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Coding- and interference-aware routing protocol in wireless networks ☆

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ABSTRACT

Network coding is considered as a promising technique to increase the bandwidth available in a wireless network. Many studies show that network coding can improve flow throughput only if an appropriate routing algorithm is used to identify paths with coding opportunities. Nevertheless, a good routing mechanism is very difficult to develop. Existing solutions either do not estimate the path bandwidth precisely enough or cannot identify the best path in some situations. In this paper, we describe our coding-aware routing protocol that provides a better path bandwidth estimate and is able to identify high throughput paths. Extensive NS2 simulations show that our protocol outperforms existing mechanisms.

1. Introduction

In a traditional wireless network, neighbor wireless links cannot be active simultaneously because the two links interfere with each other. This phenomenon seriously limits the bandwidth provided in a wireless network. Fortunately, the recently developed technique link-layer network coding (LNC) [1] allows two or more packets to be delivered at the same time. If used smartly, throughput can be enhanced significantly, and many works study the maximum throughput gain obtained by using network coding [2,3]. Nevertheless, a significant throughput gain can be achieved only if appropriate routes are selected to utilize coding opportunities. This paper aims at developing a proactive coding-aware routing protocol to realize the benefits of network coding. Our protocol identifies high throughput path from a source to a destination without sacrificing existing flows. In other words, our protocol also supports service guarantees that once a flow is admitted, the bandwidth it enjoys will not be reduced due to newly admitted flows [4].

Quality-of-Service (QoS) routing in wireless networks is challenging. Some works analyze the maximum throughput a new flow can have theoretically [5,6]. However, optimal algorithms are usually computationally expensive and centralized in nature. Distributed protocols are thus required in practice. A common approach to develop distributed protocols is to apply a metric that reflects the bandwidth availability in an existing routing algorithm [7–10]. When wireless interference and network coding are jointly considered, the QoS routing problem becomes more complicated.

We use an example to illustrate the complexity of the issue we consider in the paper. Let the interference range be two hops and the transmission rate of each link be 1 unit in Fig. 1. There is an existing flow with data rate $\frac{1}{4}$ unit on $\langle 3,2,1\rangle$. We want to understand how much bandwidth a new flow request from Node 1 to Node 6 can have. To carry the flow on $\langle 3,2,1\rangle$, both links $(3,2)$ and $(2,1)$ have to be active for $\frac{1}{4}$s in each second. As all links interfere with each other, a link has to remain silent when another link is active. Thus, the remaining portion of time in a second that a link can carry a new flow is only $\frac{1}{2}$s. If we use path $p_1 = \langle 1,4,5,6\rangle$ to carry the flow from Node 1 to Node 6, each link can at most be active for $\frac{1}{6}$s in each second to send the traffic, implying the maximum throughput of the flow without violating the service guarantees of the existing flow is $\frac{1}{6}$ unit. On the other hand, if path $p_2 = \langle 1,2,3,6\rangle$ is used, coding can be applied at Node 2. Suppose there are four time slots in each second, and we schedule the packet transmission in the following way: Link $(1,2)$ transmits packet of the new flow at time slot 1; Link $(3,2)$ transmits packet of the existing flow at time slot 2; Node 2 codes the two received packets and sends the encoded packet at time slot 3; In slot 4, $(3,6)$ sends the packet of the new flow. We can send a packet of $\frac{1}{4}$ unit in each slot. Thus, the new flow can have a throughput of $\frac{1}{4}$ unit on path p_2. Note that the existing flow on $\langle 3,2,1\rangle$ does not need to sacrifice and still enjoys a throughput of $\frac{1}{4}$ unit. The available bandwidth (or throughput) of a path is defined as *the maximum additional rate a flow can push before saturating its path* [11].

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In a proactive routing protocol, each source precomputes the maximum available bandwidth path (widest path) to a destination. When the source receives a new connection request, it will accept the connection if the widest path satisfies the bandwidth requirement. Therefore, accurately estimating the available bandwidth of a path is fundamental to provide QoS guarantees. Besides, a routing protocol should also identify the path for carrying the flow and ensure the packets are forwarded consistently along the path. This paper aims at providing a complete solution to the coding-aware routing problem. The contributions in this work are.

1. We introduce a method to estimate the available bandwidth of a multi-hop path with network coding.
2. We design a coding-aware routing metric which captures the available path bandwidth information, and we prove that the proposed routing metric is *isotonic*, which is necessary to ensure packets are forwarded consistently on the identified path in a distributed manner.
3. We present our NS2 simulation results and compare our routing protocol with the existing ones.

The rest of the paper is organized as follows: Representative related works are discussed in Section 2. Section 3 gives some preliminaries for path bandwidth calculation. In Section 4, we describe how to estimate path bandwidth with network coding. Afterwards, we develop a coding-aware routing protocol in Section 5, and Section 6 presents our simulation results. Finally, Section 7 concludes our work.

2. Related works

Network coding has been studied to combat performance loss due to poor link quality. The works in [12–17] apply network coding to increase unicast throughput by using opportunistic routing in the face of lossy wireless links. The network coding studied in these works is called intra-session network coding, where packets in the same session are encoded together [18]. Another research line is to encode the packets in different sessions, which is called *inter-session network coding*. The work in [19] is the first work applying network coding on two flows going in opposite directions on the same path. Refs. [20,22] proposed physical-layer network coding (PNC). The work in [21] analyzes the rate and BER performance when applying PNC in two-way relay channel. We consider LNC in this paper, since LNC does not require strict synchronization at the physical layer, which is simpler to implement. The work in [1] develops the first practical link-layer network coding architecture, called *COPE*, for multi-hop wireless networks.

The work in [18] studies the tradeoff between increasing the coding opportunity and lowering the transmission rate, in order to maximize network throughput. The work in [23] concerns the coding-aware scheduling problem based on the TDMA model. The works in [2,3,24] analyze the theoretical throughput gain provided by network coding. Both [2,3] consider the COPE-type network coding, and give the upper bound of the throughput gain in multi-hop wireless networks. The work in [24] proposes a M-tuple coding and formulates its theoretical throughput gain. The theoretical analysis on throughput gain sheds lights on the advantage of network coding. Nevertheless, such gain cannot be realized without appropriate routing and scheduling mechanisms.

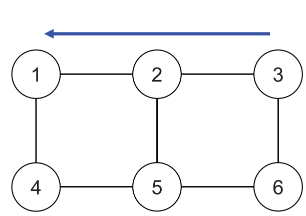

Fig. 1. An illustration for routing with network coding.

The work in [25] considers the coding-aware routing problem in multi-hop wireless networks. Linear programming is used to develop a theoretical formulation. Our focus, on the other hand, is to develop a practical distributed routing protocol for identifying high throughput paths. The works in [26–29] develop new coding-aware routing metrics to identify high throughput paths. The routing metric proposed by [26] uses the buffer length to reflect how busy the node is, and a path with the minimum aggregate buffer length is selected. Coding opportunities are considered when calculating the buffer length at each node. The metrics described in [27,28] are both based on ETX [7]. ETX reflects the number of transmissions needed for successful delivery of a packet over a link. The coding opportunity is converted into a weighted factor on the ETX. Unfortunately, all these metrics do not directly indicate how much bandwidth a path can support. We cannot use these routing metrics to perform admission control decision because we do not know whether a path has the enough bandwidth resources to support a new connection.

The work in [29] gives a formula to estimate the path bandwidth when network coding is considered. The interference model among links considered in this work is too conservative. In this work, we aim at developing a more accurate estimation. The preliminary version of this paper appears in [30]. In this paper, we refine our formula to develop a complete proactive distributed routing protocol. We also conduct extensive simulations to compare our protocol with existing ones.

3. Preliminaries

The network is represented as $G = (V, E)$ where V represents the set of nodes in the network and E denotes the set of directed edges. Each link $e = (i, j) \in E$ means that node i can transmit to node j. We assume links are symmetric that if $(i, j) \in E, (j, i) \in E$ as well. Whether two links interfere with each other depends on the interference model adopted. For instance, if we apply the 802.11 interference model [5], both the sender and the receiver of a link should not be interfered. Note that the sender of a link has to receive ACK according to 802.11, and so it should not fall within the interference range of the sender and/or receiver of another link. In other words, links (i, j) and (k, l) interfere with each other if k (or l) is in the interference range of i (or j). In this paper, we describe our results based on the 802.11 model but our mechanisms can be extended to other models, such as the protocol interference model in which only the receiver has to be free from interference. Based on the current flows on each link in the network, we can determine the residual bandwidth of each link e, denoted by $B(e)$. $B(e)$ means that if all the links interfering with e do not transmit any new flow, link e can possess the channel $\frac{B(e)}{C}$ time for each second to transmit the new flow, where C is the channel capacity. Lots of works study the residual link bandwidth estimation [4,31], and so we assume that $B(e)$ for each link e is known. If the bit error rate of a link is considered in the link estimator, the available bandwidth of each link becomes the *expected available link bandwidth* [32].

Given a path $p = \langle v_1, v_2, \ldots, v_h \rangle$, denote $\mathbf{Q}_p$ as the set of *maximal interference link sets*. Each $\mathbf{q} \in \mathbf{Q}_p$ contains the set of links on p which interfere with each other. For each $\mathbf{q}_i \in \mathbf{Q}_p$, we cannot find $\mathbf{q}_j \in \mathbf{Q}_p$ such that $\mathbf{q}_i \subset \mathbf{q}_j$, where $j \neq i$. $\mathbf{q}_i$ is also referred as a maximal clique in a contention graph which contains all the links on p [5]. For instance, in Fig. 2, assume that the interference range is two hops. Given path $\langle 1, 2, 3, 4, 5, 6 \rangle$, $\mathbf{Q}_p$ contains $\mathbf{q}_1 = \{(1, 2), (2, 3), (3, 4), (4, 5)\}$ and $\mathbf{q}_2 = \{(2, 3), (3, 4), (4, 5), (5, 6)\}$. Generally speaking, if two links on a path interfere with each other, all the links between them along the path conflict with each other [32].