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Impact of the Net Neutrality Repeal on Communication Networks

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ABSTRACT Network neutrality is the principle of treating equally all Internet traffic regardless of its source, destination, content, application or other related distinguishing metrics. Under net neutrality, Internet service providers (ISPs) are compelled to charge all content providers (CPs) the same per Gbps rate despite the growing profit achieved by CPs. In this paper, we study the impact of the repeal of net neutrality on communication networks by developing a techno-economic Mixed Integer Linear Programming (MILP) model to maximize the potential profit ISPs can achieve by offering their services to CPs. We consider an ISP that offers CPs different classes of service representing typical video content qualities. The MILP model maximizes the ISP profit by optimizing the prices of the different classes according to the users' demand sensitivity to the change in price, referred to as Price Elasticity of Demand (PED). We analyze how PED impacts the profit in different CP delivery scenarios in cloud-fog architectures. The results show that the repeal of net neutrality can potentially increase ISPs profit by a factor of 8 with a pricing scheme that discriminates against data intensive content. Also, the repeal of net neutrality positively impacts the network energy efficiency by reducing the core network power consumption by 55% as a result of suppressing data intensive content compared to the net neutrality scenario.

INDEX TERMS Net neutrality, AT&T, IP over WDM networks, profit, power consumption.

I. INTRODUCTION

Network (net) neutrality regulations prohibit Internet service providers (ISPs) from applying different treatment to IP packets based on their content e.g. prioritizing, blocking or throttling certain Internet content or allowing quality differentiation. Net neutrality, which was scrapped by the US Federal Communications Commission (FCC) in December 2017, has been the subject of remarkable debate in recent years between ISPs and content providers (CPs) with each side trying to exploit their assets and expand their profit and influence. The debate is fueled by the rapidly escalating demand for CPs services as a result of the interconnection between Internet and broadcasting markets. Cisco forecasts [1] that by 2021, annual global Internet traffic will hit 2.2 Zettabytes per month and CPs datacenters will be the source of 71% of this traffic. Online video services are the primary cause of this accelerated growth in Internet traffic. Video streaming is poised to consume 78% of the total CPs bandwidth with 75% of Internet video traffic originating from higher video services quality (High definition (HD) and Ultra-HD (UHD)).

Proponents of preferential treatment of Internet traffic complain that the increasing demand for data-intensive content creates a significant burden on the communication network. They argue that removing net neutrality will give ISPs further control of their infrastructure, which is crucial in order to improve QoS and reduce security threats. Another argument is that a significant fraction of the profit of this tremendously growing market is seized by CPs whereas ISPs act as a transit or transport medium into CPs customers. In the US, the quarterly profit margin of AT&T (an ISP) has been almost stable over the last six years whereas Netflix (a CP) profit margin has risen up in rapid pace from 0.7% to 9.8% within the same period [2], [3]. In contrast, advocates warn that removing net neutrality will slow down the innovation in the Internet and its content and will limit the content

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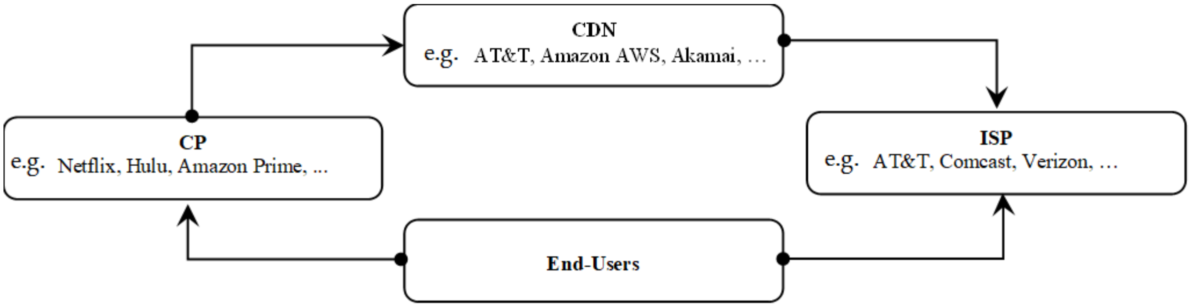

FIGURE 1. Main stakeholders in Internet ecosystem. Arrows represent customer-provider relationship.

competition by disadvantaging small businesses, and subsequently, diminish online services.

Deploying traffic discrimination in video delivery services has many challenges, e.g. detecting video packets and enforcing a policy on a certain video quality. Traffic discrimination in IP communication networks has been surveyed intensively in the literature. Several traffic management practices have been surveyed in [4]. The authors highlighted that traffic discrimination taxonomy has four features: (i) characteristics or condition of the traffic (e.g. based on content, protocol or source/destination). Real-time Transmission Protocol (RTP) is the Internet-standard protocol for the transport of real-time data. To identify the video content type (e.g. UHD, HD etc) transported over the network, the payload type in the RTP header can be inspected [5]. (ii) traffic classification (e.g. based on flow rate or header information). (iii) mechanism of discrimination (e.g. modify, delay, drop or block); and i(iv) perceived discrimination by end-users. To maximize QoE of providing video streaming service, traditional CPs typically use HTTP-based adaptive bitrate video streaming algorithms to provide video streaming over the Internet. Video is encoded at different bitrates with different video qualities at the CP's server to dynamically adjust the video bitrate (e.g. based on available network bandwidth) and such content is cached [6], [7]. Video traffic can be analyzed using two mechanisms; deep packet inspection (DPI) [8] or traffic profiling [9]. DPI examines the data packets that are sent over the network and traffic profiling detects abnormal network traffic by comparing new traffic against previous traffic profile. For example, an alarm can be triggered if the data rate transmitted over the network (measured in bps) spikes above the desired data rate, which could indicate an increase in data rate. QoS for video services delivery can be applied either by reserving network bandwidth for video packets (e.g. using IntServ) or labelling video content as high priority e.g. by applying Differentiated Services (e.g. using DiffServ) [10].

The Internet ecosystem is complex with many stakeholders. As illustrated in Fig. 1, the main stakeholders in the Internet ecosystem are: ISPs, CPs, content delivery networks (CDNs) and end-users. Users pay ISPs a subscription fee to get Internet access and subscribe to CPs (if required) to access their content. CPs subscribe to a CDN to access storage and processing capacity and to deliver their content to customers. CDNs are responsible for sending CPs content at large scale over ISPs network infrastructure, e.g. the CP Netflix collaborates with the CDN Amazon Web Services (AWS) to reach their customers [11]. ISPs play as the key intermediary in the delivery process as they provide the required connectivity between users and content. Most ISPs such as AT&T [12] and Comcast [13] are now providing CDN services in additional to networking services. To simplify our analysis, we consider a direct relationship between ISP and CPs.

Due to net neutrality regulations, current pricing policy of ISP networking services applies a fixed charge which is not linked with bitrate usage. For example, in the US, AT&T uses a fixed pricing model by charging CPs $3,282 per 10 Gbps per month [14] regardless of the content type transferred to users (either UHD video content or a simple text message). In this paper, we provide a novel techno-economic Mixed Integer Linear Programming (MILP) model built to study the potential profit an ISP can achieve by a differentiated pricing scheme under the repeal of net neutrality. The model optimizes the pricing scheme of differentiated service classes to maximize the ISP profit based on price elasticity of demand (PED). The MILP model finds the resulting equilibrium pricing, core network power consumption and traffic. To the best of our knowledge, this techno-economic MILP model is the first that studies the potential profit an ISP can achieve by proposing differentiated service classes to deliver CPs content of different data rate requirements at a varying price per bit rate.

The rest of this paper is organized as follows: Section II briefly summarizes related work. We describe the pricing scheme we used in this paper and the profit-driven model we adopted in Section III. Our results are presented in Section IV. In Section V, we provide concluding remarks.

II. RELATED WORKS

Many papers in the literature discussed and analyzed various aspects of net neutrality. From a legalization and regulation perspective, net neutrality in the Internet ecosystem has been surveyed by the authors in [15]. They emphasized that cloud computing has initiated the net neutrality battle between ISPs and CPs. In [16] the authors analyzed the Internet video streaming contest, taking into account all of ISPs and CPs assets (e.g. content rights, network access, users, … etc). They stated that video distribution makes the dilemmas of net neutrality solid and perceptible. Their analysis demonstrates that net neutrality correlates highly with video service delivery at different points including competition between CPs and ISPs, competition between stand-alone CP and CP owned by ISPs in providing video delivery services and growth of video traffic.

A number of papers in the literature focus on providing mathematical models to investigate the influence of the repeal of net neutrality on communication networks. Paid service differentiation where CPs voluntarily pay a monopoly ISP for prioritizing their traffic under shared network infrastructure was investigated by the authors in [17]. The differentiation occurs where ISPs offer service classes for CPs to choose from where traffic of a higher-priority class will be processed before those of a lower-priority. They studied the optimal pricing based on either maximizing the CPs' choices of service classes or minimizing system delays. Consequently, they highlighted that ISPs optimal pricing strategy can result in an efficient differentiation among CPs maximizing social welfare. Also, they found that applying paid prioritization can lead to money flows (profit) from CPs to ISPs. The authors in [10] modelled the competition of video services delivery market between an ISP's own integrated CP and stand-alone CP. They studied the impact of applying different QoS (marking video traffic as high priority) pricing strategies either by selling QoS to CPs, selling QoS to users, or choosing to not provide QoS at all. They investigated the impact of QoS pricing on the video service prices and CPs profit. The analysis showed that ISPs can sell QoS to CPs at a higher price than when QoS is sold to users, and the CPs are able to make more profit when QoS is directly sold to users than the case when QoS is sold to CPs. Also, they found that an ISP is more likely to use QoS exclusively for its own video services when it provides a similar content of CPs. The cloud infrastructure needed to host and deliver the video content was optimized in [18]–[21] and the impact of the delivery of large data volumes on the network was evaluated in [22]–[25]. Particular attention was paid to the core network which forms the heart of the ISP infrastructure and hosts the CDN with attention given to the network energy efficiency, latency and other QoS [26]–[28]. The work in [29] considered the impact of maximizing profit of CDN providers considering users who access CPs content from either cloud or fog server. In the case of competitive CPs, the CDN always places the content of the popular CP in fog servers, even when a less popular CP pays more, as the CDN tries to reduce core network transit cost.

The problem of optimizing pricing in competitive environments by considering a user-centric approach with usage-based pricing policies has been studied in the literature. In [30], the authors introduced power control via a pricing algorithm in wireless networks for the efficient management of network resources using a game theory framework. The framework achieved improvements in QoS compared to the case with no pricing. In [31], the authors addressed the problem of efficient utility-based power control in the uplink of a wireless network via convex pricing. A game theory framework was employed to obtain an efficient power allocation in the uplink of CDMA networks. The results showed improvement in the quality of experience (QoE) and reduction in the power consumption compared to linear pricing.

In this paper, a techno-economic Mixed Integer Linear Programming (MILP) model is developed to maximize the ISP profit by optimizing the ISP pricing scheme to charge different classes of service differently subject to PED. We considered three classes of service that represent different data rate requirements of video content. We build on our MILP optimization, network, cloud and fog modelling background [32]–[35] and consider ISPs that offer the CP service classes, which represent different data rate requirements.

III. REPEALING NET NEUTRALITY

In this paper, we consider the economic concept of PED to study the impact of ISP's price change on the number of users accessing CPs content. In the following subsections, we present the pricing scheme used in this work followed by the developed network and pricing MILP model.

A. PRICING SCHEME

In economics, the relationship between users demand and price is referred to as price elasticity of demand (PED) [36]. PED measures the percentage change in demand resulting from one percent change in price. To decide pricing strategy of a product, the seller looks at different sensitivities to various factors that may affect their decision to purchase a product. The dominant factor in determining PED is the users' ability and willingness at any given price. Many factors have an effect on users' behavior such as substitution availability, market competition, frequency of purchase, necessity of the product, and how much the product price represents in users' income. The PED is calculated as follows:

$$PED = \frac{\%\ Change\ in\ Demand}{\%\ Change\ in\ Price} \tag{1}$$

In telecommunications, it is not an easy task to estimate an exact value of PED for various Internet applications as the factors that affect the elasticity change from area to another e.g. wealth, popularity of an application, quality of service provided by ISPs/CPs or competition between different CPs. However, PED for broadband subscriptions in Organization for Economic Co-operation and Development (OECD) countries has been analyzed in [41] by studying the relationship between price, income and broadband adoption. Additional factors have been included in [42], which are age and education to study PED for broadband subscriptions in Latin America and the Caribbean countries. They found that 1%

decrease in price would lead to 0.43% and 2.2% increase in demand, respectively, over the two selected areas.

B. PROFIT-DRIVEN MILP MODEL

Mathematical representation is the most concise and accurate representation of a problem and can help understand and solve the problem in hand. The problem considered is linear in nature, with a large number of variables. This lends itself to mixed integer linear programming (MILP) optimization which has been used intensively in the literature to solve network design problem such as maximizing the profit achieved by infrastructure providers [39] and minimizing the power consumption of delivering clouds services [40].

We develop a profit-driven MILP model where the objective is to maximize the total profit of an ISP offering core network infrastructure to CPs to deliver content from distributed clouds and/or fog nodes to their users. This paper considers a single ISP provider, a monopoly, which exists in many countries. This may exist directly, i.e. there is one ISP in the country, or there is one ISP only which is able to provide full coverage of the country. According to FCC data, 40% of total US Internet subscribers, around 177 million people, only have a single ISP option in their area [41].

Under the net neutrality repeal, the ISP can deliver CPs content of different data rate requirements at a varying price per bit rate. We consider three classes to represent different data rate requirements of CPs services:

- Class A for high data rate content (i.e. UHD video service).
- Class B for medium data rate content (i.e. HD video service).
- Class C for low data rate content (i.e. SD video service). Note that other types of services (e.g. emails, images, audio etc.) can be categorized as Class C as they usually require low download rates.

The ISP needs to optimize the price of the three classes to maximize its profit. We consider content with higher data rate, which causes extra burden on the core network, to be priced higher per bit rate than content with a lower data rate. End-users will perceive varied video definitions from CPs based on their CP subscribed class. We assume that CPs will transfer the ISP new prices to their users to maintain their profit margin. Therefore, the CPs offer the same classes to their users. The proposed model maximizes the ISP profit which is a function of the price per bit rate of each class and the number of users per class which are related by (1), e.g. 1% increase in price, under PED = 1, would lead to 1% decrease in the number of users. The model selects the price per class that results in the maximum profit for the ISP at a given PED.

We assume a certain number of users to initially subscribe to each class under net neutrality. As the ISP and consequently the CPs vary the per bit rate charges for the different classes, users can choose to upgrade, downgrade or unsubscribe to the service. The number of users subscribing to each class depends on the PED. We assume that users leaving class A will join class B, users leaving class B will join class C and users leaving class C will unsubscribe to the service. Note that the proposed framework ensures that we can deliver different classes without blocking and without time constraints. Also, the proposed model can support mechanisms, similar to Call Admission Control (CAC) [42] by applying constraints on data intensive applications. Here, the network is driven into a state where it does not carry large traffic volumes of a certain class. In generic terms however, CAC is used to optimize the allocation of available resources of IP multimedia traffic to either guarantee QoS or ensure the best utilization of resources.

Before introducing the model, we define the parameters and variables used in the model:

1) PARAMETERS

s and d	Indices of source and destination nodes of a traffic demand.
m and n	Indices of the end nodes of a physical link.
i and j	Indices of the end nodes of a virtual link.
N	Set of IP over WDM network nodes.
Nm_m	Set of neighbouring nodes of node m.
α	Set of service classes.
W	Number of wavelengths per fibre.
B	Wavelength data rate.
CN	Number of clouds hosted in core network.
u	Total number of users in net neutrality scenario (i.e. before net neutrality is repealed).
LB	Minimum percentage of users served by CP to be maintained by the pricing scheme.
d_i	Download rate of class i.
Ͼ	The cost in US$ of provisioning a Gbps of IP over WDM network bandwidth per month.
Ͽ	The cost in US$ of provisioning a Gbps of metro and access network bandwidth per month.
PS	The net neutrality selling price in US$ of a Gbps of network bandwidth per month.
E_i	Price elasticity of demand of class i.
$N_{d,i}$	Number of users of class i located in node d under net neutrality scenario.
δ_s	$\delta_s = 1$, if a cloud datacentre is hosted in node s, otherwise $\delta_s = 0$.
F_d	$F_d = 1$, if there is no fog datacentre hosted in node d, otherwise $F_d = 0$.
Ƨ	Set of all possible solutions.
$\rho_{s,i}$	The price of class i under solution s and class i.
$yn_{s,d,i}$	The number of users in solution s subscribing to class i in node d as a result of its PED, where $\frac{PS}{\rho_{s,i-}PS} E_i = \sum_{d \in N} \left(\frac{yn_{s,d,i} - N_{d,i}}{N_{d,i}} \right)$ $\forall i \in \alpha, s \in \text{Ƨ}$.

2) VARIABLES

$C_{i,j}$	Number of wavelengths in virtual link (i, j).
$W_{m,n}$	Number of wavelengths in physical link (m, n).

APC_s	Number of router ports in node s that aggregate the traffic from clouds.
F_{mn}	Number of fibres on physical link (m, n).
$L_{i,j}^{s,d}$	Amount of traffic flow between node pair (s, d) traversing virtual link (i, j) .
$W_{m,n}^{i,j}$	Number of wavelengths of virtual link (i, j) traversing physical link (m, n).
r_i	ISP's revenue achieved by delivering traffic of class i to CP users.
R	Total ISP's revenue in US$ of delivering networking services to CPs content.
C	Total ISP cost in US$ of provisioning core network.
P_i	The price in US$ per Gbps of network bandwidth per month charged to the class i.
$U_{d,i}$	Number of users who subscribe to class i located in node d.
$CD_{i,d}$	Cloud flow from users in node d subscribed to class i.
$\mathcal{Z}_{s,i}$	$\mathcal{Z}_{s,i} = 1$, if solution s is selected for class i, otherwise $\mathcal{Z}_{s,i} = 0$.
$ys_{s,d,i}$	The number of users in solution s subscribing to class i in node $dys_{s,d,i} > 0$ if solution s is selected for class i, otherwise $ys_{s,d,i} = 0$.

Total ISP's cost and revenue of delivering CP contents are calculated as follows:

Cost of provisioning core, metro and access networks infrastructure (C):

$$\sum_{s\in N} APC_s\, B\, \text{Ͼ} + \sum_{i\in\alpha}\sum_{d\in N} U_{d,i}\, \text{Ͽ}\, d_i \tag{2}$$

Revenue of delivering networking services to CP users (R):

$$\sum_{i\in\alpha} r_i \tag{3}$$

The model is defined as follows:

The objective:

Maximize total profit given as:

$$\sum_{i\in\alpha} r_i - \left(\sum_{s\in N} APC_s\, B\, \text{Ͼ} + \sum_{i\in\alpha}\sum_{d\in N} U_{d,i}\, \text{Ͽ}\, d_i\right) \tag{4}$$

Equation (4) gives the total profit in US dollar.

The total profit is maximized by maximizing the revenue and minimizing the cost of serving users in different classes.

Subject to:

Revenue of each class:

$$r_i = \sum_{d\in N} U_{d,i}\, d_i\, P_i \quad \forall i \in \alpha \tag{5}$$

Constraint (5) calculates the revenue the ISP achieves by delivering a service class by considering the class price and the total traffic in each class. Note that, the total revenue is obtained by multiplying two variables ($U_{d,i}$ *and* P_i) which is a non-linear process. A look up table of solutions under different PED values defined by parameters ρ_{si}, $ys_{s,d,i}$, $yn_{s,d,i}$ is used for linearization. Constraints (6) - (10) select the optimum number of users and price for each class and calculate the resulting revenue.

$$ys_{s,d,i} \begin{cases} = \left(yn_{s,d,i}\mathcal{Z}_{s,i}\right) & \mathit{if}\ i = 1 \\ \leq \left(yn_{s,d,i} + N_{d,1}\right)\mathcal{Z}_{s,i} & \mathit{if}\ i = 2 \\ \leq \left(yn_{s,d,i} + N_{d,2}\right)\mathcal{Z}_{s,i} & \mathit{if}\ i = 3 \end{cases}$$

$$\forall i \in \alpha,\ s \in \text{Ƨ},\ d \in N \tag{6}$$

$$P_i = \sum_{s\in\text{Ƨ}} \left(\rho_{s,i}\mathcal{Z}_{s,i}\right) \quad \forall i \in \alpha \tag{7}$$

$$\sum_{s\in\text{Ƨ}} \mathcal{Z}_{s,i} = 1 \quad \forall i \in \alpha \tag{8}$$

$$U_{d,i} = \sum_{s\in\text{Ƨ}} ys_{s,d,i} \quad \forall d \in N, i \in \alpha \tag{9}$$

$$r_i = \sum_{s\in\text{Ƨ}} \left(\sum_{d\in N} ys_{s,d,i}\, d_i\, \rho_{s,i}\right) \quad \forall i \in \alpha \tag{10}$$

Constraint (6) calculates the number of users in solution s subscribing to class i in node d, $ys_{s,d,i} > 0$ if solution s is selected for class i, otherwise $ys_{s,d,i} = 0$. $\mathcal{Z}_{s,i} = 1$, if solution s is selected for class i, otherwise $\mathcal{Z}_{s,i} = 0$. The number of users in class A is the number of users subscribing to the class as a result of its PED (from a look up table). In the case of class B, the number of users available to class B includes all users subscribing to the class B as a result of its PED plus any users downgrading their subscription from class A to class B. In the case of class C, the number of users available to class C includes users subscribing to class C as a result of its PED plus any users downgrading their subscription from class B to class C. Constraint (7) gives the price of each class based on the solution selected from the lookup table. Constraint (8) ensures that only one solution is selected. Constraint (9) calculates the number of users of class i in node d. Constraint (10) calculates the revenue the ISP achieves by delivering a service class by multiplying the class price by the total traffic in each class.

Constraints on number of users and prices:

$$\sum_{d\in N}\sum_{i\in\alpha} U_{d,i} \geq u\, LB \tag{11}$$

$$P_1 \geq P_2 \geq P_3 \tag{12}$$

$$\frac{\sum_{d\in N} U_{d,i}}{\sum_{d\in N}\sum_{i\in\alpha} U_{d,i}} = \frac{U_{d,i}}{\sum_{i\in\alpha} U_{d,i}} \quad \forall i \in \alpha,\ d \in N \tag{13}$$

Constraint (11) defines the minimum user percentage the CP service needs to maintain. Constraint (12) ensures that the price of a lower class does not exceed the price of upper classes, i.e. the price of class C does not exceed the price of class B and the price of class B does not exceed the price of class A. Constraint (13) ensures that the ratio of users in different nodes is identical.

Core network traffic:

$$CD_{d,i} = U_{d,i}\, F_d\, d_i \quad \forall\, d \in N,\ i \in \alpha \tag{14}$$

$$\sum_{s\in N} L_{s,d} = \sum_{i\in\alpha} CD_{d,i} \quad \forall\, d \in N \tag{15}$$

Constraint (14) ensures that nodes with a fog built in their proximity are not served by a cloud. Constraint (15) calculates the download traffic from CP cloud to users in different nodes.

User demands can be used to decide on datacenter locations as follows:

$$L \sum_{d \in N} L_{s,d} \geq \delta_s \quad \forall s \in N \tag{16}$$

$$\sum_{d \in N} L_{s,d} \leq L \, \delta_s \quad \forall s \in N \tag{17}$$

Constraints (16) and (17) relate the binary parameter that indicates whether there is a datacentre built in node s or not (δ_s) to the traffic between users in node d and datacentre in node s.

Traffic flow conservation constraint in the IP layer:

$$\sum_{j \in N : i \neq j} L_{i,j}^{s,d} - \sum_{j \in N : i \neq j} L_{i,j}^{s,d} = \begin{cases} L_{s,d} & i = s \\ -L_{s,d} & i = d \\ 0 & otherwise \end{cases} \quad \forall s, d, i \in N : s \neq d \tag{18}$$

Constraint (18) represents the flow conservation for IP layer in the IP over WDM network. It ensures that the total incoming traffic equal the total outgoing traffic in all nodes; excluding the source and destination nodes.

Virtual link capacity constraint:

$$\sum_{s \in N} \sum_{d \in N : s \neq d} L_{i,j}^{s,d} \leq C_{i,j} \, B \quad \forall i, j \in N : s \neq d \tag{19}$$

Constraint (19) ensures that the traffic transmitted through a virtual link does not exceed its maximum capacity.

Flow conservation constraint in the optical layer:

$$\sum_{n \in Nm_m} W_{m,n}^{i,j} - \sum_{n \in Nm_m} W_{m,n}^{i,j} = \begin{cases} C_{i,j} & m = i \\ -C_{i,j} & m = j \\ 0 & otherwise \end{cases} \quad \forall i, j, m \in N : i \neq j \tag{20}$$

Constraint (20) represents the flow conservation for the optical layer. It ensures that the total number of incoming wavelengths in a virtual link is equal to the total number of outgoing wavelengths in all nodes excluding the source and destination nodes of the virtual link.

Physical link capacity:

$$\sum_{i \in N} \sum_{j \in N : i \neq j} W_{m,n}^{i,j} \leq WF_{m,n} \quad \forall m, n \in N \tag{21}$$

Constraint (22) represents the physical link capacity limit. It ensures that the number of wavelengths in virtual links traversing a physical link does not exceed the maximum capacity of fibres in the physical link.

Total number of aggregation ports in a core node:

$$APC_s = \frac{1}{B} \sum_{d \in N} L_{s,d} \quad \forall s \in N \tag{22}$$

Constraint (22) calculates the total number of router ports in each core node that aggregate the traffic from/to the clouds.

The mathematical model given above maximizes the total profit of an ISP. To calculate the core network power consumption achieved from the profit- driven model, the following parameters and variables are introduced;

3) PARAMETERS

S	Maximum span distance between two erbium doped fibre amplifiers (EDFAs).
$D_{m,n}$	Distance in kilometres between node pair (m, n).
$A_{m,n}$	Number of EDFAs between node pair (m, n) . $A_{m,n} = \left\lfloor \frac{D_{m,n}}{S} - 1 \right\rfloor$ where S is the reach of the EDFA.
$G_{m,n}$	Number of regenerators between node pair (m, n) . Typically $G_{m,n} = \left\lfloor \frac{D_{m,n}}{R} - 1 \right\rfloor$, where R is the reach of the regenerator.
Prp	Router port power consumption.
Pt	Transponder power consumption.
Pe	EDFA power consumption.
Pos	Optical switch power consumption in node s.
Prg	Regenerator power consumption.
n	Core network power usage effectiveness.

Under the non-bypass approach [44], the IP over WDM network power consumption is composed of:

The power consumption of routers ports:

$$n \left(\sum_{s \in N} Prp \, APC_s + \sum_{m \in N} \sum_{n \in Nm_m : n \neq m} Prp \, W_{m,n} \right) \tag{23}$$

The power consumption of transponders:

$$n \left(\sum_{m \in N} \sum_{n \in Nm_m : n \neq m} Pt \, W_{m,n} \right) \tag{24}$$

The power consumption of EDFAs:

$$n \left(\sum_{m \in N} \sum_{n \in Nm_m : n \neq m} Pe \, F_{m,n} A_{m,n} \right) \tag{25}$$

The power consumption of optical switches:

$$n \left(\sum_{s \in N} Po_s \right) \tag{26}$$

The power consumption of regenerators:

$$n \left(\sum_{m \in N} \sum_{n \in Nm_m : n \neq m} Prg \, RG_{m,n} \, W_{m,n} \right) \tag{27}$$

The total traffic carried over the core physical links is given as:

$$\sum_{\boldsymbol{m \in N}} \sum_{\boldsymbol{n \in Nm_m : n \neq m}} \boldsymbol{W_{m,n} \, B} \tag{28}$$

TABLE 1. **Input parameters of profit-driven model.**

Router port power consumption (Prp)	638W [51]
Transponder power consumption (Pt)	129W [52]
Regenerator power consumption (Prg)	114W, reach 2000 km [53]
EDFA power consumption (Pe)	11W [54]
Optical switch power consumption (Po)	85W [55]
Number of wavelengths in a fiber (W)	32 [56]
Bit rate of each wavelength (B)	40 Gbps [56]
Span distance between two EDFAs (S)	80 km [54]
Network power usage effectiveness (n)	1.5 [57]
Total users (u)	1.8 million users [46]
The cost of provisioning 1 Gbps of core network bandwidth per month (Ͼ)	$28
The cost of provisioning 1 Gbps of metro and access network bandwidth per month (Ͽ).	$90
The net neutrality selling price of downloading 1 Gbps of network bandwidth per month (Ps)	$131 [47]
Set of classes (α)	3 classes; A, B and C
Number of users of class i located in node d under net neutrality scenario ($N_{d,i}$)	19% of total users for class A, 56% for class B, and 25% for class C [45]. Number of users in each node is based on the population of the state where the node is located (see Fig. 2).
Download rate of class i (d_i)	18 Mbps for class A, 7.2 Mbps for class B, and 2 Mbps for class C [45]
Price elasticity of demand (E_i)	0.2, 0.4, 0.6, 0.8, 1 or 2
Minimum percentage of users served by CP to be maintained by the pricing scheme (LB).	0 or 100

In terms of computational complexity, we do not need to run the model in real-time as the optimization of pricing is an offline problem solved at the service planning and service update phases. However, it is important to ensure that we can obtain solutions for networks with large number of nodes. The above MILP optimization model has a total of $O(N^4)$ variables and $O(N^3)$ constraints where N is the number of nodes. For a network of $N = 25$, there is a total of about 25^4 variables and 25^3 constraints. Using a 2.5 GHz Intel core i7 with 16 GB memory, the model runs for a maximum of 7 minutes to obtain the optimum pricing for each price elasticity of demand (PED) scenario.

IV. PROFIT-DRIVEN MODEL RESULTS

In this section, we evaluate the increase in ISP profit and the reduction in network traffic and subsequently power consumption resulting from the optimized pricing scheme under the repeal of net neutrality. We define the three services classes as follows;

- Class A; for UHD video service; 18 Mbps download rate.
- Class B; for HD video service; 7.2 Mbps download rate.
- Class C; for SD video service; 2 Mbps download rate.

We investigate CP's end users' choices of service classes based on different PED. We show how users behavior under the different PED; 0.2, 0.4, 0.6, 0.8, 1 or 2 affects the equilibrium price of each class the ISP charges the CP for delivering its content.

As discussed above, we assume that the CP will transfer the price increase to their customers at the same rate (if the CP absorbs some of the increase in prices, then this may represent a different PED). As a benchmark, we consider users to be distributed among classes according to the Cisco forecast report [45], where UHD, HD, and SD users distribution are 19%, 56% and 25% respectively. We consider 1.8 million users active simultaneously in the network. This figure is obtained as follows: The number of users is 44 million users in Netflix in the US and the average user spent around 1 hour per day watching movies in 2015 [46]. Therefore, the average number of users during one hour of the day is 1.8 million users, which is an average number that does not consider the popularity of different viewing times in the day. The concentration of users at any node in AT&T network is based on the population of the state where the node is located (see Fig. 2).

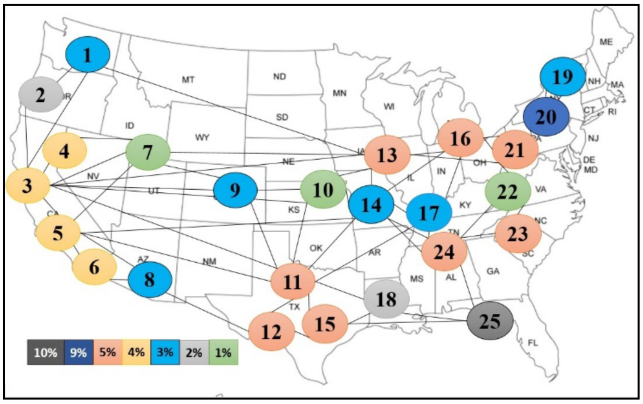

FIGURE 2. **AT&T core network with percentage of population in each node.**

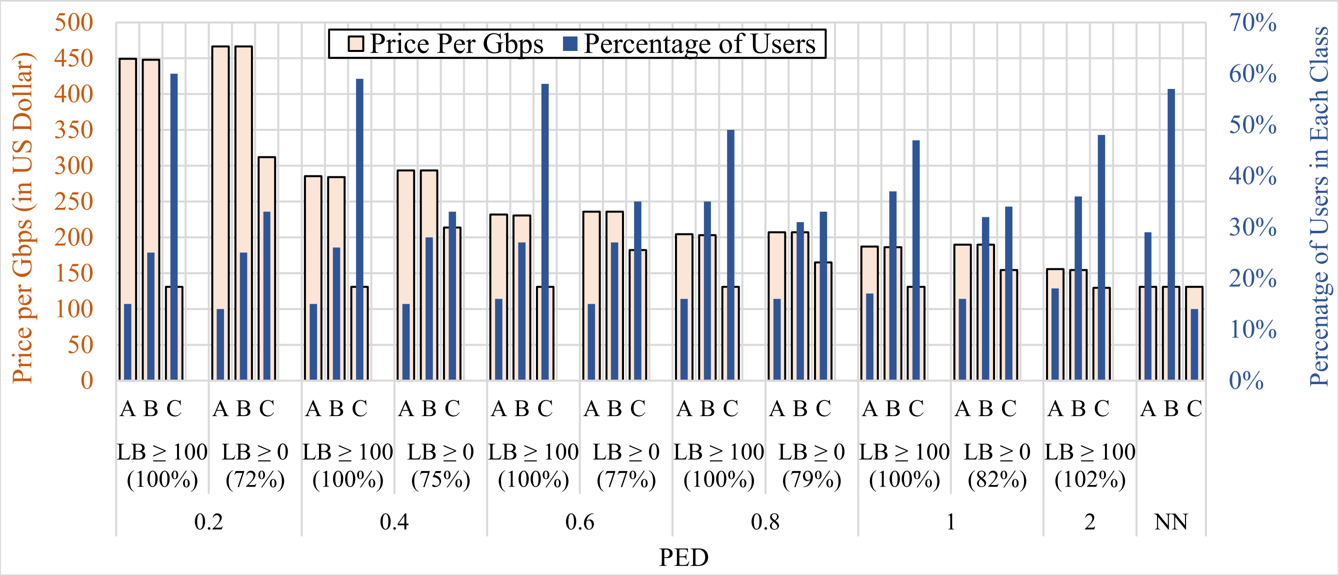

FIGURE 3. Price per Gbps per month and the corresponding number of users in each class based on different PED after repealing net neutrality (cloud-based delivery).

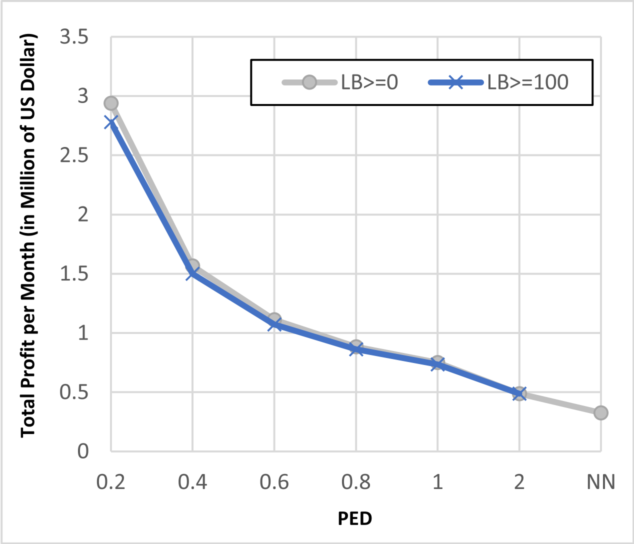

FIGURE 4. Total profit per month of profit-driven model under different PED scenarios for cloud-based delivery.

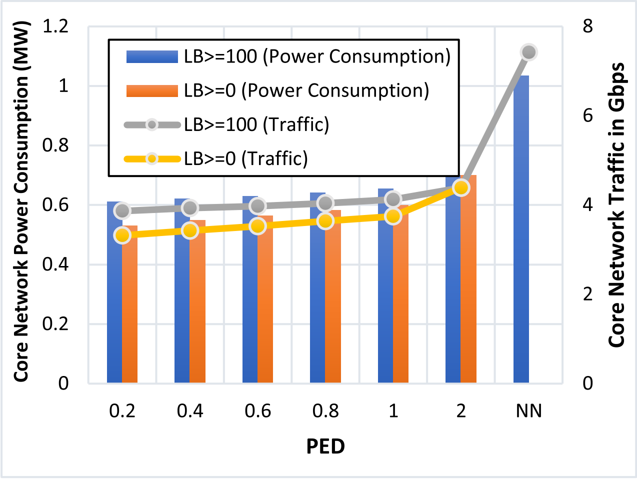

FIGURE 5. Total core network traffic and power consumption of profit-driven model under different PED scenarios for cloud-based delivery.

We consider the BT network connectivity selling price as the net neutrality price of the three classes where 10 Gbps connectivity is priced at £12,600 ($15,750) per year [47], i.e. $131 per 1 Gbps link per month. The actual cost of provisioning ISP core network infrastructure is sensitive information and not usually shared by ISPs. However, we estimate the cost of provisioning 1 Gbps of network as $118 considering 10% as the ISP profit margin (the average profit margin for AT&T [2] and Comcast [48] were approximately 9% and 12%, respectively between 2013-2018). We divided the cost among the three network layers; core, metro and access network based on their power consumption percentages: 24%, 6% and 70%, respectively [49] which corresponds to $28, $7, $83, respectively. The cost of $28 per Gbps in the core network is associated with a single hop. For the AT&T architecture the average hop count between clouds and other nodes is 1. Note that, the access networks can use any technology including technologies supporting mobility (LTE, 5G).

As shown in Fig. 2, we choose AT&T core network (a primary core network topology in the US) as a core network topology example. This core network consists of 25 nodes and 54 bidirectional links. AT&T hosts datacenters in nodes 1, 3, 5, 6, 8, 11, 13, 17, 19, 20, 22, and 25 [50]. These nodes are used to host datacenters to serve distributed CPs users. The input parameters used are given in Table 1.

In the following subsections, we evaluate two scenarios; equal PED for all classes and different PED for different

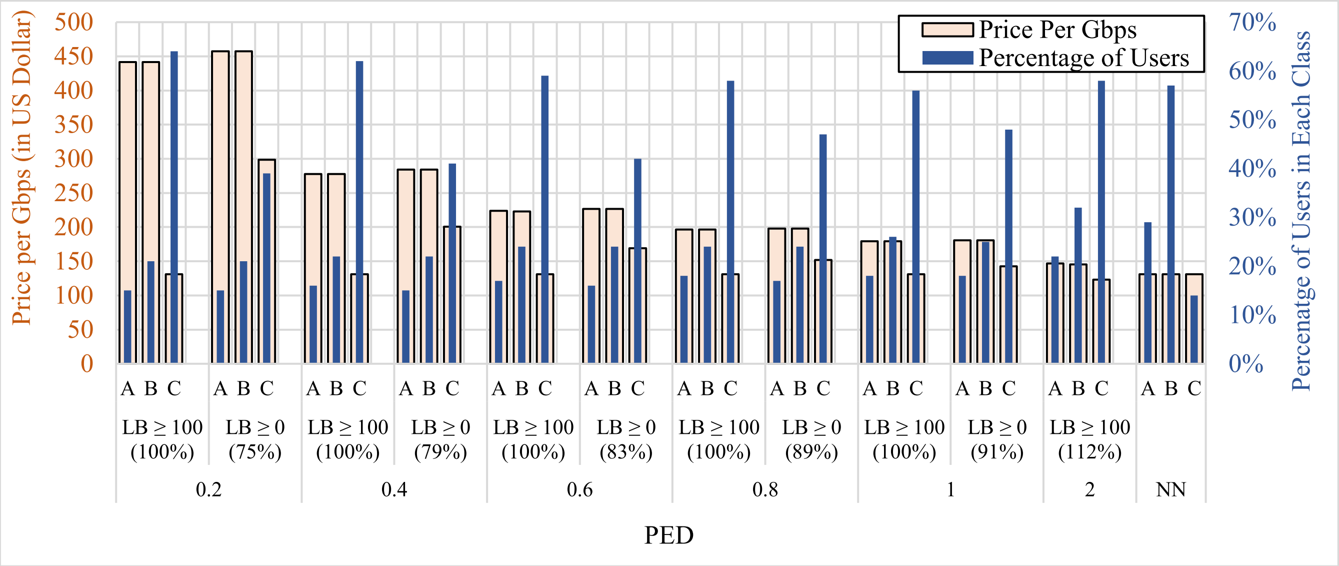

FIGURE 6. Price per Gbps per month and the corresponding number of users in each class based on different PED after repealing net neutrality (cloud-fog based delivery).

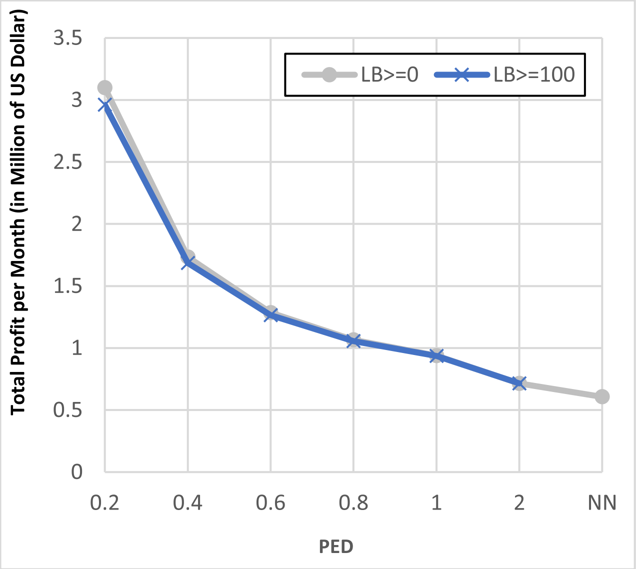

FIGURE 7. Total profit per month of profit-driven model under different PED (cloud-fog based delivery).

classes. Under each scenario we study three scenarios of delivering CPs contents to users; a cloud-based delivery and a cloud-fog based deliver and fog-based delivery.

A. EQUAL PED AMONG CLASSES

In the following, we study three scenarios of delivering CPs contents to users: cloud-based delivery, cloud-fog based delivery and fog-based delivery.

1) CLOUD BASED DELIVERY

Figs. 3 to 5 show the profit-driven model results for AT&T core network where content is delivered from the 12 datacenters in the AT&T topology [50]. The number of users and the corresponding price of each class under different PED are illustrated in Fig. 3. The primary y-axis shows price per Gbps per month of each class in US dollar. These prices represent the equilibrium point of users' willingness to follow the price increase which results in maximum profit for the ISP. The secondary y-axis corresponds to the percentage of users subscribed to each class. The x-axis shows different PED scenarios from 2 to 0.2. The former represents the highest sensitivity to the price change considered, whereas, the latter represents the contrary. PED values are shown along with the case of net neutrality where the price of different classes is fixed at $113 and the percentage of users in each class follows Cisco forecast report [45] as discussed above.

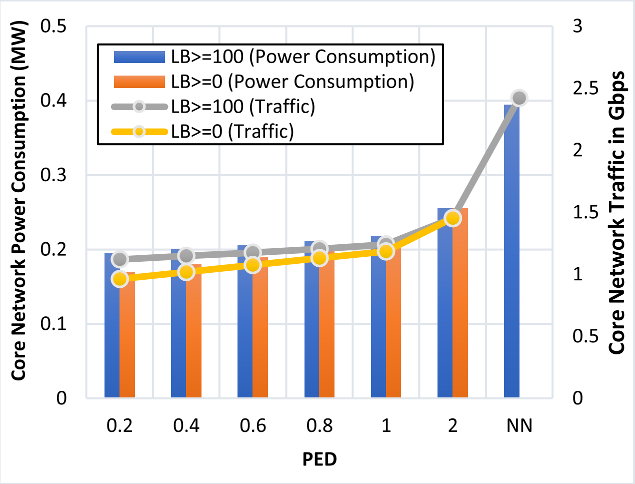

FIGURE 8. Total core network power consumption and traffic of profit-driven model under different PED (cloud-fog based delivery).

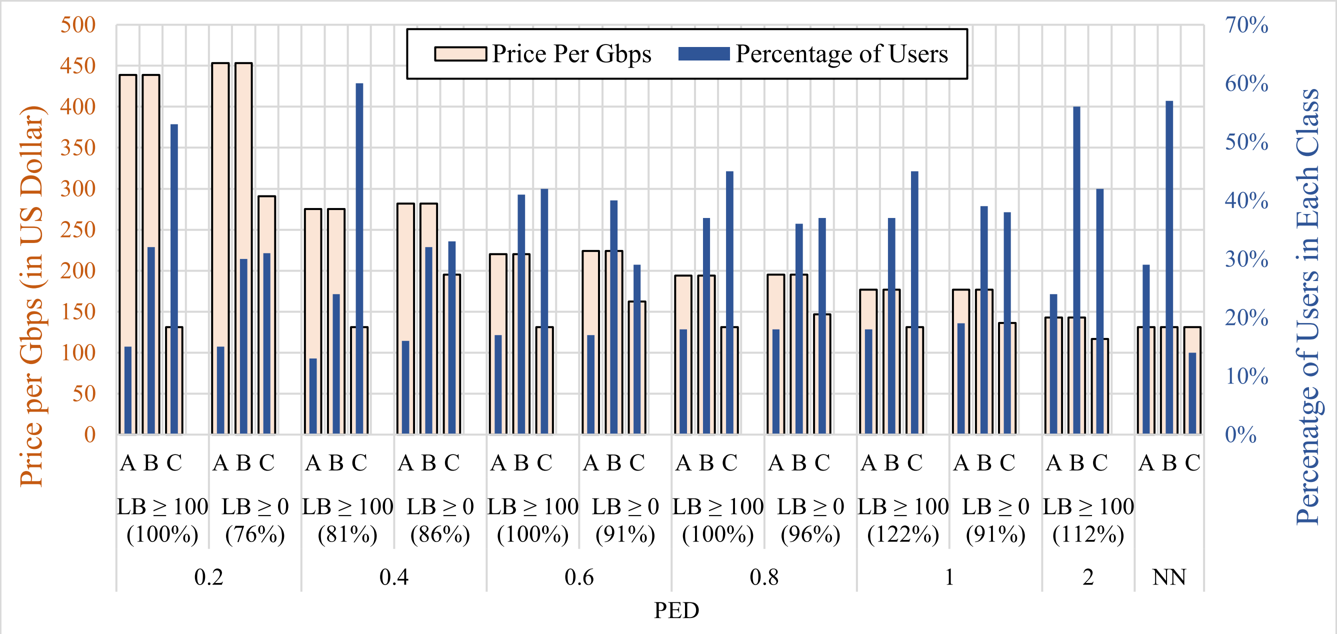

FIGURE 9. Price per Gbps per month and the corresponding number of users in each class based on different PED after repealing net neutrality (fog-based delivery).

For each PED value we consider two cases; a case where the optimized pricing scheme should maintain 100% of the users that existed under net neutrality ($LB \geq 100$) and another case where the pricing scheme can result in users leaving the service ($LB \geq 0$).

Fig. 4 is a plot of the monthly profit of ISP considering different PED values as well as net neutrality scenario. Total traffic of core network and the power consumption due to this traffic under different PED scenarios and the net neutrality scenario are plotted in Fig. 5. In case of content with $PED = 2$, under $LB \geq 100$ or $LB \geq 0$, Fig. 3 shows that repealing net neutrality has increased class C users to 48% of the total number of users compared to 14% only under the net neutrality pricing scheme. This increase is a result of some users of class B downgrading to class C as the class B price increased slightly by 18% (the number of users in class B reduced to 36%) and due to new users joining the service (the total number of users increased to 102%) attracted by the 1% decrease in class C price. The users of class A are reduced to 18% of the total number of users as a result of the slight increase in price by 19%. This pricing scheme and distribution of users have resulted in an increase in the total profit by 54% compared to the net neutrality scenario as seen in Fig. 4. For a less sensitive content with $PED = 0.2$ under $LB \geq 0$, the equilibrium pricing scheme resulted in 28% of the users leaving the service as the increase in the classes price resulted in an increase in the profit by a factor of 8 (800%) compared to the net neutrality scenario. Maintaining all the users of the service ($LB \geq 100$) has slightly reduced the profit by 10%.

In addition to growing ISP profit, the proposed pricing scheme has resulted also in reducing the traffic volume in the network. We observe in Fig. 5 a decline in the core network traffic by up to 55% under $PED = 0.2$, $LB \geq 0$ and a consequent reduction in power consumption by 49%. This reduction in core network traffic and power consumption occurred for two reasons; 1) some cloud service users leave classes A and B to subscribe to class C as the charges per Gb/s of the classes A and B increase. 2) the total cloud service subscribers diminished due to the increase in class C price (in case of $LB \geq 0$).

2) CLOUD-FOG BASED DELIVERY

Next, we introduce 10 fog nodes in addition to the 12 datacenter locations. These fog nodes are assumed to be built in the proximity of nodes with the highest population in the AT&T core network, so no core network cost (C) is incurred by serving the demands of these nodes. Fig. 6 shows that the prices per Gbps per month under different PED are less than the previous case (cloud-based delivery) as we reduced the cost of the core network by introducing the fog nodes. Under $PED = 2$, the prices compared to the net neutrality case in class A and B increased by 12% and 11%, respectively, while the price of class C dropped by 1% as opposed to 19%, 18% and 1% with cloud-based delivery. The reduced prices attracted more users resulting in increase in the profit by 18% compared to the net neutrality case as seen in Fig. 7 as opposed to a 54% increase in profit with cloud-based delivery. Fig. 8 shows a reduction in core network traffic (40%) and

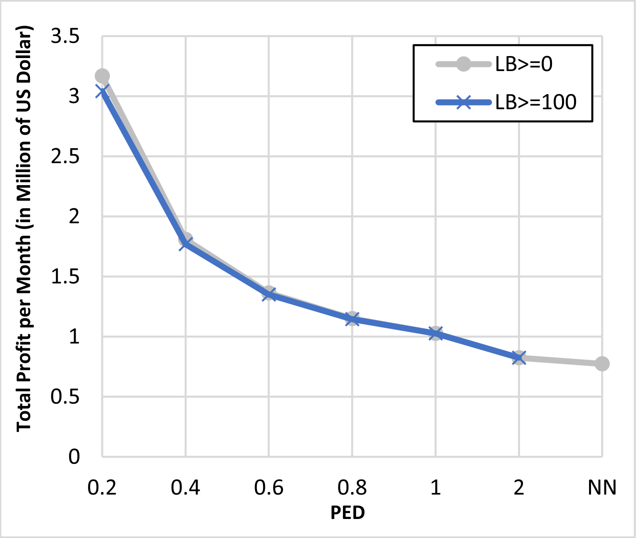

FIGURE 10. Total profit per month of profit-driven model under different PED (fog-based delivery).

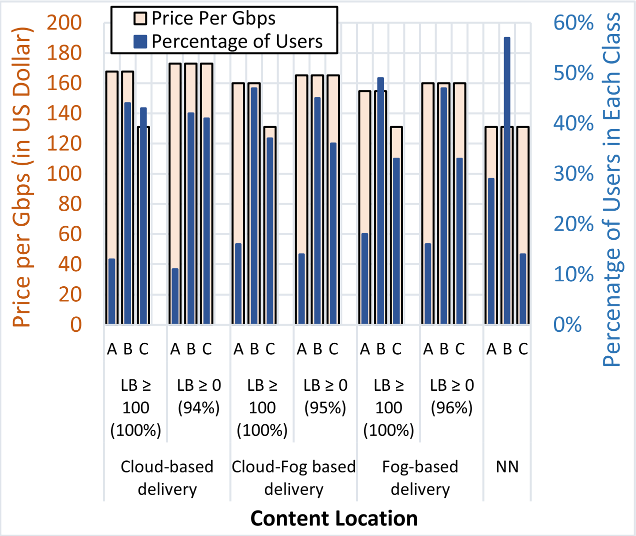

FIGURE 11. Price per Gbps per month and the corresponding number of users in each class of profit-driven model for different CP delivery scenarios where PED values of different classes A, B and C are 2, 0.8 and 0.2, respectively.

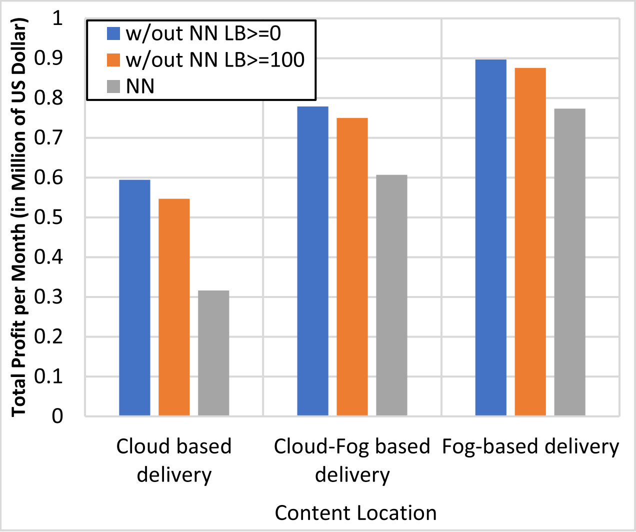

FIGURE 12. Total profit per month of profit-driven model for different CP delivery scenarios where PED values of different classes A, B and C are 2, 0.8 and 0.2, respectively.

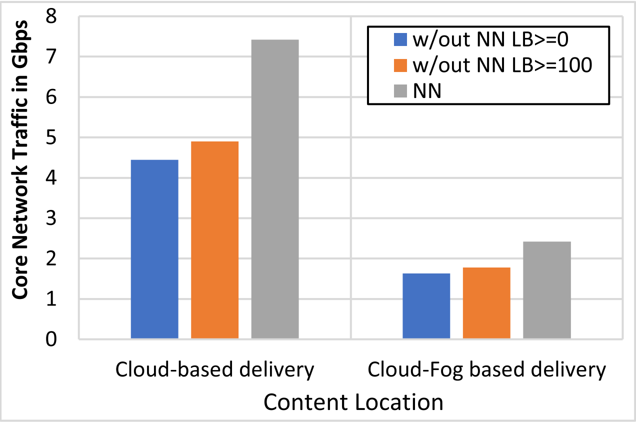

FIGURE 13. Total traffic resulting from profit-driven model for different CP delivery scenarios where PED values of different classes A, B and C are 2, 0.8 and 0.2, respectively.

power consumption (35%) by repealing net neutrality in the cloud-fog architecture.

3) FOG BASED DELIVERY

Here, we consider a scenario in which all users access CP contents from a local fog node. Although deploying a fog node locally, to serve CP customers, increases the capital expenditure (CAPEX) and operating expenses (OPEX) of provisioning multiple locations (i.e. 25 fog nodes in AT&T network), it reduces the communication network transit cost burden to the minimum. However, fog nodes are not always an option due to the finite capacity of processing and storage. The results show that the prices are further reduced under fog-based delivery (Fig. 9) as no core network cost ($\mathbb{C}$) is incurred by serving demands. For instance, under *PED* = 2, the prices compared to the net neutrality case in class A and B increased by 9% while the price of class C is decreased by 11% resulting in increase in the profit by 6% compared to the net neutrality scenario as seen in Fig. 10.

B. DIFFERENT PED AMONG CLASSES

In this section, we consider a scenario where elasticity of demand varies among the different classes of service. We consider class C to be less sensitive to price change than class B. Also, we considered class B to be less sensitive than class A. The elasticity of demand for classes A, B and C are considered to be 2, 0.8 and 0.2, respectively. Fig. 11 shows the price per Gbps for classes A and B is the same under different scenarios and delivery schemes as a result of the high

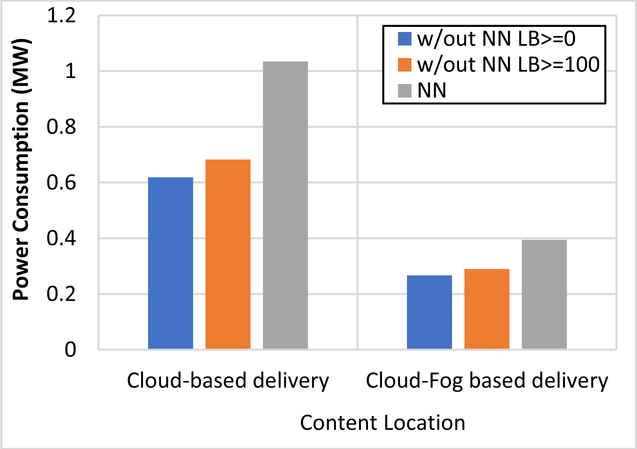

FIGURE 14. Total core network power consumption resulting from profit-driven model for different CP delivery scenarios where PED values of different classes A, B and C are 2, 0.8 and 0.2, respectively.

PED of class A. Class C is priced at the same level of classes A and B for $LB \geq 0$ as the low PED of class C limits the number of users leaving the services as a result of increase in the price. Fig. 12 shows an increase in profit by up to 88%, 29% and 16% under cloud-based delivery, cloud-fog based delivery and fog-based delivery, respectively, compared to the net neutrality scenario. Fig 13 shows a decrease in core network traffic by up to 43% and 30% under cloud-based delivery and cloud-fog based delivery, respectively, compared to the net neutrality scenario. Also, the total reduction in the core network power consumption (as shown in Fig 14) is up to 40% and 32% under cloud-based delivery and cloud-fog based delivery respectively.

V. CONCLUSION AND FUTURE WORK

In this paper, we developed a MILP model to optimize the pricing scheme used by ISPs to charge CPs for delivering their video content under the repeal of net neutrality where ISPs can treat data intensive traffic less favorably. A techno-economic Mixed Integer Linear Programming (MILP) model is developed to maximize the ISP profit by optimizing the ISP pricing scheme to charge different classes of service differently subject to PED. We considered three classes of service that represent different data rate requirements of video content. The analysis addressed three CP delivery scenarios; cloud-based delivery, cloud-fog based delivery and fog-based delivery. The results show that the discriminatory pricing scheme can increase the ISPs profit by a factor of 8. The results also show that by influencing the way end-users consume data-intensive content, the core network traffic and consequently power consumption are reduced by up to 49% and 55%, respectively, compared to the net neutrality scenario. In this work we consider a monopoly ISP provider. The competition between ISPs and its effect on pricing and the dynamics of users will be considered in future work where multiple ISPs exist hence affecting pricing and the dynamics of users. The problem of the competitive ISP market can be mathematically solved by game theory, where the strategic interaction between rational decision-makers is considered. In game theory, each ISP chooses the best decision taking into account the decisions of other ISPs'.

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