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On the Economics of Mobile Content Pre-Staging

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***Abstract*—The explosive demand for data in wireless devices has driven mobile carriers and the research community to seek nearly all intriguing technical and economic solutions to data demand problem. Content pre-staging is the idea to push content as close to the device as possible, either at the network edge or on the device itself in order to reduce bandwidth needs at peak demand times. We posit an interesting twist on this arrangement, namely to explore the economic implications if mobile device storage could be made available either by the user or indirectly by the wireless operator. We model the interplay between the mobile service carrier, the content provider, and end users as a Stackelberg game. Utilizing economic levers, the carrier sets the price for content providers to pre-stage content on mobile device storage, and provides monetary reward to compensate users for the usage of their mobile device storage. Through analyzing the impact of content localization on the economic well-being of all players, we demonstrate the improvement in network efficiency from the social welfare perspective. While the carrier may set prices strategically to retain a larger share of the increased profitability of the business, such practice benefits all the three parties in the game, i.e., users gain QoE and content; the carrier gains in saved capacity and new revenue; and the content provider gains in increased revenue and increased content access.**

I. Introduction

The past few years have seen a tremendous expansion in the demand for wireless data across a wide variety of wireless devices. Traditionally, meeting this rising demand requires large investments in wireless capacity. Furthermore, given the limited wireless spectrum available and the slow process by which new spectrum is re-purposed, the growth in the supply of wireless capacity is unlikely to keep pace with the massive increase in demand. Wireless carriers are faced with the reality of both trying to improve capacity via efficiency or acquisition whilst simultaneously considering the economic implications of allocating said limited resources.

For wireless carriers, techniques that improve the efficiency of the network without significant infrastructure changes can be quite appealing. The notion of caching as a fundamental principle has been a significant driver of efficiency for the Internet since its original inception. Caches can be widely used throughout the network to improve the Quality of Experience (QoE) of end users by reducing the pressure on service providers throughout the network. Unlike in the wired network whereby an in-network cache might reduce link bandwidth needs, the mobile device tends to operate best when it participates in the caching process due to changing link quality and mobility dynamics. Unfortunately, caching tends to be reactive, saving bandwidth primarily against future accesses but offering little benefit when the content is first downloaded.

In contrast, content pre-staging is the process by which content is pro-actively pushed to the device during off-peak times or secondary access mechanisms (ex. D2D [1]). When done correctly, content pre-staging can be quite effective [2] but when done poorly, that bandwidth and energy for said pre-staging is wasted. In this paper, we step back and look at the notion of content pre-staging from an economic perspective. Namely, if there existed mechanisms whereby spare mobile device storage could be made accessible to the carrier via a well-understood API [3], how might that change the economic of pre-staging?

In this paper, we study what would the economic impact be on wireless Internet service providers (ISPs) and mobile carriers should operator-accessible mobile device storage be put into practice. In particular, we seek pricing schemes as economic levers to lead the mobile network players to a socially optimal state. Traditionally, ISPs and mobile carriers have used simple flat-rate broadband data plans for both wired and wireless network access. With the popularity of mobile devices and expansion of data demand, carriers around the world have started to explore various broadband access pricing, penalty, and accounting mechanisms to manage the data demand [4]. Pre-staging content on mobile devices owned by end users introduces new revenue streams for carriers, for example, content providers may have the incentive to pay carriers to localize their content to guarantee advertising income from smooth delivery of advertisements. Content localization on user mobile devices imposes at least two more pricing questions on the carrier: how much to charge the content provider for localizing their content, and how much to reward end users for the usage of their mobile device storage.

The carrier's choice of pricing strategy can impact the behaviors of the content provider and end users which, in turn, affect the profitability of the carrier. We model the interplay between the carrier, the content provider, and end users as a Stackelberg game, where the carrier is the leader, and the content provider and end users are the followers. The carrier has the control over unused storage on mobile devices owned by end users and manages free storage on mobile devices as part of its system capacity. The economic

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analysis shows that pushing content to local mobile device storage is feasible by providing appropriate financial incentives to various stakeholders in the game. The subgame perfect Nash equilibrium of the three-way game shows that content localization increases total social welfare, i.e., the *combined* economic well-being of the carrier, the content provider, and end users. The practice benefits each party in the game. First, end users receive improved QoE by reducing delay in data delivering since the content is readily available locally on their devices. Users may additionally receive reward in return for renting their relatively cheap and unused storage. Users also gain in consumer surplus while enjoying more content access. Second, the carrier saves operational cost for time-shifting demands. With proper pricing, the carrier can maximize its profitability through new revenue from the content provider to optimize its content delivery. Third, the content provider gains from satisfied users and increased advertising revenue from more content access by users. We note that the split of increased profitability from localizing content between the carrier and the content provider is arbitrary. The carrier, as the leader in the game, has a range of pricing strategies to charge the content provider to make the content provider willing to join the game.

II. The Base-Case Model

In this section, we first model the key interactions between the mobile service carrier and mobile users without content pre-staging. The framework of the Stackelberg game and the subgame perfect equilibrium derived from backward induction are discussed.

The Interplay between the Carrier and End Users Before content localization is adopted, the interplay is mainly between the carrier and end users. The carrier is of unity, i.e., there is one of carrier that can be understood as the representative of all carriers. The carrier sets a per-byte price to charge end users their data usage. End users choose how much data to consume. The best strategies of the carrier and end users can be modeled in a Stackelberg game. In the game the carrier is the Stackelberg leader, and end users are the followers. They make decisions in a two-stage game. In the first stage, the carrier chooses the per-byte data access rate (denoted by p) to charge end users. In the second stage, users choose how much data to consume.

Formulating the Carrier-User Game Consider one carrier with a set of end users. End users own mobile devices and use them for web browsing, video streaming, reading e-books, playing games, taking photos, and running applications of all kinds. Users save photos, applications, music etc. on mobile devices so that they have both allocated/used storage (downloaded music, applications, saved photos, etc.) and free/unused storage on their mobile devices. Users value both consumption of network content and data saved on mobile devices. Let x_j be a representative user j's actual consumption of Internet content, and A_j be her actual usage of mobile device storage (i.e., consumed storage for personal data such as photos). User j acts so as to maximize her consumer surplus function denoted by $U_j(x_j, p, A_j)$ for each end user $j = 1, 2, ..., J$ for a unit data access price p.

In particular, we assume all data demand by users comes from accessing content provided by the content provider. Each user generates n_j (a random number) accesses and the average size of heterogenous content is θ, thus the data consumption by user j for accessing content is $x_j = \theta n_j$. Due to possible network congestion, not all content requests can be successfully served. The user may give up after certain trials, and an arbitrary content request is supposed to have a success probability $\delta \in (0, 1]$. Since x_j is defined as the actual Internet content consumption by user j (realized demand as perceived by the carrier), the user's real (optimal) demand for content is $\frac{x_j}{\delta}$. δ depends on the total congestion on the network, and it essentially measures user QoE: the higher δ is, the better is the content access quality experienced by the user.

We assume that end users' preferences are additively separable on content access and usage of mobile device storage so that $U_j = v_j(x_j, p) + v_j(A_j)$ where user j's total surplus is the sum of her user surplus from web content access and the usage of allocated storage. The two components of user surplus function $v_j(x_j, p)$ and $v_j(A_j)$ are assumed to have the same functional form. They are both concave and second-order differentiable with $v' > 0$ and $v'' < 0$, consistent with the economic principles of increasing total utility and diminishing marginal utility. The simplified assumptions allow for better illustration of model insights. Relaxing the assumptions will not affect model conclusions in any essential way.

When the carrier has no access to mobile device storage, the storage allocation of each user's mobile device plays no role in the carrier-user game in the base case.

We now consider the carrier's problem of choosing link capacity X and data access rate p so as to maximize profit. The carrier's costs are assumed to be linear: b is operating cost per unit of capacity and β is the constant marginal cost incurred to the carrier in case of network congestion, such as rationing cost of having to allocate scarce capacity or the cost of temporarily acquiring additional capacity. Both b and β are exogenous to the carrier. Thus, the cost function $C(X)$ is composed of both capacity operation and capacity failure components, i.e.,

$$C(X) = bX + \beta(D(p) - X) \tag{1}$$

where $D(p) = \sum_j x_j$ is the realized demand for capacity by end users at a given price p.

According to the cost function, the carrier chooses whether to maintain sufficient capacity by comparing the two cost parameters b and β,

$$X = \begin{cases} D(p) & \text{if } b \leq \beta \\ 0 & \text{if } b > \beta \end{cases} \tag{2}$$

We assume the cost of system failure always dominates the operating cost of the capacity, i.e., $b \ll \beta$. Thus the carrier uses the pricing strategy to manage data requests by end users to prevent network failure from happening.

Equilibrium Analysis in the Base Case We analyze the game using backward induction and first study users' optimal strategy. Since the carrier chooses the value of p, user j takes the price as given and chooses data access request so as to maximize her consumer surplus U_j. We denote this optimal demand for data as $x_j^*(p)/\delta$. Realized (or served) user demand is thus x_j^*.

We take an isoelastic utility function, a commonly used functional form of utility in economics. We assume that users incur a linear data cost. User j's realized demand for online content and mobile storage usage solve the following consumer surplus maximization problem.

$$\begin{aligned} \max_{x_j, A_j} \quad & U_j = \frac{(x_j/\delta)^{1-\alpha_j}}{1-\alpha_j} + \gamma_j \frac{A_j^{1-\alpha_j}}{1-\alpha_j} - p x_j \\ \text{s.t.} \quad & A_j \le s_j \end{aligned} \tag{3}$$

with $\alpha_j \in [0, 1)$. s_j is the total storage capacity of user j's mobile device. γ_j is a scaling factor to differentiate user j's self valuation of her consumption of content and allocated mobile device storage. If the user prefers online content to data saved on allocated storage, $\gamma_j < 1$. If the user assigns a higher value on data stored on mobile device than accessing online content, $\gamma_j > 1$.

We use the underline to denote optimal solutions to the base model, the first order condition of Equation (3) with respect to x_j provides us with the realized online data demand by user j,

$$\underline{x}_j^* = p^{-\frac{1}{\alpha_j}} \delta^{1-\frac{1}{\alpha_j}} \tag{4}$$

The quantity of content access by the user is accordingly $\underline{n}_j^* = \frac{x_j^*}{\theta} = \frac{p^{-\frac{1}{\alpha_j}} \delta^{(1-\frac{1}{\alpha_j})}}{\theta}$.

In the base case, how much storage users occupy is independent of the carrier's behaviors. The optimal choice of A_j can be found from the first order condition of Equation (3) with respect to A_j,

$$\underline{A}_j^* = (\frac{\lambda_j}{\gamma_j})^{-\frac{1}{\alpha_j}} \tag{5}$$

where λ_j is the Lagrange multiplier associated with the mobile storage cap constraint.

We now consider the carrier's profit (π) maximization problem by setting price p and capacity X so that the price limits end users' actual Internet content access to no higher than its chosen capacity,

$$\begin{aligned} \max_{p, X} \quad & \pi = p \sum_j x_j^* - C(X) \\ \text{s.t.} \quad & \sum_j x_j^* \le X \end{aligned} \tag{6}$$

Given a price p, the carrier can find $X^*(p)$, the optimal link capacity as a function of the price p, so as to maximize profit. We use $S(p) = X^*(p)$ to denote this supply side function. When end users and the carrier are at a market equilibrium, supply equals demand, i.e., $S(p) = D(p)$. At such an equilibrium price $\underline{p}^*$, each end user maximizes her own user surplus by consuming $\underline{x}_j^*(p^*)$ capacity, and the carrier maximizes its profit by providing just enough capacity $\underline{X}^*(p^*) = \sum_j \underline{x}_j^*(p^*) = \sum_j \underline{p}^{*-\frac{1}{\alpha_j}} \delta^{1-\frac{1}{\alpha_j}}$ from Equation (4). The carrier's optimal profit is $\underline{\pi}^* = (\underline{p}^* - b) \sum_j \underline{p}^{*-\frac{1}{\alpha_j}} \delta^{1-\frac{1}{\alpha_j}}$.

Suppose initially there is no contractual relationship between the carrier and the content provider to pre-stage content. The content provider thus plays no part in the game between the carrier and its end users. Assuming advertisements are inserted in content which generates revenue for the content provider, and the cost function of the content provider is held fixed, therefore profit maximization is equivalent to generating the maximum advertising revenue to the content provider. We suppose the content provider earns an average revenue a for a content of average size θ. The advertising revenue received by the content provider in the base case is hence $a \sum_j \underline{n}_j^*(p) = \frac{a}{\theta} \sum_j \underline{p}^{*-\frac{1}{\alpha_j}} \delta^{1-\frac{1}{\alpha_j}}$.

III. Three-Player Game Model

The section introduces an extended model in which the carrier implements the content localization policy to access unused storage on users' mobile devices. In the meantime the carrier forms a contractual relationship with the content provider to pre-stage selected content on mobile devices. To facilitate the practice of pushing content to local mobile device storage, the carrier provides proper financial incentives for the content provider and end users to follow.

Mobile Storage Access Game Formulation Pushing content to mobile device storage may save scarce capacity, generate content pre-staging revenue, improve user QoE, and guarantee stable advertising income. Realizing such gains requires properly chosen pricing schemes. We add a third party, the content provider to the Stackelberg game. In this three-party, two-stage game, the carrier is the leader who sets the data access price (denoted by p), reward rate to pay end users for the usage of their mobile device storage (denoted by q), and the content pre-staging rate charged on the content provider (denoted by r). All the three prices are on a per-byte basis. To focus the analysis on the two new prices q and r associated with content localization, we suppose the carrier keeps the same data consumption rate as in the base case, i.e., $p^* = \underline{p}^*$, and chooses optimal q and r. The followers making choices at the second stage are the content provider and end users. The content provider responds by determining the maximum amount of content it is willing to pay to store locally. End users respond by choosing how much content to consume and the distribution of mobile device storage between allocated space and free space. The backward induction process leads to a subgame perfect equilibrium of the game.

Content Provider's Best Response In contrast to the base case, maximizing the content provider's profit is no longer equivalent to maximizing its revenue when it can pay a fee to pre-stage content. Its advertising revenue depends on end users' access to content. The content provider's decision making is to choose the quantity of content pre-staging on mobile devices, subject to the maximum available unoccupied storage.

Consider a hypothetical scenario in which the carrier allows the content provider to pre-stage content in the device storage of users. If the content is not pre-staged, it is successfully accessed with probability δ as in the base case. The content provider is willing to pre-stage content on mobile devices if the increased advertising revenue exceeds the cost of pre-staging. Staging content locally increases the chance the content being accessed by $(1-\delta)$ on average. Thus the gain in advertising revenue per-byte of pre-staged content is $\frac{(1-\delta)a}{\theta}$.

Let g be the units of content that the content provider chooses to pre-stage on mobile devices. Given the per-byte pre-stage rate set by the carrier, the content provider's best response g^* is straightforward, i.e.,

$$g^* = \begin{cases} \sum_j (s_j - A_j)/\theta & \text{if } r \leq (1-\delta)a/\theta \\ 0 & \text{if } r > (1-\delta)a/\theta \end{cases} \tag{7}$$

The content provider's profit increases as long as the cost of pre-staging content on mobile devices stays below the increased advertising revenue from the increased viewing of content. In such case, the content provider chooses to pre-stage its content up to the limit the system capacity allows.

End Users' Best Response The consumer surplus function of end users depends on the benefits users obtain from Internet content access, mobile device storage usage, and cost/income associated with the two. In contrast to the base case, users now face a tradeoff between their own mobile device storage usage and the forgone possible reward for unused storage (to be incorporated into the carrier's system capacity). The amount of mobile device storage that users would be willing to share to the carrier depends on the reward rate. Therefore, the current form of the consumer surplus function is $U_j(x_j, p, A_j(q))$ where user j's choice of allocated mobile device storage depends on the reward rate q set by the carrier.

Users do not have to be aware of whether a particular content is pre-staged or not. User j consumes x_j amount of data towards the goal of maximizing her consumer surplus, of which $s_j - A_j$ is served locally with pre-staged content. The rest is delivered directly from the content provider via the bottleneck link of the carrier when the content is not pre-staged, denoted by $x_j - (s_j - A_j)$. User demand for data is thus $\frac{x_j-(s_j-A_j)}{\delta} + (s_j - A_j)$. User j's net data cost is $px_j - q(s_j - A_j)$, data consumption fee net off rewards for mobile device storage.

Take an isoelastic utility function, user j's consumer surplus maximization problem is

$$\begin{aligned} \max_{x_j, A_j} \quad & U_j = \frac{\{\frac{x_j-(s_j-A_j)}{\delta} + (s_j - A_j)\}^{1-\alpha_j}}{1-\alpha_j} \\ & \quad + \gamma_j \frac{A_j^{1-\alpha_j}}{1-\alpha_j} - (px_j - q(s_j - A_j)) \\ \text{s.t.} \quad & A_j \leq s_j \end{aligned} \tag{8}$$

Given a price p, user j's optimal choice of data consumption x_j^* is provided by the first order condition of Equation (8) as

$$x_j^* = p^{-\frac{1}{\alpha_j}} \delta^{1-\frac{1}{\alpha_j}} + (1-\delta)(s_j - A_j) \tag{9}$$

At this content access level, the user generates $\frac{a}{\theta}\{p^{-\frac{1}{\alpha_j}} \delta^{1-\frac{1}{\alpha_j}} + (1-\delta)(s_j - A_j)\}$ advertising revenue to the content provider. Pre-staging a certain content increases the probability of successful access by $(1-\delta)$. When the content provider chooses to take full unused storage on mobile devices, user j's actual content consumption increases by $(1-\delta)(s_j - A_j)$ (from Equation 4 to Equation 9) at the same data consumption rate charged by the carrier.

From the first order condition of Equation (8) with respect to A_j, we derive the optimal allocated storage usage by user j as $(\frac{q-p(1-\delta)}{\gamma_j})^{-\frac{1}{\alpha_j}}$. Considering the mobile storage cap constraint, the user's optimal choice of allocated mobile device storage A_j^* is

$$A_j^* = min\{(\frac{q-p(1-\delta)}{\gamma_j})^{-\frac{1}{\alpha_j}}, s_j\} \tag{10}$$

The Carrier's Decision When unused mobile device storage is manageable by the carrier, it becomes part of the system capacity of the carrier, and may be allocated as seen fit by the carrier to pre-stage selected content. The carrier's own link bandwidth is used to serve users' online content access requests that cannot be fulfilled locally.

The carrier has two revenue sources: capacity consumption payment by end users and content pre-staging payment by the content provider. The carrier's costs include the cost of link capacity and the rewards to end users for the usage of their mobile device storage. The carrier sets three rates (p, q, r) and chooses link capacity (X) with the goal of maximizing profit.

$$\begin{aligned} \max_{p,q,r,X} \quad & \pi = p\sum_j x_j + r\theta g - q\sum_j (s_j - A_j) - C(X) \\ \text{s.t.} \quad & \sum_j \{x_j - (s_j - A_j)\} \leq X \end{aligned} \tag{11}$$

In equilibrium, the actual capacity consumption by end users is equal to the link capacity of the carrier, i.e., $\sum_j \{x_j^* - (s_j - A_j^*)\} = X$. The choice of optimal capacity X^* and the optimal data access price p^* have the following relationship.

$$X^* = \sum_j \{p^{*-\frac{1}{\alpha_j}} \delta^{1-\frac{1}{\alpha_j}} - \delta(s_j - A_j^*)\} \tag{12}$$

We call the triple (p^*, q^*, r^*) the optimal pricing strategy of the carrier. To solve for the strategy, we turn to social welfare analysis of how content localization may affect the economic well-being of the mobile service business.

Social Welfare Analysis & The Carrier's Pricing Strategy Combining the economic well-being of all three interested parties (the carrier, the content provider, and end users), the social welfare function is of the following form.

$$W = \pi + ES + CS \tag{13}$$

where W = net social benefit, π = profit of the carrier, ES = end users' surplus, and CS = the content provider's surplus. Since the payments made by one party to another (such as content pre-staging fee paid to the carrier by the content provider) do not affect social welfare, the net economic benefit of mobile services depends on users' valuation of mobile services and the usage of mobile devices, the carrier's costs of providing mobile services, and the advertising revenue generated from users' content access, i.e.,

$$W = \sum_j V_j - C(X) + a \sum_j \frac{x_j}{\theta} \tag{14}$$

where V_j is user j's total utility received from content access and the usage of mobile device storage.

Compared to the base case, the change in social welfare is

$$\Delta W = \Delta \sum_j V_j + \frac{a}{\theta} \Delta \sum_j x_j - \Delta C(X) \tag{15}$$

In particular, the change in link capacity cost is

$$\begin{aligned} \Delta C(x) &= b(X^* - \underline{X}^*) \\ &= -b\{\sum_j \delta^{1-\frac{1}{\alpha_j}} (\underline{p}^{*^{-\frac{1}{\alpha_j}}} - p^{*^{-\frac{1}{\alpha_j}}}) + \delta \sum_j (s_j - A_j^*)\} \end{aligned} \tag{16}$$

and the change in advertising revenue is

$$\begin{aligned} \frac{a}{\theta} \Delta \sum_j x_j = \frac{a}{\theta} \{ &\sum_j \delta^{1-\frac{1}{\alpha_j}} (p^{*^{-\frac{1}{\alpha_j}}} - \underline{p}^{*^{-\frac{1}{\alpha_j}}}) \\ &+ (1-\delta) \sum_j (s_j - A_j^*)\} \end{aligned} \tag{17}$$

The change in end users' total utility depends on the change in utility from accessing content and allocated mobile device storage where

$$\begin{aligned} \Delta \sum_j V(x_j) = \sum_j \{ &\frac{(p^{*^{-\frac{1}{\alpha_j}}} \delta^{1-\frac{1}{\alpha_j}} + (1-\delta)(s_j - A_j^*))^{1-\alpha_j}}{1-\alpha_j} \\ &- \frac{(\underline{p}^{*^{-\frac{1}{\alpha_j}}} \delta^{1-\frac{1}{\alpha_j}})^{1-\alpha_j}}{1-\alpha_j}\} \end{aligned} \tag{18}$$

$$\begin{aligned} \Delta \sum_j V(A_j) = \gamma_j \sum_j \{ &\frac{(min\{\frac{q^* - p^*(1-\delta)}{\gamma_j})^{-\frac{1}{\alpha_j}}, s_j\})^{1-\alpha_j}}{1-\alpha_j} \\ &- \frac{(\frac{\lambda_j}{\gamma_j})^{-\frac{1-\alpha_j}{\alpha_j}}}{1-\alpha_j}\} \end{aligned} \tag{19}$$

For simplicity, let $q^* - p^*(1-\delta) = \lambda$ for all end users so that users do not change the way they use mobile device storage, thus $A^* = \underline{A}^*$ and $\Delta \sum_j V_j = \Delta \sum_j V(x_j)$. Alternatively, suppose at the initial optimal mobile storage consumption level $\underline{A}^*$, the marginal cost of giving up one unit of storage is equal to the mobile storage access fee q, thus the user is neutral to the financial reward of q.

Therefore, if the carrier chooses the same data consumption price as in the base case, i.e., $p^* = \underline{p}^*$, all of the three components of social welfare improves, i.e., user utility increases as they consume more content; the advertising revenue increases from increased content viewing by users; link capacity cost is saved as part of the content demand is met locally, hence $\Delta W > 0$. Localizing content on mobile devices increases the combined economic well-being of the three parties involved.

However, there is still one question remaining: how are the gains distributed among the parties? To provide financial incentives for each party, the distribution of social welfare must satisfy $\Delta\pi \geq 0$, $\Delta ES \geq 0$, and $\Delta CS \geq 0$. That is, no party is worse off than before in the scenario of content localization.

The change in the carrier's profit is $r \sum_j (s_j - A_j) - q \sum_j (s_j - A_j) - \Delta C(X)$. Combined with Equation (16), we get

$$\Delta\pi = (r - q + b\delta) \sum_j (s_j - A_j) \geq 0 \tag{20}$$

For the content provider, $\Delta CS \geq 0$ requires that the additional gain from advertising revenue must be no less than the pre-staging cost of the content, i.e.,

$$\frac{a}{\theta} \Delta \Sigma_j x_j \geq r \sum_j (s_j - A_j^*) \tag{21}$$

Combining Equations (17) and (21), we derive

$$r^* \in [0, \frac{(1-\delta)a}{\theta}]$$

which is consistent with the best response of the content provider in Section III.

For end users, their gain in consumer surplus is $\Delta CS = \Delta \sum_j V(x_j) + q \sum_j (s_j - A_j) > 0$ so that users gain at any level of reward rate for content pre-staging on their mobile devices. Therefore, the lower bound on q^* is zero, and the upper bound is the reward rate that satisfies $\Delta\pi = 0$. That is,

$$q^* \in [0, r^* + b\delta]$$

Therefore, when the carrier initiates content localization with no change in service charge on end users, the theoretical optimal pricing strategy is $(p^* = \underline{p}^*, q^* = 0, r^* = \frac{(1-\delta)a}{\theta})$. In this case, users gain from improved QoE, the content provider is equally well between content pre-staging or not, and the carrier receives the maximum possible gain in profitability:

$$\Delta\pi^* = (\frac{(1-\delta)a}{\theta} + b\delta) \sum_j (s_j - A_j^*)$$

Nevertheless, charging the content provider a pre-staging rate at $\frac{(1-\delta)a}{\theta}$ may not be feasible since the content provider does not gain from content pre-staging. To motivate the content provider, the carrier may lower r to share profit with the content provider. The extra profitability of the mobile service business ($\Delta\pi^*$) may be shared between the carrier and the content provider in an arbitrary manner.

Although users gain from improved QoE and increased content consumption at $q^* = 0$, for customer psychology consideration, q^* may have to be positive to overcome psychological hurdles, such as users' unwillingness to yield part of the control of their mobile devices out of privacy concern, etc.

Users may receive financial benefits from content localization in two alternative ways: being rewarded a fee for the carrier's usage of their mobile device storage, as in the model setup, or via reduced (discounted) data consumption rate p based on the level of content pre-staging. The two scenarios are equivalent at appropriately chosen prices. The difference is whether the financial benefit to end users is perceived explicitly. In practice, charge-then-refund has just entered the pricing model of the mobile industry when it appeared as part of the pricing structure of Google Fi [5].

IV. Related Work

Content caching and prefetching can significantly reduce the mobile bottleneck link pressure and improve the QoE of users. Research shows users are highly likely to view the data in prefetched videos indicating a promising opportunity to reduce network load [6]. Technical efforts have ranged from characterizing data and energy consumption by smartphone applications [7] to actively examining the efficiency of the data transfers themselves [1], [2], [8]. More recent research efforts have explored the extent to which device-to-device (D2D) communications might be leveraged to share cached information in cellular networks [9].

Time dependent pricing is one of the economic solutions towards the goal of time shifting demand in wireless data networks [10]. By charging users dynamically over time, time dependent pricing may flatten the temporal fluctuation of demand by motivating users to shift their usage to off-peak hours with lower price [11].

A common theme in recent cache economics research is to seek for service providers' optimal strategies to monetize caching, from optimal caching and pricing policies of service providers [12] to the design of caching contracts between service providers and content providers [13]. Content caching can also be combined with dynamic pricing. For example, users may take advantage of D2D communications to cache contents during off-peak time and trade cached contents with each other during peak time to save payments [14].

Another revenue source for mobile carriers is to seek compensation from content providers. One of recent economic proposals is content sponsoring, i.e., charging content providers instead of users for resources consumed in accessing the content [15], [16]. The content sponsoring, however, does not alleviate the problem of matching limited network capacity with network demand because content sponsoring works on the supply side of the problem.

V. Conclusions

One of the largest challenges in wireless communications has been the dramatic growth in demands for data. In this paper, we studied the economic impact of pre-staging selected content on unused mobile device storage. The interactions among multiple players: the carrier, the content provider, and end users, were modeled in a Stackelberg game, and equilibrium solutions were analyzed. We investigated the optimal pricing strategies of mobile carriers to provide proper financial incentives for content localization to content providers and end users while maximizing profitability of carriers themselves. We showed that content localization via carrier-accessible mobile device storage is welfare enhancing, i.e., increase of combined benefit gains for all players and efficiency in capacity management.

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