JUSTEK : JURNAL SAINS DAN TEKNOLOGI
http://journal.ummat.ac.id/index.php/justek
ISSN 2620-5475
Vol. 8, No. 4, December 2025, pp. 388-399

Quasi Linear Utility Optimization for Selfish User Model in C-RAN With Demand Response and Bundling

Nafisah Aura Prayoga[1], Fitri Maya Puspita[2], Sisca Octarina[3]
[1,2,3] Program Studi Matematika, Universitas Sriwijaya, Indonesia
Email: nafisaha909@gmail.com[1], fitrimayapuspita@unsri.ac.id[2], sisca_octarina@unsri.ac.id[3]
Corresponding Author: nafisaha909@gmail.com

ARTICLE INFO

Article History:

Received : 16-11-2025
Revised : 10-12-2025
Accepted : 11-12-2025
Online : 15-12-2025

Keywords:
Bundling scheme;
Cloud Radio Access Network (C-RAN);
Demand response;
Quasi Linear Utility Function;
Selfish User Behavior

ABSTRACT

This study aims to develop two optimization models that provide a realistic representation of interactions between selfish users and C-RAN networks by integrating demand response mechanisms, heterogeneous incentives, and quasi-linear utility functions. The first model is designed to formulate selfish user behavior in a C-RAN system based on utility structures and incentive schemes, while the second model extends this framework through the incorporation of a bundling scheme to evaluate improvements in network efficiency and user utility. The research methodology involves collecting and formulating 30 days of traffic data, defining relevant model parameters and variables, constructing the optimization models, and solving them using LINGO 13.0 under three pricing schemes: usage-based, flat-fee, and two-part tariff. The results reveal that the flat-fee pricing scheme with bundling in Case 2 provides the most efficient configuration, achieving the highest objective value of 6408.49 and the lowest iteration count. These findings demonstrate that integrating bundling strategies into C-RAN pricing models can enhance network efficiency, improve bandwidth utility, and increase ISP revenue.

Crossref
https://doi.org/10.31764/justek.vXiY.ZZZ

A. INTRODUCTION

The rapid growth of information technology has made the internet an essential resource, driving increasing data demand and creating challenges such as traffic overload, high power consumption, and limited spectrum availability (Farhat et al., 2024; Oleksandrivna, 2025; Szymkowiak et al., 2021). The C-RAN architecture offers an efficient solution through centralized processing, energy savings, and flexible resource management, particularly important for meeting massive connectivity requirements in the 5G era (Aktar et al., 2023; AlQahtani, 2023; Han et al., 2021; Israr et al., 2022).

Network performance, however, is also influenced by user behavior. Users often act selfishly by maximizing their own utility, which reduces overall network efficiency (Boujnoui et al., 2022; Georgiev et al., 2022; Kampitaki & Economides, 2023; Prospero et al., 2021). Demand response, heterogeneous incentives, and pricing schemes such as flat-fee, usage-based, and two-part tariff are thus employed to regulate consumption and sustain ISP profitability (Indrawati et al., 2023; Yin et al., 2020). Furthermore, recent studies indicate that scheduling and pricing approaches can enhance network performance and increase ISP revenue (Hu et al., 2022; Puspita et al., 2020).

In modeling user decision-making, quasi-linear utility functions are widely adopted because they offer simplicity, stability, and an accurate representation of user preferences concerning the trade-off between service quality and price (Puspita, Haloho, et al., 2021; Puspita, Rezky, et al., 2021). This function has been applied in studies focusing on bundling, user differentiation, and consumer satisfaction in information services (Indrawati et al., 2021; Monardo, 2022). Meanwhile, resource allocation in modern heterogeneous network environments such as HetNet, MEC, and edge-cloud systems has become increasingly complex, requiring strategies including pricing-based allocation, distributed optimization, and game-theoretic approaches (Du et al., 2021; Passas et al., 2020).

Although previous studies have examined C-RAN, selfish user behavior, pricing strategies, and quasi-linear utility functions, these topics have largely been explored independently. No prior research has integrated C-RAN selfish users, demand response, heterogeneous incentives, quasi-linear utility functions, and bundling schemes into a unified optimization framework (Puspita et al., 2023; Puspita, Arda, et al., 2022; Puspita, Indriani, et al., 2022). This research gap forms the basis of the novelty of this study, which proposes two optimization models that simultaneously incorporate these components to capture realistic user–network interactions and improve pricing efficiency.

Based on these considerations, this study aims to develop an optimization framework that integrates C-RAN selfish user behavior with demand response mechanisms, heterogeneous incentives, quasi-linear utility functions, and bundling strategies. Model I formulates selfish user behavior within the C-RAN system, while Model II extends the formulation by incorporating a bundling scheme to assess improvements in network efficiency, bandwidth utility, and ISP revenue potential.

B. RESEARCH METHODS

This study employs a quantitative research design using a mathematical modeling and optimization approach. The method applied is an optimization framework based on a quasi-linear utility function, developed to represent selfish user behavior in a C-RAN system integrated with demand response, heterogeneous incentives, and bundling schemes. All computations and model solutions were generated using the LINGO optimization software.

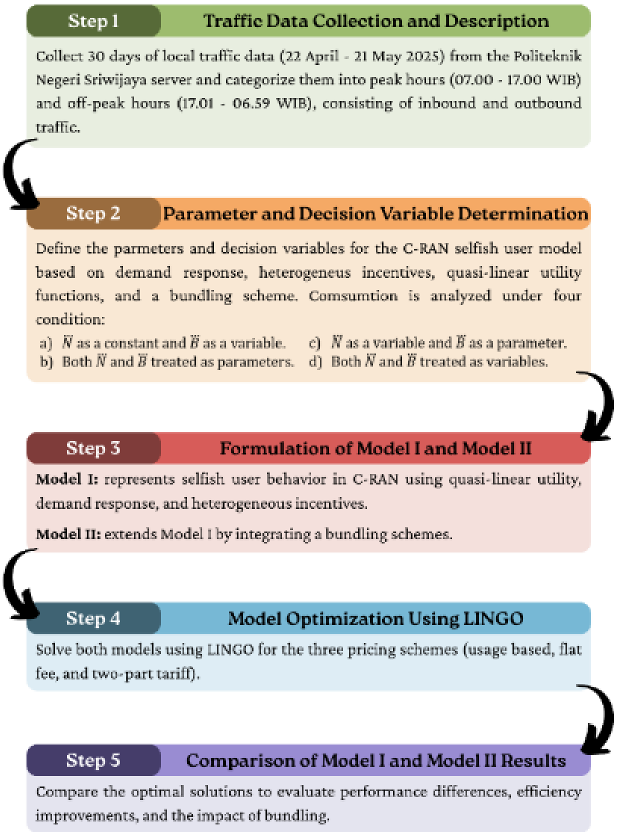

Figure 1. Research Methodology Flowchart for the C-RAN Selfish User Model with Pricing and Bundling Schemes

Figure 1 illustrates the research methodology flow, covering five stages from traffic data collection to the comparison of Model I and Model II results, as detailed in the following explanation:

1. Describing the local traffic data collected over 30 days (22 April – 21 May 2025) from the Politeknik Negeri Sriwijaya server. The data were categorized into peak hours (07:00 – 17:00 WIB) and off-peak hours (17:01 – 06:59 WIB), each consisting of inbound and outbound traffic measured in bits per second.
2. Determining the parameters and decision variables for the C-RAN selfish user model based on demand response with heterogeneous incentives, quasi-linear utility functions, and a bundling scheme. The consumption analysis was performed under four conditions:
   a) $\ddot{N}$ as a constant and $\ddot{B}$ as a variable.
   b) Both $\ddot{N}$ and $\ddot{B}$ treated as parameters.
   c) $\ddot{N}$ as a variable and $\ddot{B}$ as a parameter.
   d) Both $\ddot{N}$ and $\ddot{B}$ treated as variables.
3. Designing the objective function and constraints for Model I, which represents a C-RAN selfish user framework based on demand response with heterogeneous incentives and a quasi-linear utility function, and for Model II, which extends Model I by incorporating a bundling scheme.
4. Solving both models using LINGO to obtain optimal solutions for each applied pricing scheme.
5. Comparing the optimal solutions from Model I and Model II to evaluate performance differences between the two models under each tariff scheme.

C. RESULTS AND DISCUSSION

This study utilizes secondary data in the form of internet traffic obtained from the local server of Politeknik Negeri Sriwijaya over a 30 period (22 April – 21 May 2025). The dataset records bandwidth usage measured in bits per second (bps), categorized into inbound and outbound traffic, and further divided into peak hours (07:00 – 17:00 WIB) and off-peak hours (17:01 – 06:59 WIB).

1. Traffic Data Description

The daily traffic dataset is summarized to describe usage patterns during peak and off-peak periods. Tables 1 and 2 present the minimum, maximum, and classification of inbound and outbound traffic.

Table 1. Traffic Data Formulated Into 24 Entries (≥ 10.26327 kbyte)

Total Daily Traffic Consumption		
Bit	***Byte***	***Kbyte***
125,185.21963	15,648.15245	15.28140
104,751.85907	13,093.98238	12.78709
116,388.62149	14,548.57769	14.20760
117,152.56002	14,644.07000	14.30085
103,687.26355	12,960.90794	12.65714
141,063.13345	17,632.89168	17.21962
185,010.65854	23,126.33232	22.58431
155,095.20219	19,386.90027	18.93252
91,193.68031	11,399.21004	11.13204
146,772.64918	18,346.58115	17.91658
5,653.95305	706.74413	0.69018
0.00000	0.00000	0.00000
122,758.64167	15,344.83021	14.98519
146,479.03098	18,309.87887	17.88074
169,341.91982	21,167.73998	20.67162
84,339.40277	10,542.42535	10.29534
90,344.18379	11,293.02297	11.02834
91,686.01852	11,460.75231	11.19214
87,708.73635	10,963.59204	10.70663
84,666.92297	10,583.36537	10.33532
86,815.36068	10,851.92009	10.59758
91,270.88473	11,408.86059	11.14147
89,923.72041	11,240.46505	10.97702
85,012.40409	10,626.55051	10.37749

Table 2. Number of Traffic Data Users During Peak and Off-Peak Hours

Consumption Level	Total Daily Traffic Consumption		
	Bit	**Byte**	**Kbyte**
$\grave{K}_1$	86,661.08504	10,832.63563	10.57875
$\grave{K}_2$	81,117.84434	10,139.73054	9.90208
$\grave{K}_{min}$	28,118.35589	3,514.79449	3.43242
$\grave{R}_1$	98,349.57350	12,293.69669	12.00556
$\grave{R}_2$	73,977.35785	9,247.16973	9.03044
$\grave{R}_{min}$	5,653.95305	706.74413	0.69018

Notes:

$\grave{K}_1$: Represents the maximum traffic usage recorded during peak hours.
$\grave{K}_2$: Represents the second-highest traffic usage recorded during peak hours.
$\grave{K}_{min}$: Represents the minimum traffic usage recorded during peak hours.
$\grave{R}_1$: Represents the maximum traffic usage recorded during off-peak hours.
$\grave{R}_2$: Represents the second-highest traffic usage recorded during off-peak hours.
$\grave{R}_{min}$: Represents the minimum traffic usage recorded during off-peak hours.

Tables 1 and 2 show substantial fluctuations in daily traffic consumption between peak and off-peak periods, with maximum values significantly higher than the minimum.

These variations highlight uneven usage patterns that are essential for modeling selfish user behavior.

2. Parameter and Decision Variable Specification

This section presents the parameters and decision variables used in modeling selfish user behavior within the C-RAN system. Traffic parameters, capacity limits, service constants, and consumption structures are defined to support the formulation of Model I and Model II. All numerical parameters, symbol descriptions, and case distinctions are provided in Tables 3 through 7.

Table 3. Parameter Values for Traffic Data

Parameter	Value (*kbyte*)
$j_1 = \grave{K}_1$	10.57875
$j_2 = \grave{K}_2$	9.90208
$j_3 = \grave{K}_{min}$	3.43242
$j_4 = \grave{R}_1$	12.00556
$j_5 = \grave{R}_2$	9.03044
$j_6 = \grave{R}_{min}$	0.69018
y_{11} and y_{12}	15.28140 and 12.78709
y_{21} and y_{22}	14.20760 and 14.30085
y_{31} and y_{32}	12.65714 and 17.21962
y_{41} and y_{42}	22.58431 and 18.93252
y_{51} and y_{52}	11.13204 and 17.91658
y_{61} and y_{62}	0.69018 and 0.00000
y_{13} and y_{23}	14.98519 and 17.88074
y_{33} and y_{44}	20.67162 and 10.29534
y_{45} and y_{46}	11.02834 and 11.19214
y_{54} and y_{55}	10.70663 and 10.33532
y_{56} and y_{64}	10.59758 and 11.14147
y_{65} and y_{66}	10.97702 and 10.37749

Table 4. Description of Parameters in the C-RAN Selfish User Model

Parameter	Description	Value
$\ddot{N}$	Bandwidth allocation set by the ISP.	5000
$\dot{\lambda}$	Unit cost of bandwidth (Rp)	500
$\dot{R}$	Upper limit of bandwidth usage during peak hours	4500
$\dot{S}$	Upper limit of bandwidth usage during off-peak hours	4000
$\dot{\delta}$	Upper bound of the Quality of Service (QoS)	128
$\dot{\mu}$	Lower bound of the Quality of Service (QoS)	64
$\dot{\varepsilon}$	Maximum allowable bandwidth consumption per user	4500
U_{max}	Maximum capacity for bandwidth transfer	500
$\ddot{B}$	Initial bandwidth usage.	150
W_{eo}	Throughput value and energy consumption associated with the user	4.4262×10^{11}
V_o	Maximum energy limit that can be utilized by RRH for the unit o	1
A_1	Weighting value for the first evaluation criterion	1
A_2	Weighting value for the second evaluation criterion	2
G	Function representing the initial demand level	1000
$\breve{K}$	Demand level under initial conditions.	100
$\breve{L}$	Demand level under final conditions	150
$\hat{T}_n$	Total service production for service type n	1
b	Service is constant during peak hours	4
v	Service is constant during off-peak hours	3
j_w	Total minimum and maximum allowable bandwidth usage	
y_{wx}	Total daily bandwidth consumption (*kbyte*)	
$X_{(b,v)}$	Utility function representing user satisfaction based on service consumption during peak (b)and off-peak (v) periods	

Case 1: $\ddot{N}$ is set as a parameter and $\ddot{B}$ as a variable

$\ddot{N}$: Bandwidth allocation determined by the ISP

Case 2: $\ddot{N}$ and $\ddot{B}$ are both treated as parameters

$\ddot{N}$: Bandwidth allocation determined by the ISP

$\ddot{B}$: Initial bandwidth usage

Case 3: $\ddot{N}$ is treated as a variable, while $\ddot{B}$ remains a parameter

$\ddot{B}$: Initial bandwidth usage

Case 4: $\ddot{N}$ and $\ddot{B}$ are both treated as variables; all notations are used.

Table 5. Description of Variables in the C-RAN Selfish User Model

Variable	Description
k_{wx}	Description of Variables in the C-RAN Selfish User Model
l_{wx}	Amount of bandwidth transferred from the RB to the RUE
o_w	Path loss value associated with the RRH on a given RB
a_w	Channel gain value associated with the RRH on a given RB
S_w	Path loss from the RB to the RUE
G_{wx}	Channel gain from the RB to the RUE
g	Bandwidth consumption when no hosting service is performed
Y_{eo}	Throughput and energy consumption generated by the user
α	Internet tariff based on current demand conditions
θ	Initial tariff applied at the beginning of the period
G	Demand function after incorporating the linear model
$\dot{T}$	Elasticity of demand with respect to price
$\bar{J}$	Total output produced
$\widehat{M}$	Unit cost obtained from production
$\tilde{\imath}$	Fixed cost per unit
$\widehat{U}_n$	Initial quantity of service k produced
H_n	Production output of service k
$\ddot{L}$	Unit tariff charged by the provider during peak hours
d	User consumption level during peak hours
$\ddot{I}$	Unit tariff charged by the provider during off-peak hours
c	User consumption level during off-peak hours
Z	Total cost charged to the user for accessing the service

Case 1: $\ddot{N}$ is set as a parameter and $\ddot{B}$ as a variable

$\ddot{B}$: Initial bandwidth usage

Case 2: $\ddot{N}$ and $\ddot{B}$ are both treated as parameters; all variables are defined above.

Case 3: $\ddot{N}$ is treated as a variable, while $\ddot{B}$ remains a parameter

$\ddot{N}$: Bandwidth allocation determined by the ISP

Case 4: $\ddot{N}$ and $\ddot{B}$ are both treated as variables

$\ddot{N}$: Bandwidth allocation determined by the ISP

$\ddot{B}$: Initial bandwidth usage

Table 6. Description of Parameters in the Bundling Model

Parameter	Description	Parameter	Value
$\tilde{O}_f$	The production tariff associated with each bundling service f	$\tilde{O}_1, \tilde{O}_2$ and $\tilde{O}_3$	650, 450 and 200
N	The total number of potential consumers targeted in the marketing segment	N	3
F	The total number of services or bundling options offered by the service provider	F	3
G	The marginal cost incurred when the ISP adds more than one bundling option to a user's choice set	G	150
T_{nf}	The willingness-to-pay level of consumer n for the primary bundling service f	T_{11}, T_{12} and T_{13} T_{21}, T_{22} and T_{23} T_{31}, T_{32} and T_{33}	800, 200 and 350 500, 650 and 200 400, 600 and 350

Table 7. Description of Decision Variables in the Bundling Model

Variabel	Description
E_f	The selling price applied to each bundling service f
$\hat{X}_n$	The utility or benefit received by consumer n from using the service
S_{nf}	The total tariff paid by consumer n for the primary bundling service f
$\breve{Q}_{nf}$	A binary variable equal to 1 if consumer n selects bundling service f, and 0 otherwise
$\check{P}_f$	A binary variable equal to 1 if the ISP offers bundling service f, and 0 if the service is not included

The tables summarize the full set of components used in the model, including traffic parameters, QoS limits, pricing functions, energy constants, and bundling attributes. The decision variables capture consumption, tariff levels, utility, and service choices.

Together, these inputs allow the model to represent user responses under four consumption conditions and to evaluate the impact of bundling on utility and network performance.

After defining all parameters and variables, the next step is to construct the C-RAN model used to formulate an internet pricing scheme aimed at maximizing the ISP's profit. In this model, three RUEs are connected to the RRH, while the remaining three RUEs are assigned to the RB. From the three available servers, two servers are dedicated to supporting the RB. Based on this configuration, the system is characterized by $W = 3, F = 3$ dan $X = 2$.

The set π is defined as follows:

$\pi_1 = \{1, \dots, W\}$; $\pi_1 = \{1, 2, 3\}$

$\pi_2 = \{W + 1, \dots, W + F\}$; $\pi_2 = \{4, 5, 6\}$

$\pi_{II} = \pi_1 \cup \pi_2$; $\pi_{II} = \{1, 2, 3, 4, 5, 6\}$

With the following descriptions:

π_1 : denotes the group of RUEs operating at the upper QoS threshold

π_2 : corresponds to the group of RUEs operating at the lower QoS threshold

π_{II} : represents the complete set of RUEs that are assigned to the RB

Table 8. Supporting Parameter Values in the Selfish User Model

Parameter	Description	Value
$\acute{S}$	Duration of usage time	2 hours
π	Value of the phi function	3.14
ϑ	Chemical parameter	0.5
q	Logarithmic base	2.71
p	Bandwidth energy consumption of a device when connected	10,240 kb
τ	Battery consumption rate per unit operational distance	6 hours
n	Propagation coefficient	2.71

Table 10 presents the parameter values used in the selfish user model, which are applied in the calculation based on the equation $\varphi(\acute{S}) = \frac{\pi^2}{3\vartheta^2} q^{-\vartheta^2} \acute{S}$. To obtain the value of $\varphi(\acute{S})$, the computation is carried out as follows: $\varphi(\acute{S}) = \frac{(3{,}14)^2}{3(0{,}5)^2} (2.71)^{-(0{,}5)^2} (2) = 21.64115$. The next step is to compute $V_j = \varphi(\acute{S}) + \tau p^n$, which yields: $V_j = 21.64115 + 6(10{,}240)^{2{,}71} = 4.4262 \times 10^{11}$. Thus, for the selfish user model in the C-RAN system, the resulting variable is $V_j = V_{jm} = 4.4262 \times 10^{11}$.

3. Formulation of Model I and Model II

This section presents the mathematical formulation of Model I and Model II used to capture selfish user behavior in a C-RAN environment. Model I is constructed using a quasi-linear utility function integrated with demand response and heterogeneous incentives, while Model II extends this structure by incorporating a bundling scheme that combines multiple services into a single offering. Both models consist of an objective function and a set of constraints covering QoS limits, RB allocation, network capacity, and pricing structures (usage-based, flat-fee, and two-part tariff). The complete formulation is provided through the equations and tables shown below.

- **Model I Formulation (C-RAN Selfish User Based on Demand Respons with Heterogeneous Incentives and Quasi-Linear Utility Function)**

Model I extends the C-RAN structure by incorporating the behavior of selfish users responding to demand response programs and heterogeneous incentive schemes. In this model, optimization is performed on a quasi-linear bandwidth-based utility function as defined in Equation (1), together with the set of constraints outlined in

Equations (2) through (21). The formulation covers three pricing mechanisms usage-based, flat fee, and two-part tariff while ensuring compliance with resource block (RB) allocation limits, quality of service (QoS) requirements, and overall network capacity.

$$\text{Max } \frac{\sum_{w=1}^{W+F}\sum_{x=1}^{X} k_{wx}\dddot{N}\log_2(1+\omega_{wx} l_{wx})}{\dot{\lambda}\sum_{w=1}^{W+F}\sum_{x=1}^{X} k_{wx} l_{wx} + \dot{R} + \dot{S}} + \frac{\left[\sum_e W_{eo}\right]^{A_1}\left[\sum_e Y_{eo}\right]^{A_2}}{\sum_e W_{eo} + \sum_e Y_{eo}} + H - \alpha\breve{K} + \hat{M}\,\hat{T}_n - \tilde{i}\left(\hat{T}_n - \hat{U}_n\right)^2 + bd + c^v - \ddot{L}d - \ddot{I}c - ZD \quad (1)$$

subject to the constraints:

$$\sum_{w=1}^{W+F}\sum_{x=1}^{X} k_{wx} = 1 \qquad ; k_{wx} \in \{0,1\} \quad (2)$$

$$\sum_{x=1}^{X} C_{wx} \geq \dot{\delta} \qquad ; x \in \pi_1 \quad (3)$$

$$\sum_{w=W+1}^{W+F} C_{wx} \geq \dot{\mu} \qquad ; x \in \pi_2 \quad (4)$$

$$\sum_{w=W}^{W+F} k_{wx}\, l_{wx}\, o_w\, a_w \leq \dot{\varepsilon} \qquad ; x \in \pi_{II} \quad (5)$$

$$\sum_{w=1}^{W+F}\sum_{x=1}^{X} k_{wx} l_{wx} \leq U_{max} \qquad ; l_{wx} \geq 0 \quad (6)$$

$$\sum_e Y_{eo} \leq V_o \qquad ; e = \{1,2\}, o = \{1,2\} \quad (7)$$

$$H = G + \theta(\breve{K} - \breve{L}) + \frac{\theta}{2\dot{T}\breve{K}}(\breve{K} - \breve{L})^2 \quad (8)$$

$$H_n \geq \bar{J} - \hat{U}_n \qquad ; n = 1, 2 \quad (9)$$

$$\hat{T}_n - \hat{U}_n = \frac{\hat{M}}{2\tilde{i}} \qquad ; n = 1, 2 \quad (10)$$

$$\frac{\hat{M}}{\hat{T}_n - \hat{U}_n} < 2\tilde{i} \qquad ; n = 1, 2 \quad (11)$$

$$\hat{T}_n \geq \hat{U}_n \qquad ; n = 1, 2 \quad (12)$$

$$\hat{M} \geq 0 \quad (13)$$

$$\tilde{i} \geq 0 \quad (14)$$

$$d \leq \bar{d}\, D \quad (15)$$

$$b \leq \bar{b}\, D \quad (16)$$

$$bd + c^v - \ddot{L}d - \ddot{I}c - ZD \geq 0 \quad (17)$$

$$D = 0 \text{ or } 1 \quad (18)$$

for the usage based scheme constraints:

$$\ddot{L} > 0; \quad \ddot{I} > 0; \quad Z = 0; \quad (19)$$

for the flat fee scheme constraints:

$$\ddot{L} = 0; \quad \ddot{I} = 0; \quad Z = 0; \quad (20)$$

for the two-part tariff scheme constraints:

$$\ddot{L} > 0; \quad \ddot{I} > 0; \quad Z > 0; \quad (21)$$

where:

$$Q_{vw} = k_{wx}\ddot{N}\, log_2(1 + \omega_{wx}\, l_{wx})$$

$$\omega_{wx} = \begin{cases} \dfrac{j_w\, y_{wx}}{\ddot{N}\, g_0} & ; x \in \pi_1 \\ \dfrac{j_w\, y_{wx}}{\dddot{B}\, S_w\, G_{wx} + \ddot{N}\, g_0} & ; x \in \pi_2 \end{cases}$$

- **Model II Formulation (C-RAN Selfish User Based on Demand Respons with Heterogeneous Incentives, Quasi-Linear Utility Function and Bundling Scheme)**

Model II extends the structure of Model I by incorporating a bundling scheme, as defined in Equations (22) through (30). This formulation integrates heterogeneous incentives and a bandwidth-based utility function with the combination of multiple services into a single package, aiming to enhance network efficiency and increase user utility.

$$\text{Max } \frac{\sum_{w=1}^{W+F}\sum_{x=1}^{X} k_{wx}\ddot{N}\log_2\left(1+\omega_{wx} l_{wx}\right)}{\dot{\lambda}\sum_{w=1}^{W+F}\sum_{x=1}^{X} k_{wx} l_{wx} + \dot{R} + \dot{S}} + \frac{\left[\sum_e W_{eo}\right]^{A_1}\left[\sum_e Y_{eo}\right]^{A_2}}{\sum_e W_{eo} + \sum_e Y_{eo}} + H - \alpha\breve{K} + \hat{M}\,\hat{T}_n - \tilde{i}\left(\hat{T}_n - \hat{U}_n\right)^2 + bd + c^v - \ddot{L}d - \ddot{I}c - ZD +$$

$$\sum_{n=1}^{N}\sum_{f=1}^{F}\left(\tilde{E}_f - \tilde{O}_f\right)\breve{Q}_{nf} - \sum_{f=1}^{F} G\breve{P}_f \quad (22)$$

accompanied by Constraints (1) through (21), as well as:

$$\hat{X}_n \geq \left(T_{nf} - \tilde{E}_f\right)\breve{P}_f \quad ; n = 1,\dots,3\ ;\ f = 1,\dots,3 \quad (23)$$

$$\hat{X}_n = \sum_{f=1}^{F}\left(S_{nf} - \tilde{E}_f\right)\breve{Q}_{nf} \quad ; n = 1,\dots,3\ ;\ f = 1,\dots,3 \quad (24)$$

$$\left(S_{nf} - \tilde{E}_f\right)\breve{Q}_{nf} \geq 0, \quad ; n = 1,\dots,3\ ;\ f = 1,\dots,3 \quad (25)$$

$$S_{nf} = \sum_{f=1}^{F} T_{nf} \quad ; n = 1,\dots,3\ ;\ f = 1,\dots,3 \quad (26)$$

$$\sum_{f=1}^{F}\breve{Q}_{nf} \leq 1 \quad ; n = 1,\dots,3\ ;\ f = 1,\dots,3 \quad (27)$$

$$\breve{Q}_{nf} \leq \breve{P}_f \quad ; n = 1,\dots,3\ ;\ f = 1,\dots,3 \quad (28)$$

$$\hat{X}_n \geq 0, \quad ; n = 1,\dots,3 \quad (29)$$

$$\tilde{E}_f \geq 0, \quad ; r = 1,\dots,3 \quad (30)$$

The formulation of Model I establishes the core structure for optimizing bandwidth-based utility while capturing user consumption behavior under network constraints. Model II enhances the model by adding bundling, resulting in more stable consumption and higher potential utility. Together, the two formulations offer a comprehensive framework for evaluating how pricing schemes and bundling strategies affect network efficiency and user utility.

4. Model Optimization Using Lingo 13.0

The optimization of Model I and Model II was carried out using LINGO 13.0 to obtain objective values and solver outcomes under three internet pricing schemes and four consumption cases. This process generated information regarding solver status, infeasibility levels, and the number of iterations required for each configuration. A summary of the optimization results is presented in Table 11.

Table 9. The Optimal Solutions Of The Three Internet Pricing Schemes and The Four Cases

Model	Pricing Scheme	Case	Model Category	State	Solver Status		Iterations	GMU	ER
					Objective	Infeasibility			
I	Usage Based	1	MINLP	Local Optimal	3108.49	0	190	64	0
		2	MINLP	Local Optimal	3108.49	0	256	64	0
		3	MINLP	Local Optimal	3108.49	5.55112×10^{-17}	264	64	0
		4	MINLP	Local Optimal	3108.49	0	268	65	0
I	Flat Fee	1	MINLP	Local Optimal	3108.49	5.55112×10^{-17}	1330	64	0
		2	MINLP	Local Optimal	3108.49	5.55112×10^{-17}	208	64	0
		3	MINLP	Local Optimal	3108.49	5.55112×10^{-17}	248	64	0
		4	MINLP	Local Optimal	3108.49	0	233	64	0
I	Two – Part Tariff	1	MINLP	Local Optimal	3108.49	0	190	64	0
		2	MINLP	Local Optimal	3108.49	0	256	64	0
		3	MINLP	Local Optimal	3108.49	5.55112×10^{-17}	264	64	0
		4	MINLP	Local Optimal	3108.49	0	268	65	0

Model	Pricing Scheme	Case	Model Category	State	Solver Status		Iterations	GMU	ER
					Objective	Infeasibility			
II	Usage Based	1	MINLP	Local Optimal	6408.49	5.55112×10^{-17}	376	82	0
		2	MINLP	Local Optimal	6408.49	1.11022×10^{-16}	173	82	0
		3	MINLP	Local Optimal	3108.49	2.21578×10^{-8}	290	82	0
		4	MINLP	Local Optimal	3108.49	0	636	82	0
II	Flat Fee	1	MINLP	Local Optimal	6408.49	1.11022×10^{-16}	116	82	0
		2	MINLP	Local Optimal	6408.49	5.55112×10^{-17}	116	82	0
		3	MINLP	Local Optimal	3108.49	1.87787×10^{-14}	291	82	0
		4	MINLP	Local Optimal	5258.49	5.55112×10^{-17}	418	82	0
II	Two – Part Tariff	1	MINLP	Local Optimal	6408.49	5.55112×10^{-17}	376	82	0
		2	MINLP	Local Optimal	6408.49	1.11022×10^{-16}	173	82	0
		3	MINLP	Local Optimal	3108.49	2.21578×10^{-8}	290	82	0
		4	MINLP	Local Optimal	3108.49	0	636	82	0

Table 11 shows that all model configurations reached a local optimal solution with very small infeasibility levels, indicating that the numerical results are valid and stable. The iteration counts reflect the computational effort required under each pricing scheme and case, while the resulting objective values represent the optimized outcomes based on the formulated model structure. These results serve as the foundation for further analysis in the next section.

5. Model Optimization Using Lingo 13.0

The optimization results indicate that both models reached *local optimal* across all pricing schemes and cases. Model I consistently produced an objective value of 3108.49. In contrast, Model II showed superior performance, particularly under the Flat Fee in Case 2 scenario, which yielded the highest objective value of 6408.49. This configuration also exhibited low iteration counts 116 and very small infeasibility values 5.55112×10^{-17}, making it the best optimal solution among all results. These findings demonstrate that incorporating bundling in Model II especially within the Flat Fee scheme enhances user utility while maintaining strong solution stability.

D. CONCLUSION AND SUGESTIONS

This study successfully formulated a C-RAN selfish user model incorporating demand response and heterogeneous incentives using a quasi-linear utility framework, applied in both Model I and Model II, where the latter integrates a bundling scheme. The optimization results reveal that Model II outperforms Model I, particularly under the Flat Fee scheme in Case 2, which achieves the highest objective value of 6408.49, with a low number of 116 iterations and an extremely small infeasibility level 5.55112×10^{-17}. This configuration stands as the most optimal solution, indicating that the inclusion of bundling significantly enhances user utility while preserving solution stability and overall network efficiency.

Future research is recommended to employ an isoelastic utility function to better capture user sensitivity to price and service quality. This approach offers a more flexible and realistic representation of consumption behavior, enabling the development of a more adaptive optimization model.

REFERENCES

Aktar, M. R., Anower, M. S., Sarkar, M. Z. I., Sayem, A. S. M., Islam, M. R., Akash, A. I., Rume, M. R. A., Moloudian, G., & Lalbakhsh, A. (2023). Energy-Efficient Hybrid Powered Cloud Radio Access Network (C-RAN) for 5G. *IEEE Access*, *11*, 3208–3220. https://doi.org/10.1109/ACCESS.2023.3234190

AlQahtani, S. A. (2023). Towards an Optimal Cloud-Based Resource Management Framework for Next-Generation Internet with Multi-Slice Capabilities. *Future Internet*, *15*(1–31). https://doi.org/10.3390/fi15100343

Boujnoui, A., Zaaloul, A., Orozco-Barbosa, L., & Haqiq, A. (2022). Stochastic Game Analysis of Cooperation and Selfishness in a Random Access Mechanism. *Mathematics*, *10*, 1–21. https://doi.org/10.3390/math10050694

Du, J., Jiang, C., Benslimane, A., Guo, S., & Ren, Y. (2021). SDN-Based Resource Allocation in Edge and Cloud Computing Systems: An Evolutionary Stackelberg Differential Game Approach. *IEEE*, 1–15. https://doi.org/10.1109/TNET.2022.3152150

Farhat, I., Awan, F. G., Rashid, U., Anwaar, H., Khezami, N., Boulkaibet, I., Neji, B., & Nzanywayingoma, F. (2024). Recent Trends in Cloud Radio Access Networks. *IEEE Access*, *12*, 175882–175904. https://doi.org/10.1109/ACCESS.2024.3437196

Georgiev, Y., Verhoeven, R., & Meratnia, N. (2022). Selfish Behavior in IEEE 802.11ah Networks: A Detection Algorithm and Mitigation Strategies. *Sensors*, *22*, 1–29. https://doi.org/10.3390/s22124472

Han, X., Zhao, Y., Yu, K., Huang, X., Xie, K., & Wei, H. (2021). Utility-Optimized Resource Allocation in Computing- Aware Networks. *International Conference on Communication Software and Networks*, 199–205. https://doi.org/https://doi.org/10.1109/ICCSN52437.2021.9463597

Hu, Y., Qiu, T., Chi, J., Yang, X., Wang, Z., & Li, W. (2022). Traffic Data Scheduling of Frequent Application Sets for Task Offloading in Multi-access Edge Computing. *IEEE International Conference on Communications*, 1605–1610. https://doi.org/10.1109/ICC45855.2022.9838928

Indrawati, I., Puspita, F. M., Nurhayati, L., Dwipurwani, O., Yuliza, E., & Octarina, S. (2023). *Validate Proof of Information Service Financing Scheme Model by Using the Customer Self-selection Bundling Strategy Based on Quasi-linear Utility Function*.

Indrawati, Puspita, F. M., Resmadona, Yuliza, E., Dwipurwani, O., & Octarina, S. (2021). Analysis of Information Service Pricing Scheme Model Based on Customer Self-Selection. *Science and Technology Indonesia*, *6*(4), 337–343. https://doi.org/10.26554/sti.2021.6.4.337-343

Israr, A., Yang, Q., & Israr, A. (2022). Power Consumption Analysis of Access Network in 5G Mobile Communication Infrastructures — An Analytical Quantification Model. *Pervasive and Mobile Computing*, *80*, 1–17. https://doi.org/10.1016/j.pmcj.2022.101544

Kampitaki, D. G., & Economides, A. A. (2023). Selfishness in Mobile Ad-Hoc Networks: A Literature Review on Detection Techniques and Prevention Mechanisms. *IEEE Access*, *11*, 86895–86909. https://doi.org/10.1109/ACCESS.2023.3305262

Monardo, J. (2022). *Quasi-Linear Utility and Demand Shape*. 1–24.

Oleksandrivna, P. I. (2025). The Huge Role Of The Internet in Modern Information Society Development. Online Communication, Ethics and Internet Security. *Information Technologies and Systems*, 115–121. https://doi.org/https://doi.org/10.26417/451fzx75d

Passas, V., Miliotis, V., Makris, N., & Korakis, T. (2020). Pricing Based Distributed Traffic Allocation for 5G Heterogeneous Networks. *IEEE Transactions on Vehicular Technology*, 1–12. https://doi.org/10.1109/TVT.2020.3012189

Prospero, L., Costa, R., & Badia, L. (2021). Resource Sharing in the Internet of Things and Selfish Behaviors of the Agents. *IEEE Transactions on Circuits and Systems II: Express Briefs*, *68*(12), 3488–3492. https://doi.org/10.1109/TCSII.2021.3121560

Puspita, F. M., Arda, S., Sitepu, R., Yunita, Yuliza, E., Octarina, S., & Yahdin, S. (2022). Validation of Improved Dynamic Spectrum and Traffic Management Models of Internet Pricing of Fair DSL-LTE Multiple QoS Network. *Science and Technology Indonesia*, *7*(1), 49–57. https://doi.org/10.26554/sti.2022.7.1.49-57

Puspita, F. M., Haloho, D. B., Yahdin, S., Yuliza, E., Nurhayati, L., & Hartono, Y. (2021). Quasi Linear

Utility Function Based-Wireless Internet Incentive-Pricing Models. *2021 4th International Seminar on Research of Information Technology and Intelligent Systems, ISRITI 2021*, 525–531. https://doi.org/10.1109/ISRITI54043.2021.9702851

Puspita, F. M., Indriani, P. E., Yuliza, E., Sitepu, R., Octarina, S., & Yunita. (2022). Mathematical Model of Traffic Management-Perfect Substitute-Selfish User Scheme. *Busicess Intelligence in Digital Era*. https://doi.org/https://doi.org/10.1109/ISRITI56927.2022.10052830

Puspita, F. M., Rahmadia, P., Yuliza, E., Indrawati, Sitepu, R., Octarina, S., & Yunita. (2023). Fair DSL-LTE Dynamic Spectrum Design Based-Utility Functions on Multiple Quality of Service Network. *Journal of Applied Science, Engineering, Technology, and Education*, *5*(2), 174–183. https://doi.org/10.35877/454RI.asci2042

Puspita, F. M., Rezky, B. J., Simarmata, A. N. Y., Yuliza, E., & Hartono, Y. (2021). Improved Incentive Pricing-Based Quasi-Linear Utility Function of Wireless Networks. *Indonesian Journal of Electrical Engineering and Computer Science*, *22*(3), 1467–1475. https://doi.org/10.11591/ijeecs.v22.i3.pp1467-1475

Puspita, F. M., Yuliza, E., Rezky, B. J., Simarmata, A. N. Y., & Hartono, Y. (2020). The Improved Model of Incentive-Pricing of Internet Schemes for Cobb-Douglas Utility Function by Using LINGO 13.0. *Journal of Physics: Conference Series*, *1663*, 1–9. https://doi.org/10.1088/1742-6596/1663/1/012017

Szymkowiak, A., Melović, B., Dabić, M., Jeganathan, K., & Kundi, G. S. (2021). Information Technology and Gen Z: The Role of Teachers, The Internet, and Technology in The Education of Young People. *Technology in Society*, *65*(1–10). https://doi.org/10.1016/j.techsoc.2021.101565

Yin, J., Fan, Y., Xia, T., Li, Y., Chen, X., Zhou, Z., & Chen, X. (2020). Mobile App Usage Patterns Aware Smart Data Pricing. *IEEE Journal on Selected Areas in Communications*, *38*(4), 645–654. https://doi.org/10.1109/JSAC.2020.2971896