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4. (10 points)

(a) **Answer:**

Since the prefix code is first-order, $n = 1$.

Part 1. (p_1)

Calculating $\overline{R}(\mathcal{C}, p_1)$ yields

$$\begin{aligned}\overline{R}(\mathcal{C}, p_1) &= \sum_{x \in \mathcal{X}} p_1(x) l(f(x)) \\ &= 3 \cdot \frac{1}{4} \cdot 1 + 4 \cdot \frac{1}{16} \cdot 2 \\ &\boxed{= 1.25 \, \frac{\text{quaternary units}}{\text{source symbol}}}.\end{aligned}$$

The theoretical limit of $\overline{R}(\mathcal{C}, p_1)$, the entropy rate $H(\boldsymbol{\mathcal{X}})$ of the DMS, is

$$\begin{aligned}H_4(\boldsymbol{\mathcal{X}}) &= H_4(X) \\ &= -\sum_{x \in \mathcal{X}} p_1(x) \log_4 p_1(x) \\ &= -\left(3 \cdot \frac{1}{4} \log_4 \frac{1}{4} + 4 \cdot \frac{1}{16} \log_4 \frac{1}{16}\right) \\ &\boxed{= 1.25 \, \text{quaternary units}}.\end{aligned}$$

Thus, we have that $\boxed{\overline{R}(\mathcal{C}, p_1) = H_4(\boldsymbol{\mathcal{X}})}$.

Part 2. (p_2)

Calculating $\overline{R}(\mathcal{C}, p_2)$ yields

$$\begin{aligned}\overline{R}(\mathcal{C}, p_2) &= \sum_{x \in \mathcal{X}} p_2(x) l(f(x)) \\ &= \frac{1}{4} \cdot 1 + 2 \cdot \frac{1}{8} \cdot 1 + 4 \cdot \frac{1}{8} \cdot 2 \\ &\boxed{= 1.5 \, \frac{\text{quaternary units}}{\text{source symbol}}}.\end{aligned}$$

The theoretical limit of $\overline{R}(\mathcal{C}, p_2)$, the entropy rate $H(\boldsymbol{\mathcal{X}})$ of the DMS, is

$$\begin{aligned}H_4(\boldsymbol{\mathcal{X}}) &= H_4(X) \\ &= -\sum_{x \in \mathcal{X}} p_2(x) \log_4 p_2(x) \\ &= -\left(\frac{1}{4} \log_4 \frac{1}{4} + 6 \cdot \frac{1}{8} \log_4 \frac{1}{8}\right) \\ &\boxed{= 1.375 \, \text{quaternary units}}.\end{aligned}$$

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Thus, we have that $\boxed{H_4(\mathcal{X}) < \overline{R}(\mathcal{C}, p_2) < H_4(\mathcal{X}) + 1}$.

(b) **Answer:**

42.