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A survey of inter-flow network coding in wireless mesh networks with unicast traffic

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ABSTRACT

Wireless network performance is much restricted by the unreliability of the wireless channel and the competition among different flows for the shared network resources such as the bandwidth. Network coding is a technique that exploits the broadcast of the wireless channel and can effectively address these two restrictions to improve network performance. For example, with network coding, an intermediate node of multiple flows can encode packets from these flows into one mixed packet and serve these flows using only one transmission instead of multiple transmissions in the traditional way, thus mitigating the competition among flows. Inter-flow network coding (XNC), as a form of network coding, considers encoding packets from different flows, and it can benefit wireless mesh networks (WMNs) with either reliable or lossy links. In this paper, we present a survey on XNC in WMNs for unicast traffic, with various design factors related to XNC being covered. Specifically, our survey considers two types of WMNs, one with reliable links and the other with lossy links, and we study how XNC can be effectively utilized in both two types of WMNs. In addition to the benefits of XNC, we also present in this survey some drawbacks of applying XNC in WMNs. With this paper, we believe that readers will have a more thorough understanding of XNC on how it effectively mitigates the resource competition among flows and the channel unreliability problem in WMNs.

1. Introduction

The design of wireless networks is challenging, primarily due to the fading and broadcast nature of wireless channels, as well as the sharing of network resources [1]. First, similar to wired networks, resources such as the bandwidth in wireless networks are shared among different flows. Flows at one common intermediate node need to compete for the use of the common channel whenever a transmission opportunity arises. This competition imposes a major constraint on network performance. Second, as opposed to the stable and reliable wired channel, wireless channels generally experience drastic variation due to channel fading, causing each transmission prone to be a failure. In this situation, retransmissions generally serve as a necessary way to guarantee the packet delivery. However, retransmissions decrease the efficiency of exploiting the bandwidth. In addition, wireless channels are broadcast channels, which could cause interference between simultaneous transmissions. This interference problem further restricts the efficiency of using the bandwidth. Fortunately, the broadcast channel on the other hand can be exploited to mitigate the first two problems to improve network performance, as will be seen from network coding later.

Network coding [2] is a promising technique for increasing wireless network performance. Proposed in [2] for achieving multicast capacity in wired networks, network

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coding introduces a new paradigm of packet processing and forwarding. That is, network coding allows an intermediate node to *encode or mix* different received packets into one single *coded* packet and send the coded packet along an outgoing channel. Clearly, this new paradigm is different from traditional non-coding scheme, where packets are simply replicated and then separately forwarded at intermediate nodes. Importantly, this new paradigm of network coding can be successfully applied to wireless environments, e.g., wireless mesh (or ad-hoc) networks (WMNs), to improve network performance even under unicast traffic [3,4]. Regarding the packets to be encoded together, network coding can be classified into inter-flow network coding (XNC) and intra-flow network coding (INC). XNC considers encoding packets from different flows whereas INC considers encoding packets from the same flow. It can be found in the literature that both XNC and INC [5,6] can be used effectively for boosting wireless network performance, and some works even consider hybrid approaches that exploit both XNC and INC [7,8,53,54]. This is because both XNC and INC can effectively address the first two challenges mentioned above. However, these hybrid approaches [7,8,53,54] show that XNC and INC have distinctly different design principles. In this paper, we put emphasis on illustrating XNC in wireless networks.

So far, a body of XNC schemes have been proposed in the literature for WMNs. A WMN [55] consists of mesh clients, mesh routers, and mesh gateways, and it provides a cost-effective solution for the last-mile Internet access. In WMNs, the clients are connected by the routers and gateways in a multi-hop fashion, and one major challenge is how to achieve high network throughput [55]. Various studies [14–17] have shown that XNC is a powerful performance booster in WMNs under unicast traffic, and that the design of the XNC scheme generally involves several important design issues or factors, as will be discussed later in this paper.

Currently, there are some works on surveying network coding [10–13], but none of them is specifically on XNC for unicast traffic in WMNs. Thus, due to the usefulness of XNC in WMNs and those identified design factors, we are motivated to give a survey on this topic in this paper. Our survey consists of two major parts, (i) XNC in WMNs under reliable links; and (ii) XNC in WMNs under lossy links. Here, by a lossy (reliable) link, we mean a wireless link between two nodes does (not) suffer from the channel fading and the retransmission problem. In each of the two parts, we will first present a typical XNC example to show how an intermediate node in XNC forwards packets received from multiple flows and compare it to that in traditional non-coding scheme, and then we will present the survey in detail on how XNC could benefit WMNs more. In addition to the advantages of XNC, we also present in this paper some drawbacks of applying XNC in WMNs as well.

2. XNC in WMNs under reliable links

Before proceeding to the survey, we first show a typical example of XNC in WMNs under reliable links. Consider a simple scenario of only two flows in Fig. 1 where flow 1 (f_1) and flow 2 (f_2) intersect at nodes 1, 2 and 3. Suppose each link is reliable and each node is required to store all data packets it has already sent. We now illustrate how the intermediate node 2 handles the packet forwarding after it receives P_1 from f_1 and P_2 from f_2 in traditional non-coding scheme and XNC, respectively.

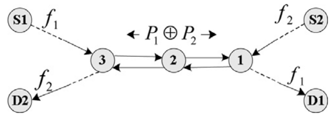

Fig. 1. An example of XNC under reliable links in WMNs.

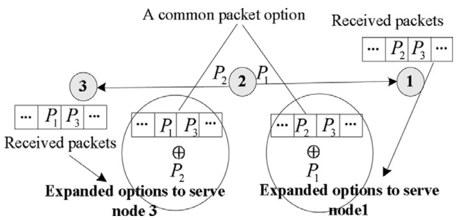

Fig. 2. Rationale behind XNC.

Traditional non-coding scheme: Here, for any received packet, node 2 simply forwards it to its next hop, as mentioned earlier. Thus, P_1 and P_2 are sent individually by node 2 to nodes 1 and 3, respectively. This means f_1 and f_2 compete for the channel use at node 2 and two transmission times are needed to forward P_1 and P_2.

XNC: Here, we consider a simple packet encoding scheme, i.e., XOR. Node 2 XORs P_1 and P_2 into a coded packet, $P_1 \oplus P_2$, and then broadcasts $P_1 \oplus P_2$ to both nodes 1 and 3. Upon receiving $P_1 \oplus P_2$, node 1 (3) XORs it with the stored packet P_2 (P_1) to yield P_1 (P_2), which is what node 1 (3) desires to receive. Consequently, with XNC exploiting the broadcast channel, one transmission of node 2 serves f_1 and f_2 simultaneously, which mitigates or even eliminates the competition between f_1 and f_2 for the channel use at node 2, and thus improves network throughput as compared with traditional non-coding scheme.

We expose the rationale behind the example of XNC in Fig. 1. Let us consider a scenario where one node, say node 1, demands a packet, P_1, from another node, say node 2. Traditionally, node 2 has only one option to satisfy the demand of node 1, i.e., node 2 only considers sending P_1 to node 1. However, the option at node 2 can actually be diversified by considering the packets previously received at node 1. For example, if node 1 has received a bundle of packets before, then, node 2 can encode any packet from that bundle with P_1 to form an optional encoded packet and send it to node 1. Thus, the packet options that node 2 can choose to satisfy node 1's demand are expanded. Further, in case of multiple different demands as shown in Fig. 2, node 2, with the expanded packet options for satisfying each demand, may find a "common packet option" to simultaneously serve them. If a common packet option is found, it means there is a network coding opportunity and thus, as shown in Fig. 1, the network throughput will be improved. Particularly, the improved performance is attained even with less energy consumption due to the reduced transmission times at the intermediate node. In fact, XNC is such a technique that exploits this commonness of packet options for different flows. The common