Mobile Data Off-loading through Ad Hoc Wi-Fi Communications using Bayesian Game Model

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I. Introduction

Mobile data traffic continues to grow explosively. This traffic growth is driven by the Internet access from mobile devices, particularly for video contents. There have been several solutions to the problem. The first one is increasing the frequency spectrum or upgrading to higher-bit rate radio access networks. However, these approaches are often limited due to the scarce frequency spectrum and high deployment cost. Another solution is off-loading 3G traffic from (macrocell) base stations to other kinds of networks/access links, such as DTN, Wi-Fi, femtocell. In particular, we are interested in Wi-Fi off-loading due to Wi-Fi's wide availability. The Wi-Fi off-loading can be implemented in two different ways. One way is to rely on Wi-Fi access points (APs) [1]–[3]. In most cases, however, Wi-Fi APs provide intermittent network connectivity due to user mobility. The other option is to let mobile devices directly communicate with each other in an ad hoc manner. In [3], Bao et al. proposed DataSpotting in which users in a data spot can exchange data with each other in an ad hoc manner. However, the off-loading is limited to the data spot areas and the solution requires continuous tracking of fine-grained users' locations using GPS, which is feasible only outdoors.

In this work, we take the ad hoc off-loading approach using direct Wi-Fi communications between mobile users. We consider users on the move, and thus Wi-Fi APs cannot be of practical help. In such cases, we model the off-loading problem as a Bayesian game, where mobile users with the content and Wi-Fi capability can participate in the game, and the base station will select the user who can contribute (i.e., transmit the data) with the least cost. We assume that, in general, there are multiple users who can transfer the content, and we would like to promote competition among the users for efficient system operations. We evaluate our solution using real life traces from a public subway system in Seoul, Korea, and download real user statistics in a commercial application market for smart devices.

II. System Model

As traffic off-loading can happen between users in proximity, they are likely to be associated with the same base station (BS). We assume that the cellular network is the only communication infrastructure available in the area of interest; that is, all nodes can be connected to the Internet only via the BS. Vehicles in public transportation systems such as subway trains or buses could provide such a scenario. A requester is interested in downloading a particular file from a content provider (CP) in the Internet (e.g., an application from an App Store, or a video clip from YouTube). We assume that the requested file is popular and has already been downloaded by other users in the network. Each user will spend a different cost (e.g. depending on the energy amount to be consumed) to transmit the content. Therefore, we should (i) select the user who will spend the least cost as the contributor, and (ii) determine the right amount of incentive to the contributor to benefit both the cellular network (who saves the link capacity) and the participators. To address both issues, we take an auction based approach, whose overall procedure is described as follows (also see Fig. 1):

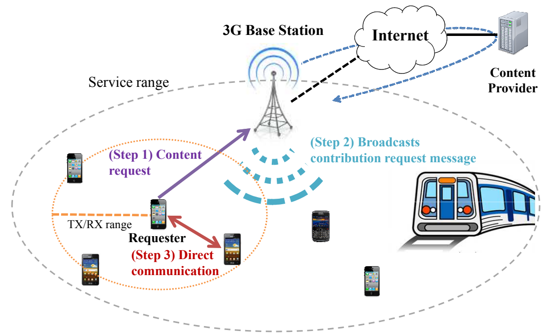
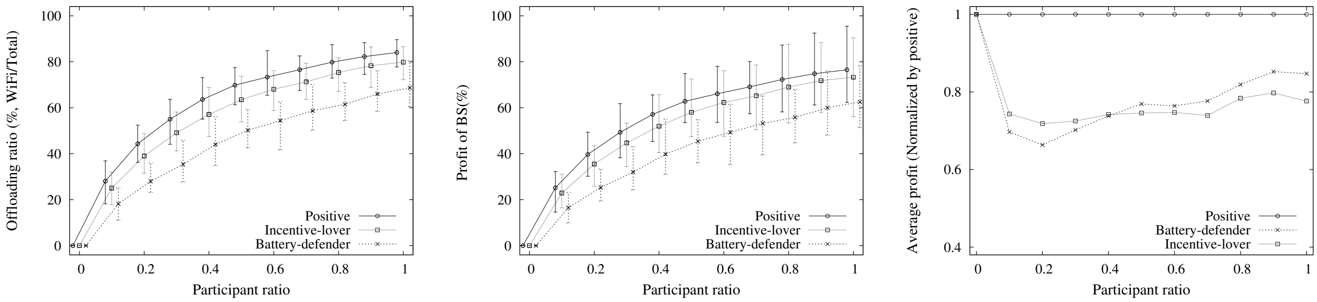


Fig. 1. Procedure of traffic off-loading.

- The requester sends a content request to the BS (Step 1).
- The BS checks the possibility of traffic off-loading.
- The BS invites candidate users (Step 2).
- Candidate users check Wi-Fi connectivity with the requester.
- Each eligible candidate sends the bidding information to the BS.
- The BS selects the contributor, who will transmit the content (Step 3).
- After the delivery, the contributor obtains the incentive.

We formulate the problem as a K-player Bayesian game, where each player with the content in proximity is a candidate contributor. The contribution value (or cost) of each of K players is assumed to be independent and to follow a uniform distribution with a range $[\underline{v}, \overline{v}]$, where the cost of each player is determined by her remaining battery and an estimated data rate to the requester. Then, we can consider a second-price sealed-bid auction (also known as the Vickrey auction [4]) modeled as



(a) Wi-Fi off-loading ratio. (b) Total profit of the BS. (c) Average profit of the contributor.

Fig. 2. We plot how much of the traffic can be off-loaded and profit of the network as the participant ratio increases. Each user already has one content on average before getting on the subway train. And the content request rate $\lambda = 0.2$. The profit of the BS and the Wi-Fi off-loading ratio show a similar pattern.

a Bayesian game. Our game model is a *second-lowest-price sealed-bid auction* based on the traditional Vickrey auction. The winner is who has offered the lowest price, and the incentive given by the BS is the second lowest price among the bids. The winner obtains the profit by being paid at a price higher than or equal to that of the resource (e.g. energy) consumed to deliver the content.

III. Performance Evaluation

To evaluate the performance of our approach, we consider real life traces of a public transportation system that are obtained from the Seoul (subway) Metro in Seoul, South Korea. We use the hourly average number of passengers during the rush-hour time (from 6 AM to 9 AM) on a weekday of Nov. 2011 [5]. We also generate traffic from real trace data of an App market for smart phones. We use the cumulative downloading counts from T Store, which is the official App market of SK Telecom [6].

Fig. 2 plots the performance of our solution for different user types. For *battery-defenders*, each contributor participates in the game with a probability proportional to her residual battery, which results in the lowest off-loading ratio in Fig. 2(a). On the other hand, *incentive-lovers* participate in the game with a probability proportional to both residual battery and expected data rate. Thus the system achieves a higher off-loading ratio. Similarly, *positive type* users participate in the game whenever the battery is sufficient for her to deliver the content, leading to the highest off-loading ratio. Fig. 2(b) shows the average profit of the BS for each user type. We model the cost of the BS as the resource consumed to deliver the content. As ad hoc Wi-Fi connectivity normally offers the higher bit rate (than 3G links), the profit of the BS is given by the BS's cost minus the incentive to the contributor. In Fig. 2(c), we normalize the average profit for each user type with respect to *positive* type users. Although the *incentive-lovers* participate in the system more actively than *battery-defenders*, their average profit is lower than that of *battery-defenders* when the participant ratio is more than 0.4. Recall that in our auction model, the incentive for the contributor is determined by a difference between the first and the second lowest prices among the bids. Then, as the number of participants in the game increases, the profit is likely to decrease. Since the system has a larger number of candidates for *incentive-lovers*, the average cost of the second lowest bid is likely to be lower (i.e., less profit for the contributor) than for *battery-defenders*. Along the same line, *positive* type users have the least profit for each content delivery (i.e., the difference between the first and second bids is the smallest). However, the total profit of *positive* type users is greater than those of *incentive-lovers* and *battery-defenders* since the total amount of off-loaded traffic is the largest for *positive* type users.

IV. Conclusion

We propose how to promote traffic off-loading directly among users to mitigate mobile data explosion problem in cellular networks. We present a game theoretic framework, where mobile users with the content and Wi-Fi capability can participate in the game. We model the off-loading problem as a Bayesian game, in which a base station selects the user who bids the least cost for the content transmission using ad hoc Wi-Fi communications, and rewards the contributor. We develop a solution using the second-price sealed-bid auction, which offers gains to the contributing users and the base station as well. We evaluate our solution through trace-driven simulations for a public subway system. We demonstrate that our solution effectively off-loads the traffic under mild assumptions on initial content caching.

References

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