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Coding-based cooperative caching in on-demand data broadcast environments

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ABSTRACT

Data broadcasting has been commonly deployed in many emerging mobile applications such as intelligent transportation systems and location-based services, because it is a scalable approach to disseminating information from a mobile support station (MSS) to a large population of mobile hosts (MHs). To provide timely data access and better data availability, MHs can store data items broadcast by the MSS in their local caches and share cached data items cooperatively among neighboring peers via peer-to-peer (P2P) communication. However, if MHs are not neighbors, they cannot cooperate even if they have each other's requested data items in their own caches. Network coding is a technique, by which multiple MHs can decode out different requested data items from an encoded packet broadcast by the MSS in one broadcast time unit. In this work, we propose a network coding based solution to enable MHs which are not neighbors to cooperate indirectly. We formulate the Maximum Channel Efficiency Encoding (MCEE) problem by introducing network coding and cooperative caching techniques in on-demand data broadcast environments. We prove that MCEE is NP-hard by constructing a polynomial-time reduction from the Minimum Clique Cover (MCC) problem. Further, we propose two schemes (NCM and NCB) for on-demand data broadcasting using network coding. In each scheme, we propose two algorithms running at the MSS and MHs for making encoding decisions and decoding requested data items, respectively. We build the simulation model for performance evaluation and the simulation results demonstrate that the proposed schemes not only increase the bandwidth efficiency of the limited downlink communication channel, but also enhance the system performance by reducing the data access latency.

1. Introduction

Data broadcast is an effective way to disseminate data items in an infrastructure network due to its scalability and flexibility. A typical infrastructure network consists of multiple mobile hosts (MHs) and a mobile support station (MSS). The MSS disseminates information to MHs within its service area. MHs could be mobile devices such as laptops, mobile phones or other devices equipped with wireless communication modules. Information is transmitted from the MSS to MHs

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via the downlink communication channel. Pull-based broadcast, which is commonly known as on-demand broadcast, is one of the most promising data broadcast techniques for disseminating information to a large population of MHs [7,17–19,22]. In on-demand broadcast environments, MHs submit requests to the MSS via the uplink communication channel. Outstanding requests are pended in the request queue at the MSS. In each broadcast time unit, the MSS selects the most rewarding data item to broadcast via the downlink communication channel according to a certain scheduling policy, such as FCFS (First Come First Served) [11]. Requesting MHs tune in to the downlink communication channel and wait for their requested data items. However, in such an on-demand broadcast environment, bandwidth efficiency of the downlink communication channel cannot be fully exploited because only MHs requesting the same data item have the chance to be served in one broadcast time unit.

Network coding [3] is a technique in which intermediate nodes can combine and forward data packets from multiple links. It has attracted researchers' attention due to its potential to enhance the system performance for both mobile ad hoc networks [23–25,31,34] and infrastructure networks [2,6,20,33]. In on-demand broadcast environments, with network coding, it is possible that multiple MHs requesting different data items can be satisfied simultaneously by utilizing their cached data items. Thus, network coding has the potential to further improve the bandwidth efficiency of the downlink communication channel.

With recent development of peer-to-peer (P2P) wireless communication technologies and the increasing capacity of MHs' storage, a new information sharing paradigm appears. MHs can not only retrieve information from the MSS, but also share information among neighboring peers. The neighboring peers of an MH refer to those MHs which reside in its transmission range. This kind of information sharing among peers is called cooperative caching [10]. In our recent studies [8–10], COCA (cooperative caching) and GroCoca (group-based cooperative caching) have been proposed for data dissemination in on-demand broadcast environments. In particular, COCA is a cooperative caching framework, in which P2P communication technology is used for information sharing among MHs. GroCoca extends COCA based on the concept of a tightly-coupled group (TCG), which is a group of MHs that are geographically and operationally close to each other [10]. GroCoca outperforms COCA in terms of reducing data access latency, which is the duration from the moment when an MH submits a request to the moment when the requested data item is received. However, in GroCoca, it is difficult for MHs in disjoint TCGs to collaborate and share their cached data items. Inspired from the advantage of network coding in terms of exploiting cached data items of MHs, this work is dedicated to exploring cooperative caching of MHs which are residing out of each other's transmission range, so as to further strengthen the information sharing paradigm and improve the overall system performance.

The main contributions of this paper are outlined as follows.

- We exploit the synergy between network coding, on-demand broadcast and cooperative caching in mobile data dissemination environments. First, network coding strengthens the information sharing paradigm of cooperative caching by enabling MHs residing in different groups to cooperate. In case they have each other's requested data items in their own caches, the MSS can encode multiple requested data items in a single packet for broadcasting and the MHs can retrieve their own requested data items simultaneously in one broadcast time unit. Otherwise, the MSS has to broadcast the requested data items one by one in multiple broadcast time units. Second, cooperative caching facilitates the operation of network coding in on-demand broadcasting. Consider a request submitted by an MH to the MSS. MHs which are in the same group of this requesting MH cannot have the requested data item in their own caches. Otherwise, they can simply share the data item with the requesting MH. Therefore, the MSS does not need to consider the cache contents of MHs which are in the same group of the requesting MH in making encoding decisions.
- We introduce a novel system model by incorporating network coding into the cooperative caching framework. In particular, we outline the communication protocol of the system. Furthermore, we formulate the Maximum Channel Efficiency Encoding (MCEE) problem by introducing network coding and cooperative caching techniques in on-demand data broadcast environments. We prove that MCEE is NP-hard by constructing a polynomial-time reduction from the Minimum Clique Cover (MCC) problem.
- We propose two schemes (NCM and NCB). NCM adopts network coding only to the MSS, while NCB adopts network coding in both the MSS and MHs. Specifically, two heuristic algorithms are proposed in each scheme. The algorithm running at the MSS makes the encoding decisions to satisfy multiple requests for different data items in one broadcast time unit. To boost the effectiveness of network coding, data items to be encoded are not restricted to the data items cached by the requesting MH but also include those cached by its peers. Another algorithm running at MHs enables the requesting MHs residing in different groups to retrieve their requested data items by decoding the data packets broadcast by the MSS. The decoding can be done not only using the data items cached by the requesting MHs but also their peers. So, these schemes seek to further improve information sharing by exploiting network coding at both the MSS and MHs.
- We build the simulation model for performance evaluation. The simulation results demonstrate that incorporating network coding into cooperative caching makes the data scheduling more flexible. The proposed schemes further increase the bandwidth efficiency of downlink communication channel, and significantly improve the system performance in terms of reducing data access latency.

The rest of this paper is organized as follows. Section 2 reviews the related work. Section 3 describes the system architecture. In Section 4, we formulate the MCEE problem and prove that it is NP-hard. Two new coding-based cooperative caching