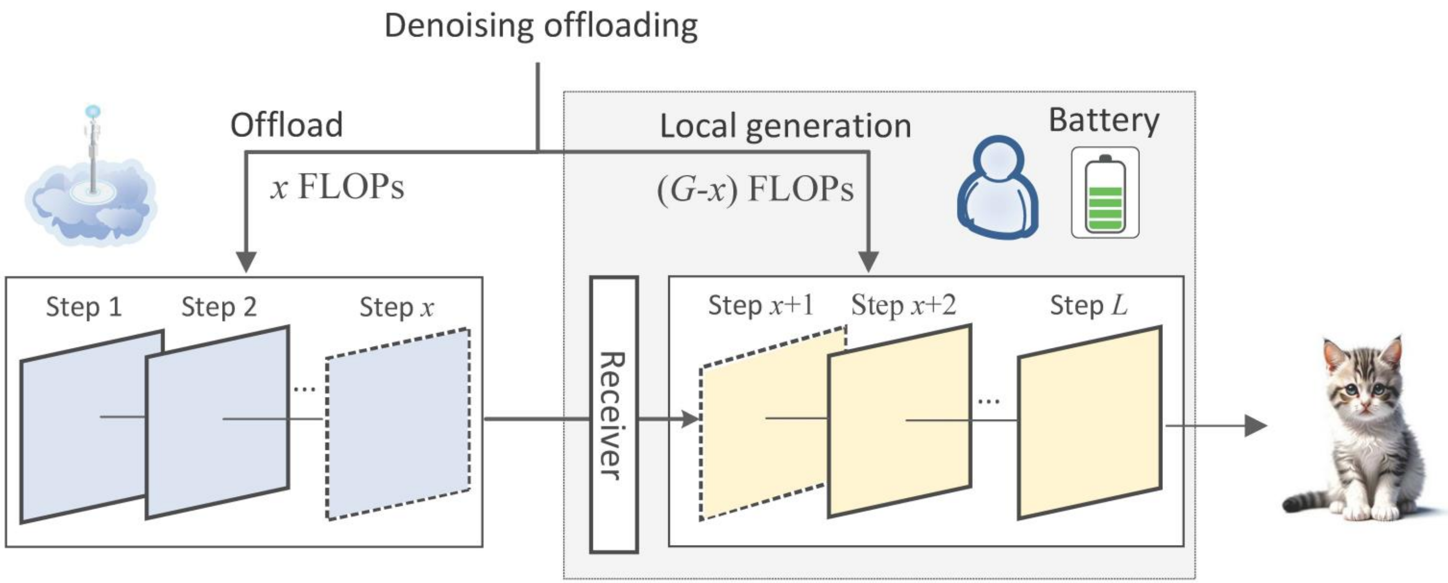
Key problem of MEG

- Low-latency collaborative generation mechanism?
- How to balance between latency and mobile energy consumption?

MEG: From Model Split to Generation Split

(Conventional) Model split based MEG

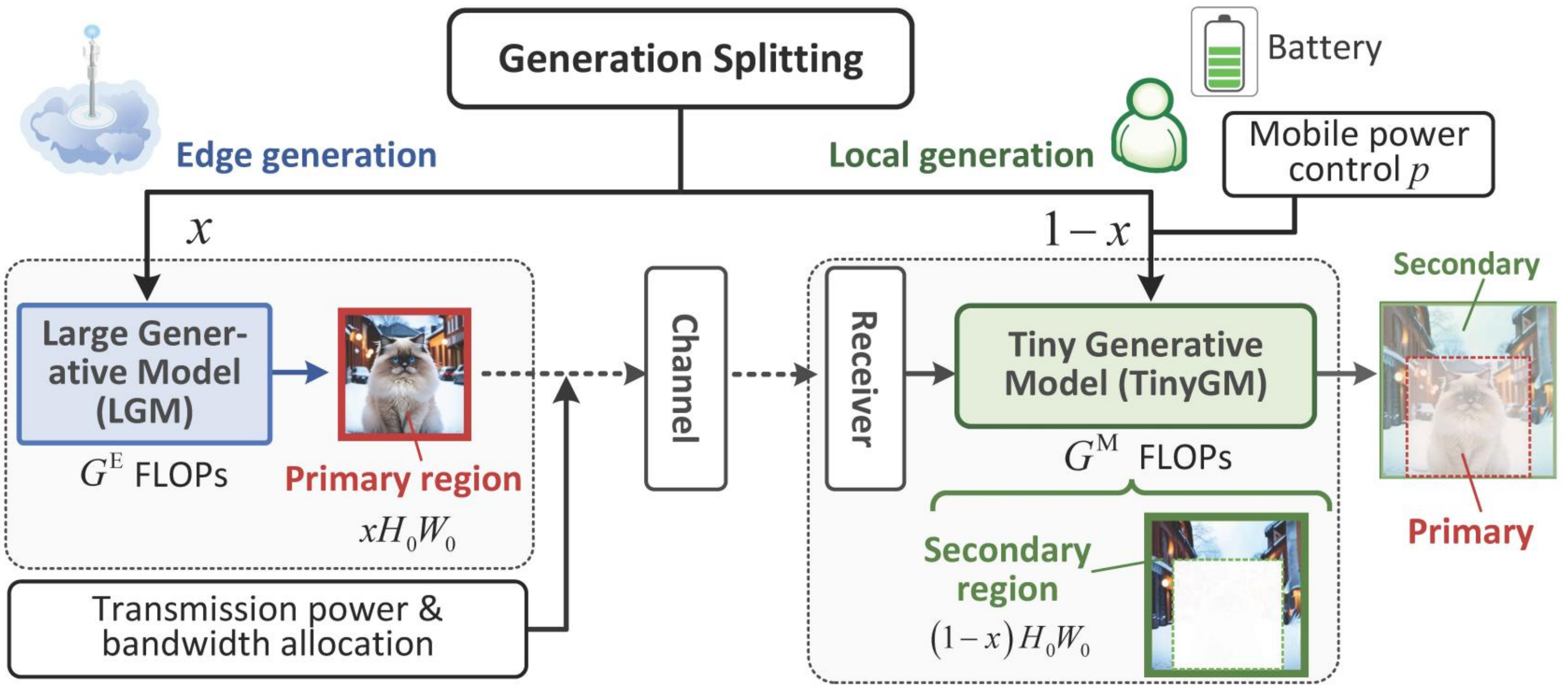
- Split LAM into two sub-models at specific neural layer
- **Pros**
  (i) Transmit intermediate features -> low transmission latency
  (ii) Achieve same quality with centralized generation
- **Cons**
  (i) Generation costs on edge/mobile devices & trans. cost inherently depend on predefined LGM structure (hidden layers) -> limits the scheduling flexibility
  (ii) Same complexity over the entire content -> ignore semantic difference



MEG: From Model Split to Generation Split

(Our proposed) Generation split based MEG

- Split generated content into primary region and secondary region
- **Exploit different model complexities and devices** over different regions
  - Edge: high-complexity LGM -> generate primary region & transmit to mobile
  - Mobile: TinyGM -> complete second region
- Mobile generation cost is **fully controllable** by **generation splitting ratio**



System Model

- **Latency model**

Mobile computing power

Mobile generation delay

$$\boxed{D^{tot}(x,p)} = \boxed{D^{\mathrm{E}}(x,p)} + \boxed{D^{\mathrm{M}}(x,p)} + \boxed{xZ^{\mathrm{bit}} / R(h)}$$

Generation splitting ratio Edge generation delay Transmission delay

$$\boxed{D^{\mathrm{M}}(x,p)} = (1-x)G^{\mathrm{M}} / \boxed{\mathrm{F}^{\mathrm{M}}(p)} \qquad \mathrm{F}^{M}(p) = v_0 \left(\frac{p}{\overline{P}}\right)^{\kappa} N_{core} N_{OPC}$$

Number of FLOPs for TinyGM FLOPS at mobile

Here, we ignore the fixed FLOPs to acquire coarse features of full region.
A more accurate model is considered in journal version

- **Mobile energy consumption**

$$E^{M}(x,p) = p(1-x)G^{M} / \mathrm{F}^{M}(x,p)$$

Joint Generation Splitting and Mobile Power Control

Multi-objective programming (MOP)

- Minimize both generation delay and mobile energy consumption

$$
\begin{aligned}
\text{(P1)}\quad & \min_{x,p} D^{tot}(x,p) = xU^{\mathrm{E}} + (1-x)U^{\mathrm{M}}p + xZ^{\mathrm{bit}}/R(h) \\
& \min_{x,p} E^{\mathrm{M}}(x,p) = (1-x)pG^{\mathrm{M}}/F^{\mathrm{M}}(p) \\
\text{s.t.}\quad & \underline{x} \le x \le \overline{x} \\
& 0 \le p \le P^{\mathrm{M}}
\end{aligned}
$$

unit generation cost at mobile

$$U^{M} = V_0 \cdot (p)^{-\kappa} = v_0 \left(\frac{p}{\overline{P}}\right)^{\kappa} N_{core} N_{OPC}$$

unit generation cost at the edge

$$U^{\mathrm{E}} = V_0 \cdot \left(P^{\mathrm{E}}\right)^{-\kappa}$$

we set $\overline{x} = 1$ by assuming a large computation capacity at the edge

- Transformation to single-objective programming (SOP) by ϵ-constraint method

$$
\begin{aligned}
\text{(P2)}\quad & \min_{x,p} D^{tot}(x,p) = xU^{\mathrm{E}} + (1-x)V_0 p^{-\kappa} + xZ^{\mathrm{bit}}/R(h) \\
\text{s.t.}\quad & E^{\mathrm{M}}(x,p) = (1-x)V_0 p^{1-\kappa} \\
& \underline{x} \le x \le \overline{x}, \quad 0 \le p \le P^{\mathrm{M}}
\end{aligned}
$$

Optimal Solution

Closed-form Optimal Solution

$$p^*(x,\ ) = \min\left\{ P^{\mathrm{M}}, \left(\frac{\ }{(1-x)V_0} \right)^{\frac{1}{1-\kappa}} \right\}$$

$$x^*(\ ) = \begin{cases} \max\left\{\underline{x}, x_0^*\right\}, & \text{if } U_{\min}^{\mathrm{M}} \quad (1-\kappa)\left(U^{\mathrm{E}} + \dfrac{Z^{\mathrm{bit}}}{R(h)}\right), \\ \max\left\{\underline{x}, x_1^*\right\}, & \text{if } (1-\kappa)\left(U^{\mathrm{E}} + \dfrac{Z^{\mathrm{bit}}}{R(h)}\right) < U_{\min}^{\mathrm{M}} \quad U^{\mathrm{E}} + \dfrac{Z^{\mathrm{bit}}}{R(h)}, \\ 1, & \text{if } U_{\min}^{\mathrm{M}} > U^{\mathrm{E}} + \dfrac{Z^{\mathrm{bit}}}{R(h)}, \end{cases} \qquad \left(U_{\min}^{\mathrm{M}} = V_0 \cdot \left(P^{\mathrm{M}}\right)^{-\kappa} \right)$$

Boundary of Pareto-optimal energy-delay (E-D) region

Compute optimal E-D objectives $\Rightarrow$ $$\mathcal{R}_{\mathrm{E-D}} = \bigcup_{\substack{\forall \epsilon \in \mathcal{E}, \\ \forall \underline{x} \leqslant x \leqslant \overline{x}}} \left\{ (E, D) : \ E \leqslant E^*(\epsilon), D \geqslant D^*(\epsilon) \right\}.$$

Optimal Solution

Lemma 2: Superiority over conventional fully edge-based generation

Given a fixed mobile power control, MEG always leads to equivalent or reduced latency compared to the fully edge-based generation, and the performance gain is given by

$$\Delta_{\mathrm{MEG}} = \frac{}{\eta^{\mathrm{M}} G^{\mathrm{M}}} \left[\frac{Z^{\mathrm{bit}}}{R(h)} + U^{\mathrm{E}} - U^{\mathrm{M}} \right]^{+}$$

- MEG strictly outperforms fully edge-based generation if channel state h and generative time costs U^{M} and U^{E} satisfy $U^{\mathrm{M}} \leq \frac{Z^{\mathrm{bit}}}{R(h)} + U^{\mathrm{E}}$. In this case, there is a tradeoff between mobile energy consumption and generation delay.
- Otherwise, if $U^{\mathrm{M}} > \frac{Z^{\mathrm{bit}}}{R(h)} + U^{\mathrm{E}}$, MEG reduces to the fully edge-based generation, and $x = 1$ is the unique minimizer of both E-D objective functions.

The performance gain of MEG over the fully edge-based generation increases as SNR or mobile generative time cost of TinyGM decreases. -> We can ensure the performance gain by deploying sufficiently lightweight TinyGM on mobile devices.

Simulation Result

Baseline

- Fully edge generation (FEG): a centralized SDXL/SD3 is deployed at the ES
- Model split (MS): SDXL is split into two parts. (i) VAE encoder + latent diffusion at the edge; (ii) VAE decoder at the mobile.

  [Note] MS generates the full-region latent feature at the edge, which is thus termed *FEG-Latent* in the paper.

Implementation of the proposed MEG framework

- Edge LGM: a 25-step standard SDXL/SD3 performs diffusion to generate primary region in latent space -> transmit primary-region latent features
- Mobile TinyGM: complete secondary region by a coarse-to-refine pipeline

  (i) Coarse module: generate coarse full-region by a downsampled & distilled 2-step SDXL

  (ii) Refinement: refine secondary region by lightweight Restormer

A demo of the above implementation is publicly available at https://github.com/xiaoxiaxusummer/MEGSplitting

Simulation Result

Prompt: A girl standing in the snowy street

Scheme	MEG, x=0.4	MEG, x=0.5	MEG, x=0.6	MEG, x=0.7	MEG, x=0.8	MEG, x=0.9	MS/FEG (baseline)
Latency (s)	2.0812	2.4722	2.8631	3.2540	3.6449	4.0358	4.1405/11.1120
FID score	0.7356	0.2516	0.2977	0.0638	0.0354	0.0129	Reference
SSIM	0.6366	0.6925	0.7624	0.8254	0.8882	0.9476	Reference

Samples generated by SDXL using different x

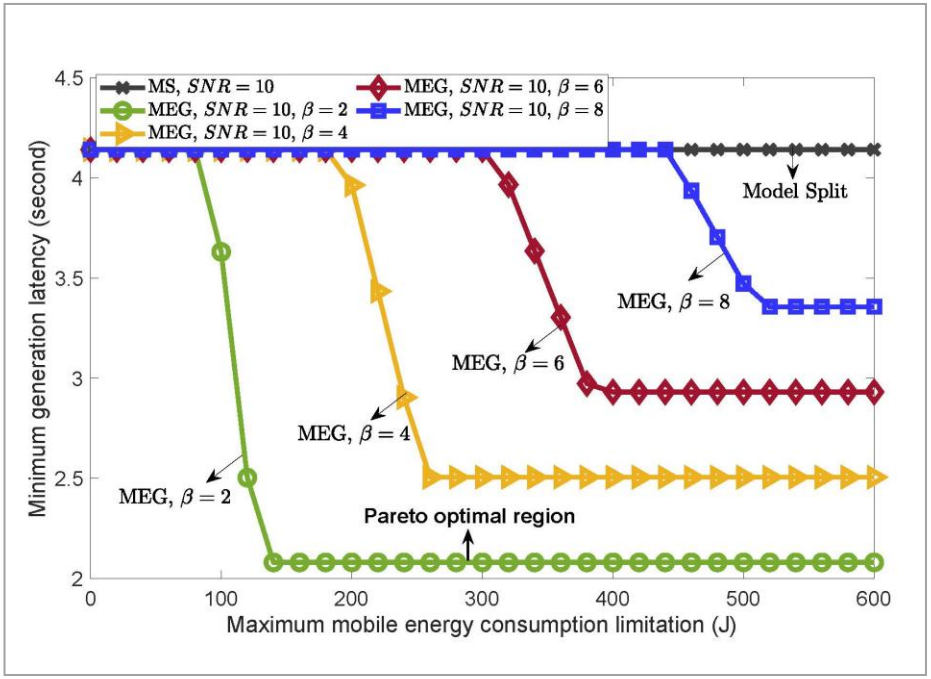
Scheme	MEG, x=0.4	MEG, x=0.5	MEG, x=0.6	MEG, x=0.7	MEG, x=0.8	MEG, x=0.9	MS/FEG (baseline)
Latency (s)	2.6948	3.2391	3.7834	4.3277	4.8720	5.4163	5.6744/12.6458
FID score	1.5303	1.0615	0.7984	0.7925	0.3833	0.0668	Reference
SSIM	0.6401	0.7100	0.7669	0.8243	0.8758	0.9381	Reference

Samples generated by SD3 using different x

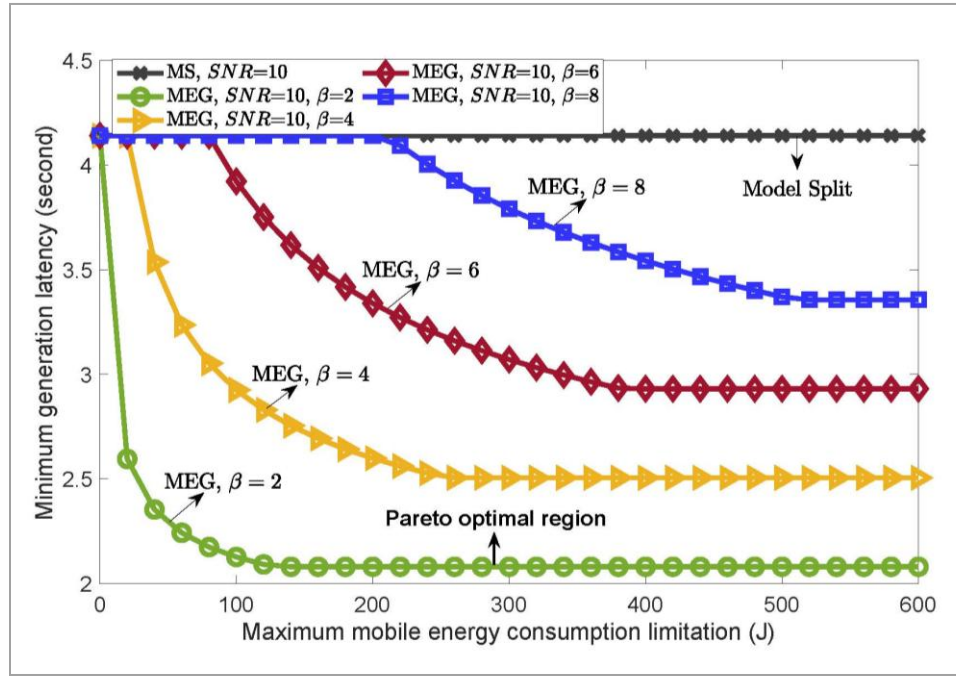
A demo to reproduce the generated samples is publicly available at https://github.com/xiaoxiaxusummer/MEGSplitting

Simulation Result

- Pareto E-D region boundary



Fixed mobile power



Optimal mobile power

- Generation delay ↓ as mobile energy consumption limitation ↑, demonstrating the E-D performance tradeoff in MEG.
- MEG reduces to MS when $\epsilon = 0$, achieves a lower generation latency than MS when $\epsilon > 0$. Performance gain ↑ as β ↓ (i.e., mobile generative time cost ↓)

Conclusion

- We proposed a novel MEG framework that enables flexible generation splitting between the edge and mobile devices -> reduce latency for edge-mobile co-generation of high-definition image
- An edge LDM and a mobile TinyGM are exploited to generate primary and secondary regions, enabling different model complexities for different contents.
- We formulated a multi-objective joint generation splitting and mobile power control problem, which simultaneously minimizes delay and mobile energy consumption. We derived Pareto-optimal solutions and E-D region boundary.
- Simulation results verified the superiority of the proposed MEG framework over centralized generation and model split schemes.

Future Direction

- Latency-distortion tradeoff based on the proposed framework
- Personalized primary region identification
- Generation splitting over noisy wireless channels
- Generation splitting in resource-constrained edge settings
- Security/privacy-aware generation splitting

Thank you

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