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Fast track article

Push-and-track: Saving infrastructure bandwidth through opportunistic forwarding[☆]

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ABSTRACT

Major wireless operators are nowadays facing network capacity issues in striving to meet the growing demands of mobile users. At the same time, 3G-enabled devices increasingly benefit from ad hoc radio connectivity (e.g., WiFi). In this context of hybrid connectivity, we propose Push-and-track, a content dissemination framework that harnesses ad hoc communication opportunities to minimize the load on the wireless infrastructure while guaranteeing tight delivery delays. It achieves this through a control loop that collects user-sent acknowledgements to determine if new copies need to be re-injected into the network through the 3G interface. Push-and-Track is flexible and can be applied to a variety of scenarios, including periodic message flooding and floating data. For the former, this paper examines multiple strategies to determine *how many* copies of the content should be injected, *when*, and to *whom*; for the latter, it examines the achievable offload ratio depending on the freshness constraints. The short delay-tolerance of common content, such as news or road traffic updates, make them suitable for such a system. Use cases with a long delay-tolerance, such as software updates, are an even better fit. Based on a realistic large-scale vehicular dataset from the city of Bologna composed of more than 10,000 vehicles, we demonstrate that Push-and-Track consistently meets its delivery objectives while reducing the use of the 3G network by about 90%.

1. Introduction

In December 2009, mobile data traffic surpassed voice on a global basis, and is expected to continue to double annually for the next five years [1,2]. Every day, thousands of mobile devices – phones, tablets, cars, etc. – use the wireless infrastructure to retrieve content from Internet-based sources, creating immense demand on the limited spectrum of infrastructure networks, and therefore leading to deteriorating wireless quality for all subscribers as operators struggle to keep up [3]. In order to cool this surging demand, several US and European network operators have either announced or are considering the end of their unlimited 3G data plans [4,5].

There are limits however to how much can be achieved by increasing infrastructure capacity or designing better client incentives. Solving the problem of excessive load on infrastructure networks will require paradigm-altering approaches.

☆ This article is an expanded version of work presented at the 12th IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM 2011) Whitbeck et al. (2011) [43]. This paper provides greater details and presents all-new results based on different scenarios (e.g., *floating data*), and different assumptions (e.g., vehicle participation ratio).

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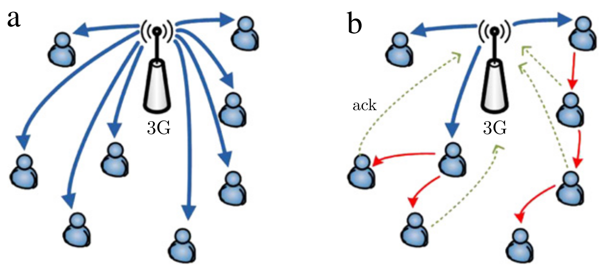

Fig. 1. Combining multiple strategies for full data dissemination. Left figure (a) shows the infrastructure-only mode, where the 3G interface is used to send copies of the data to all nodes. In (b), we show the Push-and-Track approach, where opportunistic ad hoc communication is preferred whenever possible. Although acknowledgments are required to keep the loop closed, the global infrastructure load will be significantly reduced.

In particular, when many users are interested in the same content, how can one leverage the multiple ad hoc networking interfaces (e.g., WiFi or Bluetooth) ubiquitous on today's mobile devices in order to assist the infrastructure in disseminating the content? Subscribers may either form a significant subset of all users, comprising for example all those interested in the digital edition of a particular newspaper, or may include all users in a given area, for example vehicles receiving periodic traffic updates in a city.

In this paper, we address the following question: *how can one relieve the wireless infrastructure using opportunistic networks while guaranteeing* 100% *delivery ratio under tight delay constraints*? In particular, we seek to *minimize* the infrastructure load while massively distributing content within a short time to a large number of subscribers.

We propose *Push-and-Track*, a framework that harnesses both wide-area radios (e.g., 3G or WiMax) and local-area radios (e.g., Bluetooth or WiFi) in order to achieve guaranteed delivery in an opportunistic network while relieving the infrastructure. Our approach is detailed in Fig. 1. A subset of users will receive the content from the infrastructure and start propagating it epidemically; upon receiving the content, nodes send acknowledgments back to the source thus allowing it to keep track of the delivered content and assess the opportunity of *re-injecting* copies. Since acknowledgments are assumed to be much smaller than the actual content, the load on the infrastructure would be significantly lightened. The main feature of Push-and-Track is the closed control loop that supervises the re-injection of copies of the content via the infrastructure whenever it estimates that the ad hoc mode alone will fail to achieve full dissemination within some target delay. To the best of our knowledge, our work is the first to explore this idea.

Unlike accessing an operator's wireless infrastructure, opportunistic forwarding, using short-range ad hoc radio, is essentially free and costs little more than expended battery life. This may not even be a concern in certain circumstances (e.g., vehicular). Unfortunately, it does not provide any guarantees as it depends entirely on the uncontrolled mobility of users.

In this paper, we explore strategies for two scenarios: *periodic flooding*, where content must be periodically distributed to all subscribers within a maximum delay, and *floating data*, where existing content must reach new nodes within a certain delay after they subscribe. Although the Push-and-Track framework may accommodate many different kinds of mobile nodes (e.g., smartphones or vehicles), this paper focuses on a vehicular scenario. All the results in this paper are based on a highly realistic large-scale vehicular simulation derived from fine-grained traffic measurements in the city of Bologna. This vehicular dataset is composed of more than 10,000 vehicles covering 20.6 km^2 and 191 km of roads. As not all nodes need necessarily participate, the above scenarios are systematically run for different percentages of participating vehicles.

In particular, in the *periodic flooding* scenario, we evaluate several re-injection strategies. Push-and-Track splits the problem into *how many* copies of the content should be injected into the network, *when*, and to *whom*. To decide the number of copies to be injected, we define different objective functions of different aggressiveness levels (slow start or fast start). If the dissemination evolution is under the objective, more copies need to be injected through the infrastructure; otherwise, the system remains in ad hoc mode only. For deciding to whom to inject copies, we consider randomized, sojourn time, location-based, and connectivity-based strategies.

We thoroughly evaluate all combinations of the proposed strategies by comparing them with both pure infrastructure and pure ad hoc approaches, as well as an oracle-based solution.

Our results reveal the following findings:

- Even under tight delay constraints, Push-and-Track reduces the infrastructure load by about 90%, when distributing periodic content to all vehicles in the city of Bologna during peak hour traffic while still achieving 100% on time delivery ratio.
- Choosing random recipients for pushing content is a straightforward and efficient strategy.
- The feedback loop is the key feature enabling Push-and-Track to adapt to and recover from sudden network splits or varying participation rates.

In the next section, we describe the Push-and-Track framework in more detail. In Section 3 we detail the different scenarios and re-injection strategies tested in this paper. Our vehicular dataset is described in Section 4, and our simulation