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Virtual overhearing: An effective way to increase network coding opportunities in wireless ad-hoc networks

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ABSTRACT

Overhearing is of great importance to wireless network coding in that it can be exploited to obtain the side information needed for packet decoding. Recently, a new technique called virtual overhearing (VOH) was proposed to allow a node to obtain the packet sent by another node that is multiple hops away for free. This can overcome the limitation of overhearing and be used to discover more coding opportunities. In this paper, we take advantage of VOH and propose two modes of exploiting VOH to increase coding opportunities in wireless ad-hoc networks. First, we make use of VOH to increase the chance of finding a route with coding opportunities for a new incoming flow. Second, and more importantly, we make use of VOH to *create* coding opportunities between two established flows which are currently unmixable. Note that most previous studies only attempt to find coding opportunities rather than create them. Based on these two modes of VOH usage, we design two routing protocols: distributed coding-aware routing with virtual overhearing (DCAR-VOH), and its enhanced version DCAR-VOH+. DCAR-VOH implements only the first mode of usage, whereas DCAR-VOH+ incorporates both modes of usage. Our extensive simulations indicate that VOH provides an effective way to discover coding opportunities, resulting in improved network performance. The positive effect of the second mode of usage stands out especially.

1. Introduction

Overhearing is of great importance to network coding in wireless networks. In the past decade, network coding [1] emerges as a promising tool to effectively boost wireless network capacity via packet encoding/mixing [2-4]. One important form of network coding is the inter-flow network coding [6-8], which encodes packets from different flows using XOR [6] or random linear combination [5] and serves those flows simultaneously with the coded packet(s). To decode the coded packet, some node(s) on one flow must be able to obtain the packet(s) or the side information [9] from the other flows; overhearing is generally exploited for the side information acquisition, as illustrated in Fig. 1(a). Many previous works [13-18] on inter-flow network coding exploit overhearing for network coding opportunity discovery. For example, DCAR [13] defines two conditions for an intermediate node to become an encoding node for two flows: (1) this node must be an intersection node, i.e., a common node on the paths of the two flows; and (2) with respect to this node, a downstream node of each of the flows must be able to *overhear* an upstream node of the other flow.

Though overhearing provides an appealing way for the side information acquisition in network coding, it only takes effect in the *one-hop* neighborhood of a node and thus is restrictive in coding opportunity discovery. Fig. 1(b) presents a general scenario in multi-hop wireless ad-hoc networks to illustrate how overhearing fails to bring about coding opportunities. It can be observed from the figure that all the previous works [13-18] could not find any coding opportunity at node M, the intersection node of flow 1 (f_1) and flow 3 (f_3). This is because none of the downstream nodes of f_3, node E or G, can overhear packets of f_1.

Recently, a new technique called virtual overhearing (VOH) [9] was proposed to overcome the limitation of overhearing for discovering more coding opportunities. VOH enables a node to obtain a packet sent by another node that can be *multiple* hops away for free. Thus, with VOH, a node can *virtually* overhear another node that is far away. In fact, given the establishment of f_1 and f_2 in Fig. 1(b), VOH can be applied to allow all upstream nodes, i.e., nodes G and F, of node H on f_2 to obtain the packet (e.g., P_1) sent by node A on f_1 at no cost, details of which will be illustrated

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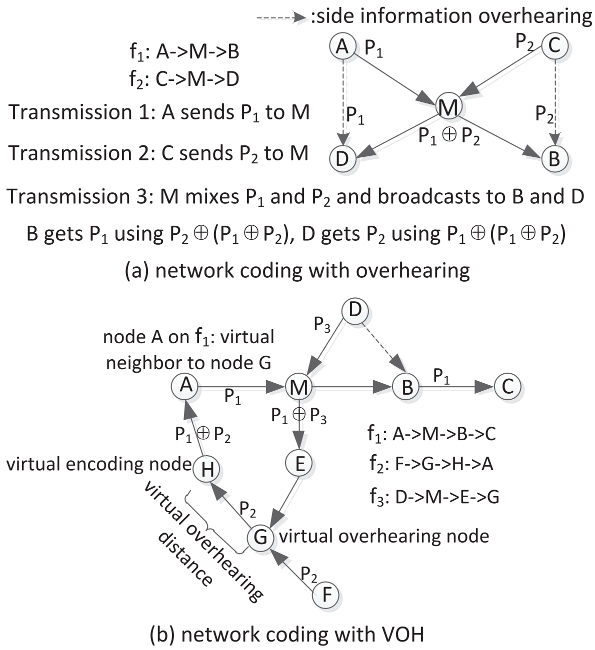

Fig. 1. Inter-flow network coding examples.

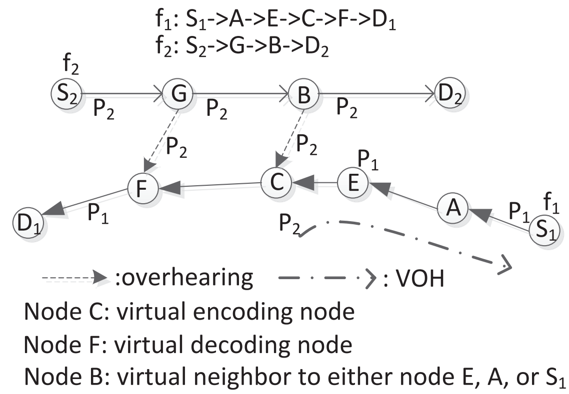

Fig. 2. Conditions of VOH.

in the next section where VOH is reviewed. Thus, with VOH in Fig. 1(b), the intersection node, node *M*, of f_1 and f_3 is now enabled to encode packets from the two flows, because node *B* on f_1 and node *G* on f_3 can obtain the packets P_3 and P_1 respectively and both can decode the coded packet, i.e., $P_1 \oplus P_3$, by node *M*.

The authors in [9] mainly investigate how the extra coding opportunities brought about by VOH improve network performance in a simple practical network, but they fail to consider how to make better use of VOH in a general network, e.g., in multi-hop wireless ad-hoc networks. In this paper, we take advantage of VOH and propose the following two modes of VOH usage to increase coding opportunities. Refer to Fig. 1(b) again.

Increasing the chance of finding a route with coding opportunities for a new incoming flow: Consider the situation when f_3 in Fig. 1(b) is the last flow to enter the network. Here, f_3 could be made aware of the existing VOH between node *G* on f_2 and node *A* on f_1, and take it into consideration in the route discovery process. By doing so, f_3 could find a route with coding opportunities, thanks to VOH. Actually, this routing strategy falls into network coding-aware routing [12], which aims to find coding opportunities for a new incoming flow with existing flows before its establishment. It is shown in many previous works [13-18] that coding-aware routing yields more coding opportunities and thus benefits network performance.

Allowing any new emerging of VOH (caused by new flow establishment) to create coding opportunities between two established flows which are currently unmixable: Consider the situation when f_1 is the last flow to enter the network. The establishment of f_1 will then enable VOH between node *G* on f_2 and node *A* on f_1, which *creates* coding opportunities for f_1 and f_3 at node *M*. It is similar if f_2 is the last flow to be established.

Our work in this paper is based on the two modes of VOH usage, and compared with [9], it has the following major contributions.

- First, we propose distributed coding-aware routing with virtual overhearing (DCAR-VOH) to implement the first mode of VOH usage. DCAR-VOH allows an incoming flow to consider existing VOH for coding opportunity discovery during its route setup.
- Second, we further propose an enhanced version of DCAR-VOH, namely DCAR-VOH+, to additionally implement the second mode of VOH usage. DCAR-VOH+ allows a third flow to create coding opportunities for two currently unmixable flows. This makes it superior to many prior network coding schemes [13-18] in general, because if two existing flows are not mixable in those prior schemes, they will never be mixable regardless of the setup of other flows.
- Third, we propose and implement an adaptive encoding mechanism in both DCAR-VOH and DCAR-VOH+. With this mechanism, the packet mixing at the encoding node is controlled such that the decoding of the coded packets could be guaranteed.
- Fourth, we conduct extensive computer simulations to study the performance of the two routing schemes in various network conditions, and show that DCAR-VOH+ stands out in most situations.

The rest of this paper is organized as follows. Section 2 reviews VOH and describes the mechanisms for its discovery. The designs of DCAR-VOH and DCAR-VOH+ are introduced in Sections 3 and 4, respectively. Section 5 gives the summary of the system implementation and analyzes the protocol complexity. Section 6 presents our simulation results, and Section 7 concludes this paper and discusses possible directions for future work.

2. VOH and its discovery

In this section, we first briefly review the conditions of VOH and illustrate how it works, and then we introduce five key definitions related to VOH. Finally, we describe the mechanisms for VOH discovery.

2.1. Conditions of VOH

For one node, say node ***A***, to virtually overhear another node, say node ***B***, the conditions are generalized in [9], which are restated as follows.

(1) Nodes ***A*** and ***B*** must be on the paths of two established flows, say f_1 and f_2, respectively.
(2) There must exist one downstream node, say node ***C***, of node ***A*** on f_1 that is able to directly overhear the packet sent by node ***B*** on f_2.
(3) There must further exist one downstream node, say node ***F***, of node ***C*** on f_1 that is able to directly overhear the packet of f_2.

Once the three conditions are met, node ***A*** on f_1 can virtually overhear node ***B*** on f_2 and obtain the packet of f_2 sent by node ***B*** for free, as will be illustrated later. Fig. 2 presents a typical scenario where node ***A*** on f_1 virtually overhears node ***B*** on f_2. Let us examine how the three conditions are met in Fig. 1(b)