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A Reverse Auction for Proactively Expressing the Delay Tolerance in Cellular Network

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Abstract: ***Cellular networks (e.g., 3G) are currently facing severe traffic overload problems caused by excessive traffic demands. So Offloading part of the cellular traffic through other forms of networks, such as Delay Tolerant Networks (DTNs) and WiFi hotspots, is a promising solution. However, since these networks can only provide intermittent connectivity to mobile users, utilizing them for cellular traffic offloading may result in a non-negligible delay. As the delay increases, the user's satisfaction decreases. In this work, we investigate the tradeoff between the amount of traffic being offloaded and the user's satisfaction. We provide a novel incentive framework to motivate users to leverage their delay tolerance for cellular traffic offloading. Users are provided with incentives; i.e., receiving discount for their service charge if they are willing to wait longer for data downloading. During the delay, part of the cellular data traffic may be opportunistically off-loaded to other networks mentioned above, and the user is assured to receive the remaining part of the data via cellular network when the delay period ends. To minimize the incentive cost given an offloading target, users with high delay tolerance and large offloading potential should be prioritized for traffic offloading. To effectively capture the dynamic characteristics of users delay tolerance, our incentive framework is based on reverse auction to let users proactively express their delay tolerance by submitting bids. We further illustrate how to predict the offloading potential of the users by using stochastic analysis for both DTN and WiFi cases. Extensive trace-driven simulations verify the efficiency of our incentive framework for cellular traffic offloading.***

Keywords: Cellular traffic offloading, auction, delay tolerant networks, WiFi hotspots

1. Introduction

The recent popularization of cellular networks (e.g., 3G) provide mobile users with ubiquitous Internet access. However, the explosive growth of user population and their demands for bandwidth-eager multimedia content raise big challenges to the cellular networks. A huge amount of cellular data traffic has been generated by mobile users, which exceeds the capacity of cellular network and, hence, deteriorates the network quality [1]. To address such challenges, the most straightforward solution is to increase the capacity of cellular networks, which however is expensive and inefficient. Some researchers studied on how to select a small part of key locations to realize capacity upgrade, and shift traffic to them by exploiting user delay tolerance [2]. Remaining the capacity of cellular networks unchanged, offloading part of cellular traffic to other coexisting networks would be another desirable and promising approach to solve the overload problem.

Some recent research efforts have been focusing on offloading cellular traffic to other forms of networks, such as DTNs and WiFi hotspots [3], [4], [5], and they generally focus on maximizing the amount of cellular traffic that can be offloaded. In most cases, due to user mobility, these networks available for cellular traffic offloading only provide intermittent and opportunistic network connectivity to the users, and the traffic offloading hence results in non negligible data downloading delay. In general, more offloading opportunities may appear by requesting the mobile users to wait for a longer time before actually downloading the data from the cellular networks, but this will also make the users become more impatient and, hence, reduce their satisfaction.

In this paper, we focus on investigating the tradeoff between the amount of traffic being offloaded and the users' satisfaction, and propose a novel incentive frame- work to motivate users to leverage their delay tolerance for traffic offloading. Users are provided with incentives; i.e., receiving discount for their service charge if they are willing to wait longer for data downloading. During the delay, part of the cellular data traffic may be opportunistically off- loaded to other networks mentioned above, and the user is assured to receive the remaining part of the data via cellular network when the delay period ends.

The major challenge of designing such an incentive framework is to minimize the incentive cost of cellular network operator, which includes the total discount provided to the mobile users, subject to an expected amount of traffic being offloaded. To achieve this goal, two important factors should be taken into account, i.e the delay tolerance and offloading potential of the users. The users with high delay tolerance and large offloading potential should be prioritized in cellular traffic offloading.

First with the same period of delay, the users with higher delay tolerance require less discount to compensate their satisfaction loss. To effectively capture the dynamic characteristics of the users' delay tolerance, we propose an incentive mechanism based on reverse auction, which is proved to conduct a justified pricing. In our mechanism, the users act as sellers to send bids, which include the delay that they are willing to experience and the discount that they want to obtain for this delay. Such discount requested by users is called "coupon" in the rest of the paper. The network operator then acts as the buyer to buy the delay tolerance from the users.

Second, with the same period of delay, users with larger offloading potential are able to offload more data traffic. For example, the offloading potential of a user who requests popular data is large because it can easily retrieve the data pieces from other contacted peer users during the delay period. Also, if a user has high probability to pass by some WiFi hotspots, its offloading potential is large. To effectively capture the offloading potential of the users, we propose two accurate prediction models for DTN and WiFi case, respectively.

The optimal auction outcome is determined by considering both the delay tolerance and offloading potential of the users to achieve the minimum incentive cost, given an offloading target. The auction winners set up contracts with the network operator for the delay they wait and the coupon they earn, and other users directly download data via cellular network at the original price. More specifically, the contribution of the paper is threefold:

a) We propose a novel incentive framework, *Win-Coupon*, based on reverse auction, to motivate users leveraging their delay tolerance for cellular traffic offloading, which have three desirable properties:
   - truthfulness,
   - individual rationality, and
   - low computational complexity.
b) We provide an accurate model using stochastic analysis to predict users' offloading potential based on their data access and mobility patterns in the DTN case.
c) We provide an accurate Semi Markov-based prediction model to predict users' offloading potential based on their mobility patterns and the geographical distribution of WiFi hotspots in the WiFi case.

The rest of the paper is organized as follows: In Section 2, we briefly review the existing work. Section 3 provides an overview of our approach and the related background. Section 4 describes the details of our incentive framework, and proves its desirable properties. Section 5 evaluates the performance of Win-Coupon through trace-driven simulations and Section 6 discusses further research issues. Section 7 concludes the paper.

2. Related Work

To deal with the problem of cellular traffic overload, some studies propose to utilize DTNs to conduct offloading. Ristanovic et al. [6] propose a simple algorithm, MixZones, to let the operator notify users to switch their interfaces for data fetching from other peers when the opportunistic DTN connections occur. Whit beck et al. [7] design a framework, called Push-and-Track, which includes multiple strategies to determine how many copies should be injected by cellular network and to whom, and then leverages DTNs to offload the traffic. Han et al. [3] provide three simple algorithms to exploit DTNs to facilitate data dissemination among mobile users, to reduce the overall cellular traffic. Many research efforts have focused on how to improve the performance of data access in DTNs. In [8], the authors provide theoretical analysis to the stationary and transient regimes of data dissemination. Some later works [9], [10] disseminate data among mobile users by exploiting their social relations. Being orthogonal with how to improve the performance of data access in DTNs, in this paper, we propose an accurate model to capture the expected traffic that can be offloaded to DTNs to facilitate our framework design.

Public WiFi can also be utilized for cellular traffic offloading. The authors of [6] design HotZones to enable users turning on WiFi interfaces when a WiFi connection is expected to occur based on the user mobility profile and location information of hot zones covered by WiFi. The authors of [5] measure the availability and the offloading performance of public WiFi based on vehicular traces. Lee et al. [4] consider a more general mobile scenario, and present a quantitative study on delayed and on-the-spot offloading by using WiFi. The prediction of future WiFi availability is important to the offloading scheme design, and has been studied in [11], [12]. The authors of [11] propose to enable mobile users to schedule their data transfers when higher WiFi transmission rate can be achieved based on the prediction. In [12], a Lyapunov framework-based algorithm, called SALSA, is proposed to optimize the energy-delay tradeoff of the mobile devices with both cellular network and WiFi interfaces. Different from the existing work, in this paper, we propose an accurate model to predict how much traffic that can be offloaded via WiFi hotspots if a mobile user is willing to wait for certain delay time.

All the existing offloading studies have not considered the satisfaction loss of the users when a longer delay is caused by traffic offloading. To motivate users to leverage their delay tolerance for cellular traffic offloading, we propose an auction-based incentive framework. Auction has been widely used in network design. Applying auction in the spectrum leasing is one of the most practical applications. Federal Communications Commission (FCC) has already auctioned the unused spectrum in the past decade [13], and there are a large amount of works on wireless spectrum auctions [14], [15]. Moreover, auction has also been applied for designing incentive mechanism to motivate selfish nodes to forward data for others [16], [17]. However, none of them has applied auction techniques to cellular traffic offloading.

This paper substantially extends the preliminary version of our results appeared in [18]. In [18], we mainly focused on how to stimulate users to offload cellular traffic via DTNs. In this paper, we propose a more general framework that considers both DTNs and WiFi case. We provide an accurate model to predict users' offloading potential in the WiFi case and perform trace-driven simulations to evaluate its performance. In addition, we change the data query model in [18] to more realistic Zipf-like distribution to evaluate our framework.

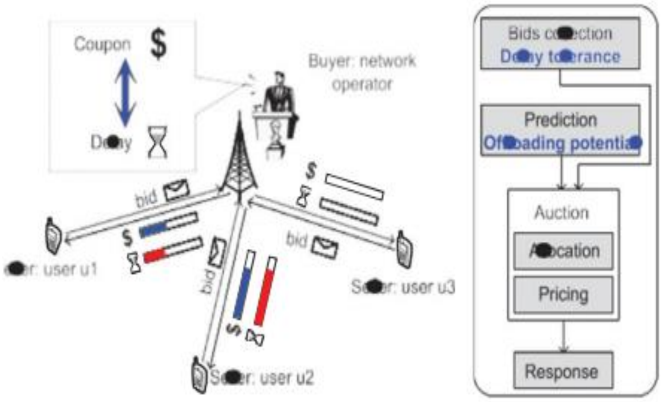

Figure 1: The main idea of Win-Coupon

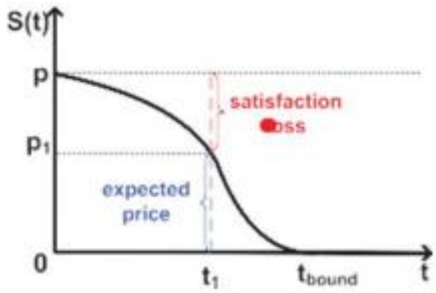

Figure 2: Satisfaction Function

3. System Architecture

3.1 The Big Picture

In this section, we give an overview of the Win-Coupon framework. By considering the users' delay tolerance and offloading potential, Win-Coupon uses a reverse auction-based incentive mechanism to motivate users to help cellular traffic offloading. Figure 1 illustrates the main idea. The network operator acts as the buyer, who offers coupons to users in exchange for them to wait for some time and opportunistically offload the traffic. When users request data, they are motivated to send bids along with their request messages to the network operator. Each bid includes the information of how long the user is willing to wait and how much coupon he wants to obtain as a return for the extra delay. Then, the network operator infers users' delay tolerance. In addition, users' offloading potential should also be considered when deciding the auction outcome. Based on the historical system parameters collected, such as users' data access and mobility patterns, their future value can be predicted by conducting network modeling, and then based on the information, users' offloading potential can be predicted.

The optimal auction outcome is to minimize the network operator's incentive cost subject to a given offloading target according to the bidders' delay tolerance and offloading potential. The auction contains two main steps: *allocation* and *pricing*. In the allocation step, the network operator decides which bidders are the winners and how long they need to wait. In the pricing step, the network operator decides how much to pay for each winner. Finally, the network operator returns the bidders with the auction outcome that includes the assigned delay and the value of coupon for each bidder. The winning bidders (e.g., user $u1$ and $u2$ shown in Figure. 1) obtain the coupon, and are assured to receive the data via cellular network when their promised delay is reached. For example, suppose p is the original data service charge, if user $u1$ obtains the coupon with value c in return for delay t, it only needs to pay p c for the data service. During the delay period, $u1$ may retrieve some data pieces from other intermittently available networks, for example, by contacting other peers that cache the data or moves into the wireless range of APs. Once delay t passes, the cellular network pushes the remaining data pieces to $u1$ to assure the promised delay. The losing bidders (e.g., user $u3$ shown in Figure. 1) immediately download data via cellular network at the original price.

3.2 User Delay Tolerance

With the users delay tolerance. To flexibly model users' delay tolerance, we introduce a *satisfaction function* S(f), which is a monotonically decreasing function of delay t, and represents the price that the user is willing to pay for the data service with the delay. The satisfaction function is deter- mined by the user himself, his requested data, and various environmental factors. We assume that each user has an upper bound of delay tolerance for each data. Once the delay reaches the bound, the user's satisfaction becomes zero, indicating that the user is not willing to pay for the data service. Fig. 2 shows an example of the satisfaction function $S(t)$ of a specific user for a specific data, where $tbound$ is the upper bound of the user's delay tolerance, p is the original charge for the data service, and the satisfaction curve represents the user's expected price for the data as the delay increases. For example, with delay $t1$ the user is only willing to pay $p1$ instead of p. p $p1$ is the satisfaction loss caused by delay $t1$.

3.3 Auctions

In economics, auction is a typical method to determine the value of a commodity that has an undetermined and variable price. It has been widely applied to many fields. Most auctions are *forward auction* that involves a single seller and multiple buyers, and the buyers send bids to compete for obtaining the commodities sold by the seller. In this paper, we use *reverse auction* [19] that involves a single buyer and multiple sellers, and the buyer decides its purchase based on the bids sent by the sellers. To begin with, we introduce some notations:

- *Bid* (b_i): It is submitted by bidder i to express i's valuation on the resource for sale, which is not necessarily true.
- *Private value* (x_i): It is the true valuation made by bidder i for the resources, i.e., the true price that i wants to obtain for selling the resource. This value is only known by i.
- *Market-clearing price*(p_i): It is the price actually paid by the buyer to bidder i. This price cannot be less than the bids submitted by i.
- *Utility* (u_i): It is the residual worth of the sold resource for bidder i, namely the difference between i's market-clearing price p_i and private value x_i.

- The bidders in the auction are assumed to be rational and risk neutral. A common requirement for auction design is the so-called *individual rationality*.
- Definition 1. *An auction is with individual rationality if all bidders are guaranteed to obtain nonnegative utility.*

The rational bidders decide their bidding strategy to maximize their utility. Let N denote the set of all bidders. The concept of *weakly dominant strategy* is defined as.

Definition 2. *$b_i = \beta_i$ is a weakly dominant strategy for user i if and only if: $u_i(\beta_i, \beta_{-i}) \geq u_i(\beta'_i, \beta_{-i}),\ \forall \beta'_i \neq \beta_i$.*

$$\beta_{-i} = \{\beta_1, \beta_2, \ldots, \beta_{i-1}, \beta_{i+1}, \ldots, \beta_{|\mathcal{N}|}\}$$

Here, denotes the set of strategies of all other bidders except for bidder *i*. We can see a weakly dominant strategy maximizes *i*'s utility regardless of the strategies chosen by all other bidders. If for every bidder, truthfully setting its bid to its private value is a weakly dominant strategy, the auction is *truthful* (strategy proof).

Definition 3. An auction is truthful if each bidder, say i, has a weakly dominant strategy, in which bi ¼ xi.

The truthfulness eliminates the expensive overhead for bidders to strategize against other bidders and prevents the market manipulation. Also, it assures the efficient allocation by encouraging bidders to reveal their true private values. Vickrey-Clarke-Groves (VCG) [20], [21], [22] is the most well-studied auction format, due to its truthful property. However, VCG only ensures truthful- ness when the optimal allocation can be found, and it usually cannot assure the truthfulness when applied to the approximation algorithms [23]. Unfortunately, the allocation problem in Win-Coupon is NP-hard. It is known that an allocation algorithm leads to be truthful if and only if it is monotone [24]. To maintain the truthfulness property, we design an approximation algorithm and make it monotone in a deterministic sense. Therefore, our incentive mechanism possesses three important properties:

1) Truthfulness, 2) individual rationality, and 3) low computational complexity.

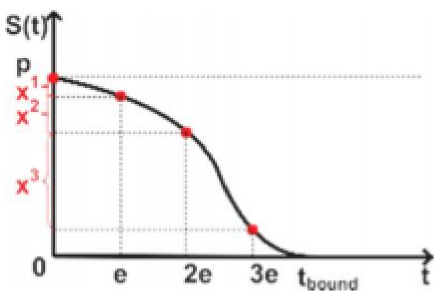

Figure 3: Private Value

determined by the network operator. Shorter time unit results in larger bids with more information, which increases the performance of the auction, but it also induces more communication overhead and higher computational complexity. To simplify the presentation, in the rest of the paper delay t is normalized by time unit e. As shown in Fig. 2, p S(f) is the satisfaction loss of the user due to delay t. Then, p S(p) represents the private value of the user to the delay, namely the user wants to obtain the coupon with value no less than p SðtÞ for delay t. Thus, the private value of the user to each additional time unit of delay is x ¼ fx1; x2; ... ; xlg, where xk (k 2 f1; ... ; lg), equals Sðk 1Þ SðkÞ. For example, as shown in Fig. 3, the user wants to obtain the coupon with value no less than x1 if it waits for one time unit, x1 þ x2 for two time units, and x1 þ x2 þ x3 for three time units. Generally, the user can set its bids with any value at will; however, we will prove that the auction in Win-Coupon is truthful, which guarantees that the users bid their private value that is bk=xk for all k.

4. Modules

1. Network Model.
2. Reverse auction.
3. Prediction of Offloading Potential: The DTN Case
4. Prediction of Offloading Potential: The WiFi Case

Module Description:

1. Network Model

In this module, focusing on offloading cellular traffic to other forms of networks, such as DTNs and WiFi hotspots and they generally focus on maximizing the amount of cellular traffic that can be offloaded.

2. Reverse Auction

In this module, we use a novel incentive framework, Win-Coupon, based on reverse auction, to motivate users to leverage their delay tolerance for cellular traffic offloading; Auction has been widely used in network design. Applying auction in the spectrum leasing is one of the most practical applications. Federal Communications Commission (FCC) has already auctioned the unused spectrum in the past decade, and there are a large amount of works on wireless spectrum auctions. Moreover, auction has also been applied for designing incentive mechanism to motivate selfish nodes to forward data for others. However, none of them has applied auction techniques to cellular traffic offloading.

3. Prediction of Offloading Potential: The DTN Case

Mobile users can share data via DTNs by contacting each other. In urban area with higher user density, mobile users have more chances to contact other users who have their requested data. Large data requests such as video clips tend to drain most of the cellular network resource, and such requests can also tolerate some delay. By offloading them via DTNs, the payload of cellular network can be significantly reduced.

4. Prediction of Offloading Potential: The WiFi Case

In this module, we model node mobility by a Semi Markov Process, in which arbitrary distributed sojourn times are allowed. To avoid state space explosion, each Markov state represents a geographical area with a fixed size. The process of a user moving from a geographical area to another is modeled as a transition of Markov processes between two states.

5. Conclusion

In this paper, we proposed a novel incentive framework for cellular traffic offloading. The basic idea is to motivate the mobile users with high delay tolerance and large offloading potential to offload their traffic to other intermittently connected networks such as DTN or WiFi hotspots. To capture the dynamic characteristics of users' delay tolerance, we design an incentive mechanism based on reverse auction. Our mechanism has been proved to guarantee truthfulness, individual rationality, and low computational complexity. Moreover, we design two accurate models to predict the offloading potential of the users for both DTN and WiFi cases. Extensive trace- driven simulations validate the efficiency and practical use of our incentive framework.

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