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Improving network coding in wireless ad hoc networks

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ABSTRACT

Wireless ad hoc networks usually have lower network throughput than wireless infrastructure networks due to the inherent nature of multi-hop communication on a shared channel in wireless ad hoc networks. Network coding is a method that can improve the network throughput by reducing the amount of workload in the network while still ensuring that all user data is transferred. With network coding, a node can improve its transmission efficiency by combining (encoding) several packets together and sending only the resultant encoded packet if the coding conditions are satisfied. In this paper, we propose the Network Coding Routing (NCRT) protocol which consists of a new set of coding conditions, and a new routing metric that takes into consideration both coding opportunities and network workload. Comprehensive simulation studies showed that NCRT gives promising performance.

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1. Introduction

Wireless ad hoc networks are decentralized communication networks formed by wireless devices called nodes organized in a mesh topology, and are characterized by dynamic network topology and multi-hop communication. Formed and operates without a pre-installed infrastructure, a wireless ad hoc network offers many advantages over a conventional wireless infrastructure network such as lower setup cost, shorter setup time, and higher flexibility in node placement and mobility. However, wireless ad hoc networks usually suffer from low network throughput due to the increased number of packet transmissions required for multi-hop communication. In multi-hop communication, the delivery of a packet from the source to the destination requires multiple packet transmissions because intermediate nodes are required to relay the packet. In a single channel wireless ad hoc network, these transmissions are performed on the same channel. Considering that the channel capacity is limited, more transmissions required for a packet translate to lower network throughput.

Wireless ad hoc networks are emerging as a promising solution for flexible and rapidly deployable communication systems. However, before they can receive widespread adoption, the problem of low network throughput has to be addressed. Example applications that can benefit from higher network throughput are vehicular video surveillance systems [1], and data transmission in wireless mesh networks to support or replace wired backbone networks.

Many methods of improving the throughput of wireless ad hoc networks have been proposed, for example, multi-path transmission, multi-channel transmission using multiple network interface cards (NICs), and network coding. Concurrent multi-path transmission in a single channel wireless ad hoc network may result in more channel contention and interference than single path transmission. Due to intra-path and inter-path interference, even when multiple paths are available, the paths may not be used to their full potential. Hence, higher network

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throughput is not guaranteed with multi-path transmission. On the contrary, multi-channel transmission using multiple NICs is a highly effective method for improving network throughput due to higher aggregate channel capacity. However, this method incurs higher cost because each node must be equipped with multiple NICs. Besides, this method also introduces new challenges such as channel assignment to maintain network connectivity and mitigate interference.

In this work, we address the problem of low network throughput in wireless ad hoc networks using network coding. The benefit of network coding is best described with the "Alice and Bob network", where Alice has a packet P1 for Bob and Bob has a packet P2 for Alice, as shown in Fig. 1 [2]. With the conventional store-and-forward scheme, four transmissions are required for Alice and Bob to exchange the packets. This can be reduced to only three transmissions by using network coding as shown in the following process: (1) Alice transmits P1 to node R, (2) Bob transmits P2 to node R, and (3) node R encodes P1 and P2 together using the exclusive-or operation and broadcasts the resultant encoded packet $P1 \oplus P2$. Assuming that Alice has P1 buffered after sending it, Alice can recover P2 by decoding $P1 \oplus P2$ using P1 ($(P1 \oplus P2) \oplus P1 = P2$). In a similar manner, Bob can also recover P1. If opportunistic listening is allowed, network coding can also occur in the network shown in Fig. 2, where nodes 2 and 4 can overhear nodes 3 and 0, respectively. When node 4 receives $P1 \oplus P2$ from node 1, node 4 can recover P2 by decoding $P1 \oplus P2$ using P1 which it overheard from node 0. Similarly, node 2 can also recover P1.

Network coding allows packets to be combined to save bandwidth, provided that the coding conditions are satisfied. To take full advantage of the network coding benefit, the number of coding opportunities must be increased. To encourage more packet encodings and prevent wrong packet encodings which result in packet loss from happening, it is important to ensure that the coding conditions used are correct and necessary. We have investigated the existing coding conditions and found some limitations in them. To overcome these limitations, a new set of coding conditions called Improved Generalized Coding Conditions (IGCC) is proposed. IGCC is then used to guide the design of a new ad hoc routing protocol called Network Coding Routing (NCRT). In addition, a routing metric that takes into consideration both coding opportunities and network workload called Coding and Load Aware Routing Metric (CLARM) is also proposed. To summarize, the contributions of this work are as follows:

- Design of an enhanced set of coding conditions to identify as many coding opportunities as possible while ensuring that the native packets in the encoded packets can be successfully recovered by their respective destinations.
- Design of an ad hoc routing protocol that allows nodes to gather the necessary information during route discoveries to determine if they can encode packets together based on the proposed coding conditions.
- Design of a routing metric that is coding-aware and load-aware to guide source nodes in selecting good paths for sending their packets, and a mechanism to update this metric periodically.

The rest of this paper is organized as follows. We review related work in Section 2. The details of the proposed methods are given in Section 3. In Section 4, we describe the experimental setup and present the results. Finally, we conclude in Section 5.

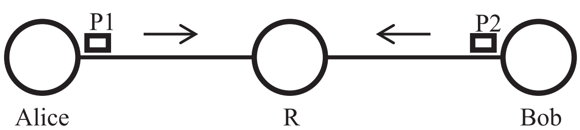

Fig. 1. The Alice and Bob network.

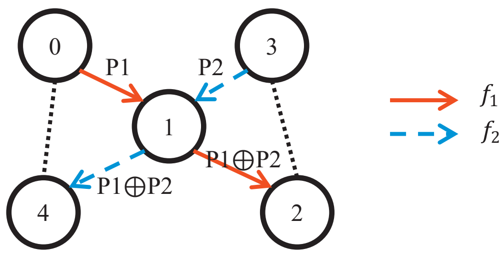

Fig. 2. Opportunistic listening allows coding in the cross topology network.

2. Related work

2.1. Network coding and coding conditions

Network coding was introduced to conserve bandwidth in wired networks for multicast flows as it is non-optimal to treat multicast flows simply as fluid [3]. Later, network coding was proposed for use in wireless mesh networks with the introduction of COPE [2]. COPE enhances the forwarding layer by inserting a coding shim between the IP and MAC layers. This allows for the increase in network throughput while ensuring backward compatibility with conventional routing and higher layer protocols. A major limitation in COPE is that network coding is limited to only two hops, and this limits the performance gain. It is stated in COPE that to transmit n different packets $p_1, \ldots, p_n$ to n different next-hops $r_1, \ldots, r_n$, a node has to ensure that each next-hop r_i has all $n-1$ packets p_j for all $j \neq i$. This coding condition ensures that every next-hop of an encoded packet can fully decode the packet but it also restricts coding structures to only two hops, where a coding structure is a unique combination of packets/flows encoded together in a single packet and the coding node at which the encoding happened.

Coding-oblivious routing is resulted when network coding is used with conventional routing protocols. In coding-oblivious routing, coding opportunity is not taken into account during route discovery and path selection. As a result, nodes wait passively for coding opportunities to arise. Obviously, the benefit of network coding cannot

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