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Network coding for unicast in a WiFi hotspot: Promises, challenges, and testbed implementation

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ABSTRACT

In offices and residential buildings, WiFi networks have become a primary means for providing Internet access to wireless devices whose dominant traffic pattern is unicast. In the meantime, the emergence of network coding has brought about great promises for multicast in communication networks where intermediate nodes are allowed to process independent incoming information flows. Little is known about network coding for unicast, however. The objective of this paper is thus to depart from multicast scenarios and shed light on several possible unicast scenarios to which network coding may be applied in a WiFi hotspot in order to obtain communication benefits such as throughput gain, fairness, and reduced protocol complexity. We identify five representative scenarios in which network coding may be used to benefit unicasting in a WiFi hotspot. Several open research issues and practical challenges related to each scenario are discussed individually. To illustrate the benefits of network coding for unicast in a WiFi hotspot, we propose and implement iCORE: The *i*nterface *CO*operation *R*epeater-aided network coding *E*ngine. iCORE is a practical system in which multi-channel multi-radio repeaters are used to relay unicast traffic for those terminals sitting far away from an access point and suffering from weak signals at a WiFi hotspot. It is based on our last scenario which illustrates the synergy among network coding, opportunistic routing, and interface management. Utilizing idle wireless interfaces and listening to traffic opportunistically, iCORE allows packets to move across the interfaces and to be coded across flows whenever it sees more transmission opportunities. We evaluate iCORE on a four-node chain-like topology testbed implemented using IEEE 802.11b/g radios and compare it to MORE – the state-of-art intra-flow network coding implementation based on opportunistic routing. Our experimental results reveal promising gains in terms of throughput over MORE.

1. Introduction

WiFi hotspots have recently become a primary means for providing Internet access to a wide range of wireless devices such as laptops, PDAs, iPod, and iPad. Based on the IEEE 802.11 standard, a WiFi hotspot is an infrastructure-based wireless local area network (WLAN) formally defined as a basic service set (BSS), or cell, in which an access point (AP) covering some geographical area provides a certain set of wireless services to a group of wireless devices.

Parallel to this explosive growth of WiFi in practice is the emergence of network coding in the academic arena. Network coding, first introduced by Ahlswede et al. in [1], is a new transmission paradigm that allows intermediate nodes in a network to not only forward but also algebraically combine several incoming packets into one or several output packets before forwarding them onto outgoing links. In doing so, the multicast capacity of a communica-

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tion network can be achieved by any source-sink pair as if it had sole access to network resources. Ahlswede et al. [1] did not recommend any particular code, but [2–4] established that it is sufficient to use linear codes to arrive at such capacity. Later, [5] proved that linear coding and decoding (i.e., which packets to combine and what coefficient to use for each packet) can be performed in polynomial time at intermediate nodes. Ho et al. [6] also showed that random coefficients, instead of the deterministic ones as in [5], can be used to achieve the multicast capacity.

Besides multicast, network coding can also be used to benefit unicast. To see how network coding can be used to benefit unicast in a WiFi hotspot, consider the scenario in Fig. 1a where Alice and Bob have packet A and packet B, respectively, to exchange with each other. For simplicity, we assume that each packet is of equal length and takes exactly one time slot to transmit. A traditional transmission solution for the AP is to treat both packets independently. That is, after receiving packets A and B in two consecutive time slots the AP relays each packet individually to each intended user in the subsequent two time slots. Four time slots are needed in this case. However, if we use network coding, as shown in Fig. 1b, only three time slots will be required. That is, after receiving packets A and B, the AP combines the two packets in the binary field (i.e., an eXclusive OR operation (XOR)) and transmits the combined packet $A \oplus B$ in the third time slot, where $\oplus$ represents an XOR operation. Now, for Alice to recover packet B she only needs to XOR her own packet with the combined packet, i.e., $B = A \oplus (A \oplus B)$. A similar procedure applies for Bob.

While the theoretical foundation of network coding for multicast has advanced very close to maturity [1–4,6,7], little is known about network coding for unicast. A search for the theoretical understanding and its applications for unicast is still ongoing [8–12]. The objective of this paper is therefore to depart from multicast scenarios by shedding light on possible unicast scenarios to which network coding may be applied, in a WiFi hotspot setting, in order to obtain communication benefits such as throughput gain, fairness, and reduced protocol complexity. Our aim is to illustrate these potential benefits by discussing five representative scenarios/examples; two scenarios for inter-flow network coding, another two for intra-flow network coding, and the last one for combined intra- and inter-flow network coding. We point out several open research issues and challenges as we discuss each scenario.

Based on the last scenario, we propose and implement i*CORE* – the *i*nterface *CO*operation *R*epeater-aided network coding *E*ngine – to illustrate the benefits of combining intra- and inter-flow network coding. iCORE is a practical system in which closer-to-AP terminals are used to relay unicast traffic for those terminals sitting far away from AP and suffering from weak signals. The discovered benefits are extracted from the synergy among network coding, opportunistic routing, and interface cooperation by enabling each terminal to be equipped with multiple interfaces and channels. Utilizing idle wireless interfaces and listening to traffic opportunistically, iCORE allows packets to move across the interfaces and to be coded across unicast flows whenever it sees more transmit opportunities. iCORE sits on top of the MAC, making it independent of the device drivers. We evaluate iCORE on a four-node chain-like topology testbed implemented using IEEE 802.11b/g interfaces and compare it to MORE – the state-of-art intra-flow network coding implementation based on opportunistic listening. Our experimental results reveal that iCORE outperforms MORE by up to 80% in throughput and is able to keep up with increased traffic load in a more stable manner.

We organize the remainder of this paper as follows. In Section 2, the basics of network coding are discussed. In Section 3, we illustrate through two representative examples the potential benefits of inter-flow network coding for a WiFi hotspot. Two representative examples for intra-flow network coding are illustrated in Section 4. The last representative example, when intra-flow network coding is employed in conjunction with inter-flow network coding, is illustrated in Section 5. Based on this last example, the implementation of iCORE is detailed in Section 6. Performance evaluation results for iCORE are presented in Section 7. We conclude this paper in Section 8.

2. Network coding preliminaries

We represent an information flow a sequence of data packets. Each packet in turn consists of a sequence of symbols each of which is one of the elements in some finite field $\mathbb{F}_{2^q}$. That is, each symbol is a group of q consecutive bits. We show for example in Fig. 2 for the case when $q = 8$.

In the following, we explain how packets are combined/coded and decoded when linear network coding is applied to a network.

2.1. Encoding

For linear combining, performing multiplication and addition over a finite field on symbols suffices. Our explanation on linear combining in this subsection applies to both *inter-flow* and *intra-flow* network coding. Whereas the former involves coding packets from different flows (i.e., packets destined to different destinations), the latter involves coding packets from the same flow (i.e., packets destined to the same destination).

With linear network coding, an output packet, or coded packet, on a particular outgoing link of any node in a network can be written as

$$\mathbf{x} = \sum_{i=1}^{n} c_i \mathbf{p}_i \tag{1}$$

where $\mathbf{p}_i$ is a native packet, and c_i is a coefficient drawn from the same finite field ($\mathbb{F}_{2^q}$) as the symbols that make up a native packet $\mathbf{p}_i$. We call a sequence of coefficients, denoted by $\mathbf{c} = [c_1, \ldots, c_n]$, an encoding vector. The addition and multiplication are performed over $\mathbb{F}_{2^q}$. The coefficients c_i can be either deterministic which are determined by a centralized controller [13], or randomly selected by individual nodes [14,6,7] in a distributed manner.

For the deterministic coefficients, this implies that there is no need for a coded packet to carry an encoding vector $\mathbf{c}$ because such an encoding vector is fixed and known to