Appendix A
The proof of lemma 1

To start with, we first linearize the product of two binary variables, and we have Lemma 4.

Lemma 4 *θ_1 and θ_2 are two different binary variables. If $\theta_1\theta_2 = \sigma$, where σ is a continuous variable, we obtain the equivalent expression*

$$\sigma \geq \theta_1 + \theta_2 - 1, \quad \sigma \geq 0,$$
$$\sigma \leq \theta_1, \quad \sigma \leq \theta_2.$$

Then, we can rewrite (21) as follow:

$$\begin{aligned}
&\sum_{j\in\mathcal{A}} \theta_j(l) \left(\sum_{l'\in\mathcal{L}} \theta_j(l') - 1 \right) \frac{c_j D_0}{u_j} \\
=&\sum_{j\in\mathcal{A}} \left[\left(\theta_j(l) \sum_{l'\in\mathcal{L}} \theta_j(l') \right) \frac{c_j D_0}{u_j} \right] - \sum_{j\in\mathcal{A}} \theta_j(l) \frac{c_j D_0}{u_j}, \\
=&\sum_{j\in\mathcal{A}} \left[\left(\theta_j(l) \left(\theta_j(l) + \sum_{l'\in\mathcal{L}\backslash\{l\}} \theta_j(l') \right) \right) \frac{c_j D_0}{u_j} \right] - \sum_{j\in\mathcal{A}} \theta_j(l) \frac{c_j D_0}{u_j}, \\
\overset{(b)}{=}&\sum_{j\in\mathcal{A}} \left[\left(\theta_j(l) + \sum_{l'\in\mathcal{L}\backslash\{l\}} \theta_j(l)\theta_j(l') \right) \frac{c_j D_0}{u_j} \right] - \sum_{j\in\mathcal{A}} \theta_j(l) \frac{c_j D_0}{u_j}, \\
=&\sum_{j\in\mathcal{A}} \sum_{l'\in\mathcal{L}\backslash\{l\}} \theta_j(l)\theta_j(l') \frac{c_j D_0}{u_j},
\end{aligned} \tag{51}$$

where (b) is obtained based on the observation that $\theta^2 = \theta$ when θ is a binary variable. Note that $\sum_{l'\in\mathcal{L}\backslash\{l\}} \theta_j(l)\theta_j(l')$ is the sum of $\theta_j(l)\theta_j(l')$, and each $\theta_j(l')$ is different from $\theta_j(l)$. Therefore, we can use Lemma 4 to obtain the $\theta_j(l)\theta_j(l') = \sigma_j(l')$ with constraints (22) and (23). Substituting these results into (51), Lemma 1 can be obtained.

Appendix B
The proof of lemma 2

It can be observed that $\phi \geq \theta T$ is equivalent to

$$\phi \geq \begin{cases} T & \text{if } \theta = 1, \\ 0 & \text{if } \theta = 0. \end{cases} \tag{52}$$

On the other hand, according to constraint (24), we have $\phi \geq 0$ and $\phi \geq -\Phi + T$ when $\theta = 0$, and $\phi \geq -\Phi$ and $\phi \geq T$ when $\theta = 1$. As Φ is a very large positive constant and T is a finite continuous variable, it is easy to confirm that $0 \geq -\Phi + T$ and $T \geq -\Phi$. Therefore, we have $\phi \geq 0$ when $\theta = 0$, and $\phi \geq T$ when $\theta = 1$, which is equivalent to (52), i.e., $\phi \geq \theta T$. The proof is completed.

APPENDIX C
THE PROOF OF LEMMA 3

(28) and (29) can be rewritten in the logarithmic form

$$\log_2(t_1(l)) + \log_2(T^{\max}) \geq 2\log_2(T^{T1}(l)), \tag{53}$$

$$\log_2(t_2(l)) + \log_2\left(T^{\max}\right) \geq 2\log_2\left(\sum_{j\in\mathcal{A}} \phi_j(l)\right), \tag{54}$$

where the $\log_2(t)$ can be replaced by the $N_{\mathcal{Y}}$-piecewise function $\mathcal{Z}_1(t)$ and $\mathcal{Z}_2(t)$, which is similar to $\mathcal{G}(\cdot)$ except the value range, satisfying the following constraints:

$$\mathcal{Z}_1(t) \leq Y_i^-(t), \quad \forall Y_i^- \in \mathcal{Y}, \tag{55}$$

$$\mathcal{Z}_2(t) \geq \min\left\{Y_i^+(t)\right\}, \quad \forall Y_i^+ \in \mathcal{Y}, \tag{56}$$

$$Y_i^-(t) = c_i^- t + d_i^-, \quad t \in \left\{t^-, t^+\right\}, \tag{57}$$

$$Y_i^+(t) = c_i^+ t + d_i^+, \quad t \in \left\{t^-, t^+\right\}, \tag{58}$$

where $\mathcal{Z}_1(t)$ is the lower bound of the approximation for $\log_2(t)$, and $\mathcal{Z}_2(t)$ is the upper bound of the approximation for $\log_2(t)$. Specifically, $c_i^- = \frac{N_{\mathcal{Y}}}{t^+ - t^-}\log_2\left[\frac{it^+ + (N_{\mathcal{Y}}-i)t^-}{(i-1)t^+ + (N_{\mathcal{Y}}-i+1)t^-}\right]$, $d_i^- = \log_2\left[\frac{it^+ + (N_{\mathcal{Y}}-i)t^-}{N_{\mathcal{Y}}}\right] - \frac{it^+ + (N_{\mathcal{Y}}-i)t^-}{t^+ - t^-}\log_2\left[\frac{it^+ + (N_{\mathcal{Y}}-i)t^-}{(i-1)t^+ + (N_{\mathcal{Y}}-i+1)t^-}\right]$, $c_i^+ = \frac{2N_{\mathcal{Y}}}{[(2i-1)t^+ + (2N_{\mathcal{Y}}-2i+1)t^-]\ln 2}$, $d_i^+ = \log_2\left[\frac{(2i-1)t^+ + (2N_{\mathcal{Y}}-2i+1)t^-}{2N_{\mathcal{Y}}}\right] - \frac{1}{\ln 2}$. For the minimum value t^- in (57) and (58), it is infeasible for $\log_2(t)$ to set $t^- = 0$. Thus, we set $t^- = \widetilde{t}$, where $\widetilde{t}$ is a small constant close to zero. For the maximum value t^+, t^+ is obtained by $t^+ = 2T^{\text{Direct}}$. T^{Direct} is the total delay obtained by solving the problem that only considers the no-aggregation case with relaxed constraints, which is detailed in Section V-D. Notice that the maximum delay experienced in the no-aggregation case should be higher than $T^{\max}$. Given the relaxed constraints, T^{Direct} is the lower bound of the delay experienced in the no-aggregation case. Thus, we set $t^+ = 2T^{\text{Direct}}$ to ensure that the value of

$T^{\max}$ is covered by the interval $\{t^-, t^+\}$. As (56) is not convex, we rewrite $\mathcal{Z}_2(t) \geq \min\left\{Y_i^+(t)\right\}$ as

$$\mathcal{Z}_2(t) \geq \sum_{i=1}^{N_{\mathcal{Y}}} \zeta_i \left\{Y_i^+(t)\right\}, \tag{59}$$

and we have

$$\sum_{i=1}^{N_{\mathcal{Y}}} \zeta_i = 1, \quad \zeta_i \in \{0, 1\}, \tag{60}$$

$$\zeta_i t_i^- \leq t \leq \zeta_i t_i^+ + (1 - \zeta_i)\widetilde{T}, \tag{61}$$

where t_i^- and t_i^+ are the known piecewise points of $\mathcal{Z}_2(t)$, i.e., $t_i^- = t^- + (t^+ - t^-)(i-1)/N_{\mathcal{Y}}$, $t_i^+ = t^- + i(t^+ - t^-)/N_{\mathcal{Y}}$, $i = 1, 2, \cdots, N_{\mathcal{Y}}$, and $\widetilde{T}$ is a large constant. However, the constraints (59) has the product of variables ζ_i's and $Y_i^+(t)$'s, which is still nonlinear. Thus, we reformulate them by using Lemma 2, and we obtain

$$\mathcal{Z}_2\left(t\right) \geq \sum_{i=1}^{N_{\mathcal{Y}}} \kappa_i^1(l), \tag{62}$$

where $\kappa_i(l)$'s satisfy the following constraints

$$\kappa_i^1(l) \geq -\zeta_i^1(l)\widetilde{T}, \tag{63}$$

$$\kappa_i^1(l) \geq -(1 - \zeta_i^1(l))\widetilde{T} + \left\{Y_i^+(t)\right\}. \tag{64}$$

As $\mathcal{Z}_1(t)$ and $\mathcal{Z}_2(t)$ are the lower bound and the upper bound of the approximation for $\log_2(t)$ respectively, we have $\mathcal{Z}_1(t_1(l)) + \mathcal{Z}_1(T_{max}) \leq \log_2(t_1(l)) + \log_2(T^{\max})$ and $2\log_2(T^{T1}(l)) \leq 2\mathcal{Z}_2(T^{T1}(l))$. With the properly designed piecewise functions, the gap between the values of $\mathcal{Z}_1(t)$, $\mathcal{Z}_2(t)$ and the values of $\log_2(t)$ is small [1]. Therefore, by using the piecewise functions with constraints (55)-(64), (53) and (54) can be reformulated as

$$\mathcal{Z}_1(t_1(l)) + \mathcal{Z}_1(T^{\max}) \geq 2\mathcal{Z}_2(T^{T1}(l)), \tag{65}$$

$$\mathcal{Z}_1(t_2(l)) + \mathcal{Z}_1(T^{\max}) \geq 2\mathcal{Z}_2(\sum_{j\in\mathcal{A}} \phi_j(l)). \tag{66}$$

The proof is completed.

REFERENCES

[1] X. Li, Y. Sun, Y. Guo, X. Fu, and M. Pan, "Dolphins first: Dolphin-aware communications in multi-hop underwater cognitive acoustic networks," *IEEE Trans. Wireless Commun.*, vol. 16, no. 4, pp. 2043–2056, Apr. 2017.