Ad Hoc Networks 25 (2015) 370–382

Contents lists available at ScienceDirect

Ad Hoc Networks

journal homepage: www.elsevier.com/locate/adhoc

Cost-Effective Multi-Mode Offloading with peer-assisted communications

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ARTICLE INFO

Article history:
Received 9 March 2014
Received in revised form 21 July 2014
Accepted 28 July 2014
Available online 7 August 2014

Keywords:
Mobile data offloading
WiFi
Opportunistic networks
Delay tolerant networks
Mobility
Peer-assisted communications

ABSTRACT

Data offloading through WiFi networks has been identified as a promising solution to cellular network congestion caused by the ongoing explosive growth in mobile data traffic. In this paper, we propose Cost-Effective Multi-Mode Offloading (CEMMO) that enhances offloading with multi-hop peer-assisted communications regardless of content and popularity. CEMMO enables three modes of communication: cellular delivery, delay-tolerant offloading, and peer-assisted offloading. Exploiting user knowledge on mobility and WiFi connectivity, CEMMO assists the cellular operator in selecting the best out of its three modes in order to reduce the overall cost in terms of financial settlement, energy consumption, and user satisfaction. Our simulations with a realistic mobility and connectivity prediction model based on a Markov process show that CEMMO offloads up to 59% of the mobile data traffic and reduces transfer cost per MB up to 16% over delay-tolerant offloading. This paper also discusses practical issues in CEMMO adoption.

1. Introduction

Due to the recent proliferation of smartphones and tablets, mobile data traffic has been explosively growing and pushing the capacity limits of cellular networks In particular, smartphones equipped with high-resolution cameras are sold globally at astounding rates, and content generated by mobile users significantly rises fueled by popular social networking and cloud storage applications such as Facebook, and Dropbox. With the global mobile data traffic forecasted to increase 13 times within the next 5 years [1], cellular network providers need to find cost-effective ways to handle the growing traffic demands with expected Quality of Service (QoS) levels. Infrastructure upgrade is the intuitive solution to deal with the congestion problem; however, it is insufficient as a financially sustainable solution. Offloading mobile data through WiFi networks is the most promising solution to tackle the congestion problem because the cost of WiFi access points (APs) required for the offloading is relatively low, WiFi technology uses unlicensed bands and offloading can satisfactorily serve delay-tolerant types of data traffic. So far, research efforts have been focused on either on-the-spot offloading (OTSO) [2], where data is offloaded only over an immediately available WiFi connection, or delay-tolerant offloading (DTO) [3], where the transmission is delayed for some time in case the user encounters an offloading opportunity later. Both offloading types offer significant benefits, mainly in environments with stable WiFi coverage.

In this paper, we target dense urban environments and propose Cost-Effective Multi-Mode Offloading (CEMMO) that enhances OTSO and DTO with a multi-hop peer-assisted offloading mode (PAO), where the offloaded traffic

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http://dx.doi.org/10.1016/j.adhoc.2014.07.028
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is delivered through intermediate mobile devices. To the best of our knowledge, PAO is the first peer-assisted offloading solution that is implemented not only for offloading data from the uplink, but also independent of its content or popularity. Given the delay-tolerant nature of a significant portion of the cellular network traffic, an offloading solution that enhances the existing delay-tolerant functionality with peer-assisted offloading (PAO) will leverage the overall offloading capability and, therefore, increase the total amount of data that is offloaded from cellular networks. For PAO, we develop a new data-forwarding scheme that uses limited flooding. By applying a mobility and connectivity prediction model based on a Markov process, CEMMO allows the cellular operator to select the most effective mode for communicating mobile data with different delay constraints based on the estimated costs of delivery through each of the three modes, i.e. cellular delivery, DTO or PAO. OTSO is always exploited when available. The cost reduction leads to lower prices that attract new users, increasing the revenue of the operator. In scenarios with extended WiFi coverage, CEMMO offloads up to 59% of the mobile data traffic and reduces transfer cost per MB up to 16% over DTO. With an energy optimization, CEMMO achieves up to 31% improvement on energy consumption over OTSO.

The novelty of CEMMO lies in the introduction of the first peer-assisted method for offloading traffic from the uplink, regardless of the offloaded content and its popularity, and the selection of the most cost-efficient alternative for data transmission, as defined by each operator. The contributions of the paper can be summarized as follows:

i. We design and evaluate CEMMO, a cost-effective scheme for mobile data offloading that integrates multiple modes of operation: cellular delivery, DTO, and PAO.
ii. We propose a mobility and connectivity prediction model based on a Markov process and we develop a forwarding scheme for PAO with low storage and energy overhead.
iii. CEMMO allows the cellular operators to automatically select the transfer policy (i.e. cellular delivery, DTO or PAO) that provides more gains. The overall cost, as defined by each operator, can include transfer and energy costs, incentives to motivate user participation, etc.
iv. CEMMO provides cellular operators with knowledge on the amount of data offloaded by each user. Such knowledge is currently unavailable and will help cellular operators design the expansion of their network accordingly.

The rest of the paper is organized as follows. In Section 2, we describe the proposed mobility and connectivity prediction model. Section 3 details DTO and the proposed PAO transfer policy. CEMMO mechanism is presented in Section 4, along with a sample scenario. Section 5 evaluates the performance of CEMMO through simulations. In Sections 6 and 7, we discuss several practical issues on the adoption of CEMMO and related work, respectively. Finally, we conclude the paper in Section 8.

2. Mobility and connectivity prediction model

According to our mobility and connectivity prediction model, a large area is divided into smaller *regions* with unique identifiers, and a time period (e.g. a day) is split into smaller *time intervals* (e.g. 10-min intervals). The region size and the time interval duration affect the spatio-temporal accuracy of the prediction model. Defining small regions and time intervals improves the accuracy of the model at the expense of increased computational complexity. Users store their own mobility information for each time interval. For example, if a one-hour time interval is selected, users store their mobility information for 24 distinct time intervals. In particular, users keep records of their location, their transitions from one region to another and the frequency at which they move between regions. For each user, we define:

- $N(X,t)$ as the number of visits in region X during time interval t (i.e. starts at time t),
- $N(A \to X,t)$ as the number of transitions from A to a neighboring region X during t,
- t_{duration} as the duration of each time interval and
- $t_{\text{next}} = t_{\text{duration}} + t$ as the start time of the next time interval.

The probability of a user located in region A to move to region X directly within t is:

$$P(X|A,t) = N(A \to X,t)/N(A,t) \tag{1}$$

The probability that the user stays in region X until the end of time interval t is:

$$P_{\text{stay}}(X,t_{\text{next}}) = P(X|X,t) = N(X \to X,t)/N(X,t) \tag{2}$$

User mobility during any time interval t is modeled as a Markov process. The next region that will be visited by a user during a time interval is assumed to solely depend on the previous one. Thus, if $NR(A)$ is the set of neighboring regions of A, the probability of a user to move from current region A to region X through any neighboring region $i \in NR(A)$ during t is:

$$P(X|A,t) = \sum_{\forall i \in NR(A)} P(i|A,t) \times P(X|i,t) \tag{3}$$

Starting from the current region (L_{current}) and time interval (t_{current}) and based on Eqs. (1) and (3), we estimate the probabilities of a user to visit any other region during any time interval $t \leqslant t_{\text{end}}$, where t_{end} is the time interval until which the user is willing to wait for the data to be offloaded through a WiFi AP. We use Eq. (2) to compute the probabilities of a user to be located in a region at the end of each time interval. We recursively use these regions as potential starting points of user movement during the next time interval and repeat this process to predict user mobility during each time interval, as described in Algorithm 1.

Each user also keeps statistics regarding WiFi connectivity within each region, since a region may only have partial WiFi connectivity. $NW(X)$ denotes the number of times WiFi connectivity was available in region X. With the selection of small time intervals, we do not need to measure the