Digital Communications and Networks ∎ (∎∎∎∎) ∎∎∎–∎∎∎

HOSTED BY

ELSEVIER

Contents lists available at ScienceDirect

Digital Communications and Networks

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

Hop-by-hop Content Distribution with Network Coding in Multihop Wireless Networks

Rami Halloush [a], Hang Liu [b,*], Lijun Dong [c], Mingquan Wu [d], Hayder Radha [e]

[a] Department of Telecommunications Engineering, Yarmouk University, Irbid, Jordan
[b] Department of Electrical Engineering and Computer Science, The Catholic University of America, Washington, DC, USA
[c] Huawei Research Center, Santa Clara, CA, USA
[d] Huawei Technologies USA, Inc., Bridgewater, NJ, USA
[e] Department of Electrical and Computer Engineering, Michigan State University, East Lansing, MI, USA

ARTICLE INFO

Article history:
Received 8 December 2015
Received in revised form
3 August 2016
Accepted 9 August 2016

Keywords:
Content distribution
Network coding
Multicast
Hop-by-hop transport
Rate adaptation

ABSTRACT

The predominant use of today's networks is content access and distribution. Network coding (NC) is an innovative technique that has potential to improve the efficiency of multicast content distribution over multihop wireless mesh networks (WMNs) by allowing intermediate forwarding nodes (FNs) to encode and then forward data packets. Practical protocols are needed to realize the benefits of the NC technique. However, the existing NC-based multicast protocols cannot accurately determine the minimum number of coded packets that a FN should send in order to ensure successful data delivery to the destinations, so that many redundant packets are injected into the network, leading to performance degradation. In this paper, we propose HopCaster, a novel reliable multicast protocol that incorporates network coding with hop-by-hop transport. HopCaster completely eliminates the need for estimating the number of coded packets to be transmitted by a FN, and avoids redundant packet transmissions. It also effectively addresses the challenges of heterogeneous multicast receivers. Moreover, a cross-layer multicast rate adaptation mechanism is proposed, which enables HopCaster to optimize multicast throughput by dynamically adjusting wireless transmission rate based on the changes in the receiver population and channel conditions during the course of multicasting a coded data chunk. Our evaluations show that HopCaster significantly outperforms the existing NC-based multicast protocols.

1. Introduction

The predominant use of today's Internet is content access and distribution. Multimedia content traffic is growing at an exponential rate. This trend is expected to continue in the foreseeable future. For example, it is forecasted by Cisco [1] that global mobile data traffic will increase nearly tenfold between 2014 and 2019. Recently, there is renewed research interest in supporting multicast distribution to deliver various services such as live event video streaming, social content pushing, file sharing, software upgrades, mobile TV, as well as other applications for which multiple users concurrently consume the same content [2]. The demand for these applications is becoming increasingly common, and multicast is much more efficient in delivering them than unicast by sharing network resources. The Third Generation Partnership Project (3GPP) recently defined the Evolved Multimedia Broadcast/Multicast Service (eMBMS) standard [3] to support streaming and downloading applications. Several operators have started field trials for eMBMS services.

These multicast applications have strict quality of service (QoS) requirements. Many of them require 100% reliability with high throughput. Any packet loss may cause severe quality degradation, and users always desire to get content as quickly as possible. It is challenging to achieve reliable and high-throughput multicast, especially in multihop wireless mesh networks (WMNs) due to interference, channel fading, and limited bandwidth. Furthermore, a unique issue in multicast is bandwidth heterogeneity amongst multicast receivers. The receivers with poor network connectivity or a low-throughput path from the source may greatly degrade the performance of receivers with good network connectivity as the reliability requirements of the worst receiver have to be met.

Traditional reliable multicast protocols, including eMBMS, are client–server based, in which intermediate routers or forwarding nodes simply duplicate and forward packets. These protocols employ end-to-end forward error correction (FEC), automatic

* Corresponding author.
E-mail address: liuh@cua.edu (H. Liu).
Peer review under responsibility of Chongqing University of Posts and Telecommunications.

http://dx.doi.org/10.1016/j.dcan.2016.08.001

repeat request (ARQ) or hybrid FEC-ARQ techniques [4–7] at the application layer of the clients and servers to achieve multicast reliability. However, their performance is limited by the multicast receivers with the worst path from the source.

Network coding (NC) is an innovative technique to improve reliability and throughput in WMNs. The basic idea of NC is to allow intermediate forwarding nodes (FNs) to encode data packets, instead of simply replicating and forwarding packets, and thus take advantage of the wireless broadcast medium to reduce the number of required transmissions for delivery of the data [8,9]. Especially, intra-flow random linear network coding [10,11] has attracted interest due to its low control overhead and high efficiency along with implementation simplicity, in which a FN randomly generates linear combinations of received packets belonging to a data flow over some fields, and forwards the coded packets. Random mixing at each FN ensures that if a group of FNs hear the same packet transmission, with high probability, the coded packets generated and forwarded by the different FNs will be linearly independent, removing duplicate packet transmissions over shared wireless medium. A node can not only receive the packets from its direct parent node but also overhear the coded packets of the same data flow transmitted by other neighbors. Intra-flow random NC thus makes opportunistic forwarding and overhearing more effective in WMNs so as to achieve significant performance gains compared to non-coding schemes.

However, the use of NC introduces new challenges in designing a practical multicast protocol. First, a FN does not need to encode and then forward a coded packet whenever it receives a packet from its upstream node because its downstream node may overhear packets from other neighbors. Consider a simple example in which a source S multicasts two packets, P_1 and P_2, to two destination receivers, D_1 and D_2 through a FN, F, as shown in Fig. 1. S transmits two coded packets, P_1+P_2 and P_1+2P_2 in sequence, which can be represented by the corresponding coding vectors (1, 1) and (1, 2). Assume that F receives both packets, and D_1 and D_2 overhear coded packets (1, 1) and (1, 2), respectively. In fact, F only needs to generate one coded packet from the received two packets, e.g. $3P_1+4P_2$, and forward it. D_1 and D_2 can decode and obtain the original packets P_1 and P_2 after they receive coded packet $3P_1+4P_2$ from F. However, F may not know that D_1 and D_2 have overheard a packet from S as it has limited knowledge of the reception status of D_1 and D_2 with regard to the two packets sent by S. It is nontrivial for F to decide the number of coded packets it should send and the time when to stop sending. Therefore, one challenge in the NC protocol design is to address how many coded packets each FN should send in order to guarantee all the multicast destination receivers obtain enough packets to decode the original data. In addition, how should the bandwidth heterogeneity of the paths from the source to the different destination

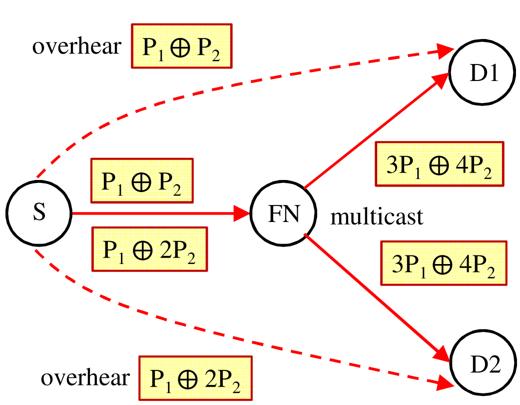

Fig. 1. A NC-based multicast example.

receivers be handled by the multicast protocol? To deliver the benefits offered by intra-flow NC, a practical protocol needs to address the above challenges.

Although various NC schemes have been studied under different network settings, practical protocol design for reliable multicast with NC in WMNs has received relatively little attention. MORE [11] and Pacifier [12] are the two state-of-the-art intra-flow NC-based multicast protocols with different selections of forwarding node topologies. Both of them employ a transmission credit (*TX_Credit*) approach, in which the source computes and assigns a *TX_Credit* to each FN based on the periodical packet loss rate measurements of the links on the network. The source transmits the coded packets from a data chunk, and the *TX_Credit* values are carried in the packet header that indicates the number of coded packets a FN should transmit upon receiving the packet from its upstream node. An intermediate FN simply determines whether and how many coded packets transmit to its downstream nodes according to the *TX_Credit* assigned to it in the received packet. The successful data delivery is verified through end-to-end acknowledgements (ACKs). The source continues sending coded packets until it receives the ACKs from all its multicast destination receivers. However, with this approach, the FNs may transmit the packets much more than necessary, significantly wasting wireless resources, because it is very difficult to obtain the accurate estimation of the *TX_Credit* for each FN in dynamic wireless environments, and the end-to-end ACKs may be delayed or lost.

In this paper, we take a different approach, and propose a novel intra-flow NC-based hop-by-hop reliable multicast protocol, termed HopCaster, to achieve high-throughput over WMNs and solve the bandwidth heterogeneity issue of multicast receivers. In contrast to the existing NC-based multicast protocols, HopCaster completely eliminates the need for estimating the *TX_Credit,* as well as simplifying multicast management and congestion control. Moreover, a cross-layer rate adaptation mechanism is proposed, which maximizes the multicast throughput by dynamically adjusting the wireless transmission rate to the changes in the receiver population and wireless channels during multicast of a coded data chunk. The evaluation results show that HopCaster achieves significant throughput gains compared to the state-of-the-art NC-based multicast protocols.

The remainder of this paper is organized as follows. Related work is reviewed in Section 2. In Section 3, we present the HopCaster protocol design. Section 4 describes the cross-layer rate adaptation mechanism. In Section 5 we show the evaluation results and performance comparison of HopCaster with the existing NC-based multicast protocol. The paper is concluded in Section 6.

2. Related work

Wireless network coding has been proposed to improve reliability and throughput. Network coding schemes are classified as inter-flow NC and intra-flow NC. With inter-flow NC [13–15], an intermediate FN encodes data packets from different flows, and forwards the coded packets. A receiver decodes the packets to obtain the flow of data targeted to it using its knowledge of another flow. However, in order to obtain inter-flow coding opportunities, the encoded flows need to pass through a common FN with certain network topologies and specific routing [15]. In addition, inter-flow NC typically requires that the sending FN knows what data packets have been buffered or overheard by each of the intended receivers in order to determine how to encode the packets across the flows. This thereby leads to increased control overhead. More recently, it is shown that the use of intra-flow NC with random linear block codes [9,10] can address wireless multicast challenges in an efficient and simple manner because it

Please cite this article as: R. Halloush, et al., Hop-by-hop Content Distribution with Network Coding in Multihop Wireless Networks, Digital Communications and Networks (2016), http://dx.doi.org/10.1016/j.dcan.2016.08.001