1. Derivation of equation (3)

To begin with, we use the integral to approximate the summation in **equation (2)** and obtain

$$R_i(\phi) \approx \frac{1}{B}\int_{f_c-\frac{B}{2}}^{f_c+\frac{B}{2}} \log_2\left(1+\rho\left|\mathbf{a}^{\mathrm{H}}\left(\frac{f}{f_c}\phi\right)\mathbf{w}_i\right|^2\right)df\ .$$

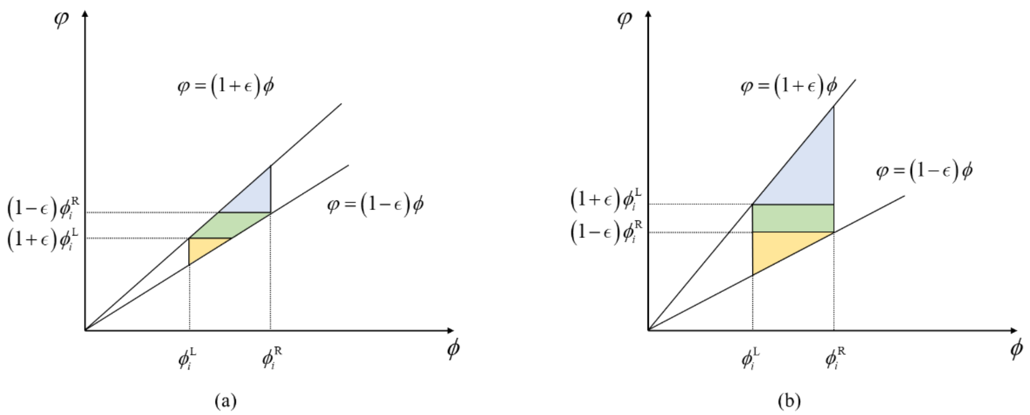
Let $\varphi = f\phi / f_c$, the above equation can be transformed as

$$R_i(\phi) \approx \frac{1}{2\varepsilon\phi}\int_{1-\varepsilon}^{1+\varepsilon} \log_2\left(1+\rho\left|\mathbf{a}^{\mathrm{H}}(\varphi)\mathbf{w}_i\right|^2\right)d\varphi\,,$$

and we can derive **equation (3)**.

2. Derivation of equation (11)

First, we denote $f(\varphi) = \log_2\left(1+\rho\left|\mathbf{a}^{\mathrm{H}}(\varphi)\mathbf{w}_i\right|^2\right)$. As shown in the figure below, when we change the integration order in **equation (3)**, the derivation can be divided into the following 2 cases.



(a). $(1+\varepsilon)\phi_i^{\mathrm{L}} < (1-\varepsilon)\phi_i^{\mathrm{R}}$, i.e., $\varepsilon < 1/(2i-1)$, we have

$$\begin{aligned}
\bar{R}_i &= \frac{L}{4\varepsilon}\int_{\phi_i^{\mathrm{L}}}^{\phi_i^{\mathrm{R}}}\frac{1}{\phi}\int_{(1-\varepsilon)\phi}^{(1+\varepsilon)\phi} f(\varphi)\,d\varphi d\phi \\
&= \frac{L}{4\varepsilon}\left(\int_{(1-\varepsilon)\phi_i^{\mathrm{L}}}^{(1+\varepsilon)\phi_i^{\mathrm{L}}}\int_{\phi_i^{\mathrm{L}}}^{\varphi/(1-\varepsilon)}\frac{1}{\phi}f(\varphi)\,d\phi d\varphi + \int_{(1+\varepsilon)\phi_i^{\mathrm{L}}}^{(1-\varepsilon)\phi_i^{\mathrm{R}}}\int_{\varphi/(1+\varepsilon)}^{\varphi/(1-\varepsilon)}\frac{1}{\phi}f(\varphi)\,d\phi d\varphi + \int_{(1-\varepsilon)\phi_i^{\mathrm{R}}}^{(1+\varepsilon)\phi_i^{\mathrm{R}}}\int_{\varphi/(1+\varepsilon)}^{\phi_i^{\mathrm{R}}}\frac{1}{\phi}f(\varphi)\,d\phi d\varphi\right) \\
&= \frac{L}{4\varepsilon}\left(\int_{(1-\varepsilon)\phi_i^{\mathrm{L}}}^{(1+\varepsilon)\phi_i^{\mathrm{L}}} f(\varphi)\ln\frac{\varphi}{(1-\varepsilon)\phi_i^{\mathrm{L}}}\,d\varphi + \int_{(1+\varepsilon)\phi_i^{\mathrm{L}}}^{(1-\varepsilon)\phi_i^{\mathrm{R}}} f(\varphi)\ln\frac{(1+\varepsilon)}{(1-\varepsilon)}\,d\varphi + \int_{(1-\varepsilon)\phi_i^{\mathrm{R}}}^{(1+\varepsilon)\phi_i^{\mathrm{R}}} f(\varphi)\ln\frac{(1+\varepsilon)\phi_i^{\mathrm{R}}}{\varphi}\,d\varphi\right)
\end{aligned}\ .$$

(b). $\left(1+\varepsilon\right)\phi_i^{\mathrm{L}} > \left(1-\varepsilon\right)\phi_i^{\mathrm{R}}$, i.e., $\varepsilon > 1/\left(2i-1\right)$, we have

$$
\begin{aligned}
\bar{R}_i &= \frac{L}{4\varepsilon}\int_{\phi_i^{\mathrm{L}}}^{\phi_i^{\mathrm{R}}}\frac{1}{\phi}\int_{(1-\varepsilon)\phi}^{(1+\varepsilon)\phi} f\left(\varphi\right)d\varphi d\phi \\
&= \frac{L}{4\varepsilon}\left(\int_{(1-\varepsilon)\phi_i^{\mathrm{L}}}^{(1-\varepsilon)\phi_i^{\mathrm{R}}}\int_{\phi_i^{\mathrm{L}}}^{\varphi/(1-\varepsilon)}\frac{1}{\phi}f\left(\varphi\right)d\phi d\varphi+\int_{(1-\varepsilon)\phi_i^{\mathrm{R}}}^{(1+\varepsilon)\phi_i^{\mathrm{L}}}\int_{\phi_i^{\mathrm{L}}}^{\phi_i^{\mathrm{R}}}\frac{1}{\phi}f\left(\varphi\right)d\phi d\varphi+\int_{(1+\varepsilon)\phi_i^{\mathrm{L}}}^{(1+\varepsilon)\phi_i^{\mathrm{R}}}\int_{\varphi/(1+\varepsilon)}^{\phi_i^{\mathrm{R}}}\frac{1}{\phi}f\left(\varphi\right)d\phi d\varphi\right) \\
&= \frac{L}{4\varepsilon}\left(\int_{(1-\varepsilon)\phi_i^{\mathrm{L}}}^{(1-\varepsilon)\phi_i^{\mathrm{R}}} f\left(\varphi\right)\ln\frac{\varphi}{\left(1-\varepsilon\right)\phi_i^{\mathrm{L}}}d\varphi+\int_{(1-\varepsilon)\phi_i^{\mathrm{R}}}^{(1+\varepsilon)\phi_i^{\mathrm{L}}} f\left(\varphi\right)\ln\frac{\phi_i^{\mathrm{R}}}{\phi_i^{\mathrm{L}}}d\varphi+\int_{(1+\varepsilon)\phi_i^{\mathrm{L}}}^{(1+\varepsilon)\phi_i^{\mathrm{R}}} f\left(\varphi\right)\ln\frac{\left(1+\varepsilon\right)\phi_i^{\mathrm{R}}}{\varphi}d\varphi\right)
\end{aligned}
$$

Thus, we can obtain $t\left(\varphi\right)$ in **equation (11)**.