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Effective opportunistic dissemination of spatio-temporal contents in mobile environments

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Dissemination of spatio-temporally valid content from content providers to consumers is critical in certain application contexts as data items could lose their validity across time and space. Content sharing in challenged opportunistic environments remains a research challenge as existing solutions fail to exploit dissemination patterns across spatio-temporal limits. In this paper, we propose spatio-temporal reachability graphs to depict reachability of time- and space-sensitive content in opportunistic mobile environments. Furthermore, we develop an analytical framework to estimate content distribution in such environments and validate its feasibility over long-term datasets. We perform extensive trace-driven simulation studies to determine content dissemination properties of environments with known mobility patterns. The analytical framework estimates dissemination ratio, optimizes parameter setting, and tests transmission capacities of opportunistic environments. Proposed scheme is useful to content providers as well as receivers.

1. Introduction

The proliferation of mobile and wearable devices has created opportunities for disseminating information/contents via peer-to-peer communication when devices encounter each other. This type of data transmission relying on a series of spatiotemporally distributed contacts is called opportunistic networking [1]. Opportunistic communication is a low-cost, high-bitrate alternative method for disseminating content on a massive scale; for example, crowd-sensing of air quality data (measuring multiple polluting gases) every minute by sensors mounted on nearly 13 000 taxis in the city of New York. Aggregation of data from large numbers of sensors can lead to air quality assessment in a given area. In such crowd sensing applications, a single measurement can be lost or delayed without introducing deviation or distorting the outcome. Hence, it is preferred to gather this type of data cost-effectively using opportunistic communication instead of the expensive cellular networks. Data is typically shared among each other by opportunistic forwarding and uploaded when WiFi is available. Furthermore, the rapid growth of Internet-of-Things (IoT) has created an opportunity for extracting more variety of information about a place, an object, and a person. But, data produced by IoT devices (e.g., augmenting taxis with air quality sensors) will significantly increase demand for bandwidth which makes existing infrastructure networks hard to cope. Data may also have validity limits across time and space domains. A more effective design of opportunistic content sharing is needed to address the ever-increasing demand for bandwidth.

We introduce the notions of *time-to-live* (TTL) and *space-to-live* (STL) to opportunistic data/content dissemination in mobile environments so that data is forwarded only within a predefined time and space boundary. When considering TTL and STL in content dissemination, it is important to determine the appropriate values to maximize reachability and minimize

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overheads due to data caching and transmission. However, it is often difficult to identify these boundaries appropriately if the mobility pattern of users in a given area is unknown. Prior work investigates opportunistic forwarding in simulation using synthesized mobility models (e.g., random walk) [2,3]. For example, Han and Srinivasan [3] studied influential mobile users in a social network context for content distribution, and evaluated their models through simulation using random walk. The results of this type of research are meaningful in general cases when we assume user mobility. Hence their opportunistic contacts conform to a normal distribution. While the random walk mobility model has been used in many opportunistic networking studies [2,4–6], the results often represent system performance in most general cases. However, despite the diversity in individual mobilities, humans tend to follow simple mobility patterns with a high degree of temporal and spatial regularity [7,8]. By capturing and modeling the regularity of human mobility, we can leverage this insight to significantly improve data forwarding algorithms and predict data dissemination in more realistic opportunistic networking settings. In the context of opportunistic content sharing, the state-of-the-art has offered some insights into opportunistic content dissemination [9], spatiotemporal information dissemination [10], and temporal reachability [11]. However, none of the existing approaches quantify the influence of changes of spatiotemporal property on reachability in different application scenarios and provide a way to adapt parameter settings to the different application contexts. Investigations on the impact of spatiotemporal property, file size, bandwidth, and other parameters on dissemination ratio and dissemination capacity are needed. Without a priori knowledge about dissemination capability of opportunistic environments, there would be no motivation for producers and service providers of opportunistic content sharing.

In this paper, we develop spatiotemporal reachability graphs (STRG) to model spatiotemporal dissemination in mobile environments where content is distributed using opportunistic forwarding. STRG captures available source–destination node pairs that satisfy end-to-end delay and geographic distance requirements. Based on STRG, we develop an analytical framework to make following types of estimations in a given scenario: expected success in content dissemination and expected transmission capacity. In particular, the framework comprises three functions: (i) estimate dissemination ratio, (ii) test transmission capacities, and (iii) optimize parameter setting. Extensive trace-driven simulation studies are performed on two large taxicab traces collected in urban areas for a period of one month. Distinguishing weekdays/weekends and time windows, our analysis reveals spatiotemporal patterns of contact opportunities. There is a high correlation between trajectories and contacts. Leveraging the patterns, the framework aims to predict content distribution parameters based on only historical mobility traces. To demonstrate the robustness of our framework, we also test the predictability by adding different degrees of variations in mobility traces. Our simulation results show the effectiveness, that is, the framework achieves more than 75% accuracy and reduces prediction error by nearly 50%, compared to a random method. Also, the analytical framework addresses above questions for an any opportunistic environment.

The paper makes three main contributions:

- *Spatiotemporal Reachability Graphs (STRG)*. A graph model has been developed to capture spatiotemporal dissemination in opportunistic environments;
- *Analytical framework for content dissemination*. Analytic functions are developed based on STRG to estimate content distribution parameters; and
- *Extensive trace-based simulations*. Applicability of the framework is demonstrated with long-term empirical datasets collected in urban areas.

The novelty of this paper lies in a generic analytical framework that can provide guidance to application developers, service providers and users in opportunistic environments. With the use of our methodology, it is possible to achieve acceptable levels of prediction of opportunistic content dissemination in such uncertain environments. The framework would be useful for opportunistic content sharing in any mobility scenario and also enable effective dissemination with fine-tuned parameter settings.

The remainder of this paper is structured as follows. First, Section 2 presents the state-of-the-art approaches to opportunistic content sharing. Section 3 discusses network models, including the introduction of the spatiotemporal reachability graph which is an extension of the time-varying graph. Section 4 introduces an analytical framework which discusses how user mobility data can be collected and fed into systems that compute the relevant estimation on spatiotemporal property and reachability in the environment. Section 5 elaborates the predicting scheme for content dissemination. Section 6 presents results trace-based simulations and discusses the effectiveness of the proposed framework. The final section concludes the paper.

2. Related work

This section presents the state-of-the-art regarding content sharing and dissemination analysis in opportunistic environments.

For opportunistic content sharing, Hyytiä et al. [9] have proposed the concept of floating content to improve performance of geo-caching within a specific region, where nodes store and distribute local spatiotemporal floating information. Information dissemination is geographically limited within the area of interest, whereas nodes are free to delete the information outside the area. They determined the length of time information remains available in the area of interest in such synthetic mobility models as Manhattan road network model and random waypoint model. The authors showed that