Computer Networks 105 (2016) 194–206

Contents lists available at ScienceDirect

Computer Networks

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

Distributed Greedy Coding-aware Deterministic Routing for multi-flow in wireless networks

Jing Chen[a], Kun He[a,*], Quan Yuan[b], Ruiying Du[a], Lina Wang[a], Jie Wu[c]

[a] State Key Laboratory of Software Engineering, Computer School, Wuhan University, Wuhan, China
[b] Department of Math and Computer Science, University of Texas-Permian Basin, Odessa, TX, USA
[c] Department of Computer and Information Sciences, Temple University, Philadelphia, PA, USA

ARTICLE INFO

Article history:
Received 4 January 2016
Revised 10 May 2016
Accepted 31 May 2016
Available online 11 June 2016

Keywords:
Network coding
Multi-flow
Reliability
Routing

ABSTRACT

As one of the compelling performance improvement techniques, network coding is widely used for designing routing protocols in wireless networks. Specifically, in deterministic routing, coding benefit is viewed as an important factor for distributed route selection. However, most of the existing deterministic routing protocols only detect two-flow coding opportunities in the route discovering phase, but the multi-flow scenario is not researched sufficiently. It is obvious that multi-flow coding can improve the coding benefit in complex network environments. In this paper, we analyze the challenges of the multi-flow coding, and propose a Distributed Greedy Coding-aware Deterministic Routing (DGCDR) for multi-flow in wireless networks. To increase the potential coding opportunities, a decoding policy and a coding condition are defined in the multi-flow environment, which exploit the coding benefit of multiple intersecting flows in a greedy way. Meanwhile, considering the interference introduced by multi-flow coding, we design an extra confirmation process in our protocol. Furthermore, to enhance the flexibility of packet delivery and coding, we propose a greedy aggregation mechanism and a greedy coding algorithm. From the simulation results, we can find that DGCDR can induce a competitive performance in terms of increased coding benefit, decreased delay, larger throughput, and smaller queue size.

1. Introduction

Wireless Network Coding (NC) [1–4], which exploits the broadcast characteristic of the wireless medium to augment the capacity of the network, highlights a novel direction in routing to improve network throughput [5–8]. Unlike the traditional forwarding mode, intermediate nodes can initially encode packets from different flows into a set of fewer packets, and then forward those packets which would be further decoded at destinations, this is known as *inter-flow* coding [9]. To optimize the transmission efficiency, researchers introduce such a technique into the routing protocol and it is called *coding-aware routing* [10–13].

The main issue addressed in the coding-aware routing schemes is how to obtain more coding opportunities in routing, leading to higher transmission efficiency [14–16]. Relevant existing work can be classified into two main categories: *opportunistic routing*, and *deterministic routing*. In the former category, each node rebroadcasts packets to its neighbors with a given forwarding probability, where network coding is employed to save transmissions. Khreishah et al. [17] proposed a distributed opportunistic routing based on network coding, by formulating the problem with arbitrary channel conditions as a convex optimization problem, and presenting an optimal back-pressure algorithm on that. CodePipe [18] is a reliable multicast protocol proposed in lossy wireless networks. By employing an LP-based opportunistic routing structure, opportunistic feeding, fast batch moving and inter-batch coding, the work offered improvements in throughput, energy-efficiency and fairness. Different from opportunistic routing, deterministic routing determines particular paths based on coding opportunities before packet delivery [13]. That means, the source node evaluates the number of coding opportunities on each candidate route, and selects the route with more coding opportunities to transmit packets. Obviously, those schemes have the advantage of controllable performance, even if some extra information is needed to calculate potential paths.

Based on the methods used for collecting extra information, those deterministic coding-aware schemes can be further subdivided into two classes: *proactive* and *reactive*. Proactive protocols [19–21] maintain a constantly updated topology understanding to estimate the availability and the coding opportunity of a path for route selection. Sengupta [19] et al. proposed CA-PATH-CODE,

* Corresponding author.
E-mail addresses: chenjing@whu.edu.cn (J. Chen), milloglobe@gmail.com (K. He).

http://dx.doi.org/10.1016/j.comnet.2016.05.027

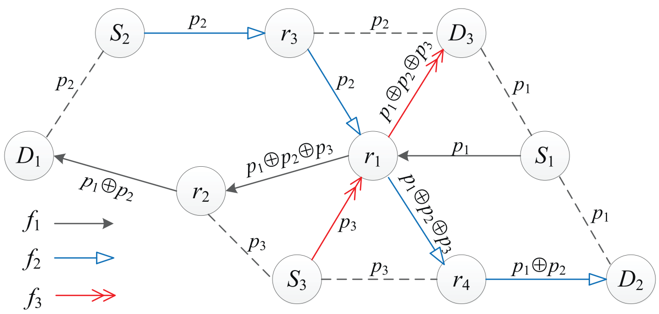

Fig. 1. Example of decoding at intermediate nodes in a multi-flow network.

a XOR-based coding-aware routing, based on the COPE [22] approach, which leveraged the coding opportunities in the two-hop range. HyCare in [20] exploited the Expected Time of the Overall Transmission (ETOX) as the link-state information, to find possible network coding opportunities in routing. [21] presented a Link State MultiPath (LSMP) protocol that utilized network coding and link state shortest path routing. Such proactive schemes usually consume extra resources to periodically collect some information, such as that regarding neighbors and flow rates, to estimate coding opportunities. In contrast, reactive protocols establish paths only upon request [23], and therefore they usually require fewer resources. Researchers in [13] presented Distributed Coding-Aware Routing, which is a reactive XOR-ed routing scheme. Generalized coding conditions (GCCs) were defined to discover paths with potential coding opportunities, which eliminated the two-hop coding limitation in COPE. Jing Chen et al. [24] proposed a Connected Dominating Set (CDS)-based and Flow-oriented Coding-aware Routing (CFCR) scheme. The scheme selected the appropriate coding nodes from the connected dominating set to discover coding opportunities.

However, most of the existing reactive protocols only consider two-flow coding when detecting paths with coding opportunities, without discussing the multi-flow coding sufficiently. Bin Guo et al. [25] presented a general discussion on the coding condition, but they did not consider the multi-flow interference and other implementation details. Such an insufficient discussion may impair the *coding benefit*, which depends on not only the number of coding opportunities but also the number of the coding flows. For example, in Fig. 1, initially there are two flows, f_1 ($S_1 \rightarrow r_1 \rightarrow r_2 \rightarrow D_1$), f_2 ($S_2 \rightarrow r_3 \rightarrow r_1 \rightarrow r_4 \rightarrow D_2$), which intersect at node r_1. Based on the two-flow coding methods, packet p_1 from flow f_1, and p_2 from flow f_2 can get coded at node r_1 as $p_1 \oplus p_2$. But, if there is a new flow f_3 ($S_3 \rightarrow r_1 \rightarrow D_3$), whose packet is p_3, intersecting other two flows at node r_1, the existing two-flow coding methods cannot *directly* code those three flows together. We observe that by allowing node r_1 to encode packets p_1, p_2, p_3 into $p_1 \oplus p_2 \oplus p_3$ directly, it can improve the coding benefit. Also, since r_2 overhears p_3 from S_3, and D_1 overhears p_2 from S_2, p_1 gets successfully recovered at D_1. Similarly, nodes D_2 and D_3 can obtain their interested native packets, respectively.

In this paper, we propose a DGCDR to improve the coding benefit in reactive routing, where multiple flows are *directly* encoded in a greedy way when they satisfy our coding condition, and the encoded packets are decoded through the collaboration of multiple decoding nodes.

1.1. Challenges

Our work introduces several key challenges needing to be solved. First of all, multi-flow coding may change nodes' forwarding behaviors, which can crash the sufficiency of the existing coding condition, defined as *multi-flow interference* in this paper. Thus, the evaluation of coding opportunities cannot only depend on the topological relationship as in the two-flow environment. Secondly, a coding opportunity is identified by whether the encoded packet can successfully get decoded. Decoding in the multi-flow situation involves the cooperation of multiple decoding nodes, while in the two-flow coding, decoding is conducted at a single node. In other words, a novel decoding policy is required to define the coding condition in the multi-flow environment. Thirdly, the multi-flow coding should not decrease coding opportunities compared with the two-flow coding, especially considering that the coding condition in the multi-flow situation is more strict. Therefore, DGCDR has to be backward compatible with the two-flow coding in the worst case, which makes the number of coding opportunities in the two-flow coding be its lower limit. Finally, in reality, the multi-flow environment introduces flow rate differences. As a practical coding system, both real-time and adaptive requirements should be considered simultaneously.

1.2. Contributions

The main contributions of our paper are summarized as follows:

- In contrast to previous coding-aware routings [13,24,25], which claim that the coding condition is sufficient or even sufficient and necessary, to the best of our knowledge, this is a first work to prove that only a necessary coding condition can be achieved by analyzing the topological relationship of nodes in a multi-flow environment;
- To identify the real coding opportunities in potential coding nodes found by the necessary condition, we propose a scheme to sense and avoid the *multi-flow interference* in the process of route discovery;
- Different from the previous two-flow protocols, which require destination nodes to decode packets, we propose a greedy decoding policy to regulate when and how to decode packets in multi-flow scenes, cooperatively;
- To ensure the backward compatibility of our routing protocol, we design a greedy aggregation mechanism to maximally code the qualified flows together, which, in the worst case, is backward compatible to the two-flow coding;
- We exploit a greedy encoding and decoding algorithm to reduce the transmission delay, and it can automatically match the different rates of flows.

Compared with our conference version [26], we make improvements in the three aspects as follows. First, we provide the details of protocol implementation to help readers to understand our protocol clearly. Secondly, we add the route maintenance process to enhance the compatibility of our protocol in dynamic wireless networks. Thirdly, we rearrange our simulations and supply the detailed comparisons in the aspects of algorithm characteristics, packet loss ratio, mobility, and average flow rate, respectively.

1.3. Paper organization

The reminder of the paper is organized as follows. The problem statement is presented in Section 2. In Section 3, we discuss the coding condition and the decoding policy in DGCDR. The routing metric and the detailed protocol construction are described in Sections 4 and 5, respectively. Section 6 evaluates the performance. The paper is concluded in Section 7.