A Novel Collaboration Scheme for Multi-Channel/Interface Network Coding

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***Abstract*—Multi-channel, multi-interface ad hoc wireless networks can obtain substantial capacity improvements by mitigating co-channel interference. Channel assignment and routing algorithms that relieve co-channel interference and balance traffic loads are critical for obtaining these large capacity increases. However, with a limited number of channels and interfaces, this approach cannot avoid traffic overload as the network traffic increases. This paper proposes a novel scheme of multi-channel/interface network coding that is based on the combination of a new concept of *coded-overhearing* and coding-aware channel assignment. The proposed algorithms overcome the radio coverage limitations present in conventional network coding schemes, and exhibit improved flexibility in terms of aggregate throughput when there are an insufficient number of interfaces and a outage of network coding opportunities. Our scheme attains significant improvement in the aggregate throughput as compared to a no network coding scheme.**

***Index Terms*—Multi-channel/multi-interface, network coding, channel assignment, wireless ad hoc network.**

I. INTRODUCTION

COMMUNICATION equipment with multiple network interface cards (NICs) have been considered for exploiting the availability of multiple channels in wireless networks [1]–[3]. One such network is IEEE 802.11 which provides up to 12 non-overlapping frequency channels in the 5 GHz band (IEEE 802.11a/h/j/n) and 4 non-overlapping frequency channels in the 2.4 GHz band (IEEE 802.11b/g/n), depending on the regulatory region. In the wireless networking literature, communication devices having multiple network interface cards are called multi-interface nodes, and consist of multiple NICs in the physical sense or multiple half-duplex transceivers in the functional sense. In spite of such multi-channel/interface equipment, traffic saturation can still occur in heavy traffic load areas such as the nodes at the center of large-scale wireless ad hoc networks.

Network coding can mitigate traffic saturation by increasing the aggregate network throughput as the network traffic increases. Since the original paper of Ahlswede *et al.* [4], many authors have considered the practical aspects of network coding. Lun *et al.* [5] proposed a minimum-energy multicasting scheme for wireless networks. They showed that network coding can improve throughput in a multiple unicast scenario. In [6], the authors propose a new architecture (COPE) for wireless mesh networks, which performs exclusive OR (XOR) operations on pairs of packets from different nodes in multiple unicasts. For COPE-type network coding, Li and Chiu [7] presented a routing algorithm combined with opportunistic network coding. Moreover, they showed that radio coverage limitations will prevent the encoding of some packets that traverse an intersecting node. References [8]–[10] present coding-aware routing algorithms for XOR encoding at intersecting nodes that reduces network traffic.

The aforementioned studies mainly considered single-channel networks. This paper extends the concepts to multi-channel/interface scenarios. In contrast to traditional network coding, our network-coding scheme uses *coded-overhearing* to cope with radio coverage limitations. Our algorithm also distributes the load of the intersecting node to its neighboring nodes by dispersing the required number of interfaces around the intersecting node. Thus, our network coding scheme improves the performance when the number of interfaces at each node is limited.

Several papers suggested the application of network coding scheme to multicasting [11] or unicasting [12]–[15] scenarios, while taking into account different network coding structures. Even though the papers focusing on unicasting consider useful and interesting network coding structures, such as the extended butterfly network [14] or n-way relay network [15], they do not consider radio coverage limitation which is important in overhearing for network coding. Furthermore, the previous work, except for [15], does not consider multi-channel/interface nodes. The authors in [15] have provided a comprehensive research framework that included the network coding scheme and channel assignment algorithm. However, the channel assignment algorithm in [15] did not regard the network coding gain as a factor to be considered.

In single-channel wireless networks, all nodes listen to a single common channel. However, in multi-channel wireless networks, the channels that a node should listen to depends upon the channels that are occupied by its neighboring nodes and are to be overheard. For this reason, channel assignment becomes one of the most important issues for network coding in multi-channel/interface wireless networks. Channel assignment has been a parallel research track for providing the bene-

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fits of multi-channel/interfaces over traditional single channel interfaces in terms of network capacity. In [1], [2], [16], the authors extended the context in Gupta and Kumar's paper [17] to multi-channel/interface scenarios. They mainly investigated the effects of the relationship between the number of channels and interfaces at each node. There has also been research on channel/interface assignment and routing algorithms. Recent results provide a graph-theoretical approach for centralized [18]–[21] or distributed [22] channel assignment. On the other hand, the results in [3], [23]–[25] present meaningful metrics and centralized/distributed channel assignment algorithms.

Although there are prior approaches that propose different sorts of channel assignment algorithms for multi-channel/interface wireless networks, they do not consider network coding gain. This paper describes a new channel assignment algorithm that accounts for network coding gain, available channel/interface capacity, and expected waiting time for network coding opportunities. Our main contributions are summarized as follows:

- A novel concept that combines multi-channel/interface network coding with channel assignment.
- A network coding scheme with coded-overhearing and a coding-aware channel assignment algorithm that are both novelties by themselves. Their combination is shown to provide a substantial improvement in the aggregate network throughput.

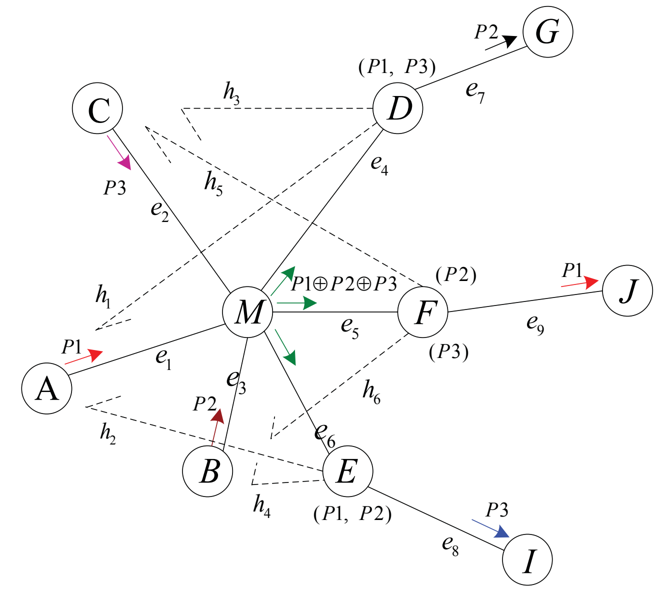
The remainder of this paper is as follows. In Sect. II, a new geographically-aware network coding algorithm is described and analyzed. Section III presents a new coding-aware channel assignment algorithm. Simulation results and comparison of the performance to the no network coding case are provided in Sect. IV. Finally, Sect. V concludes the paper.

II. Geographically-aware Network Coding

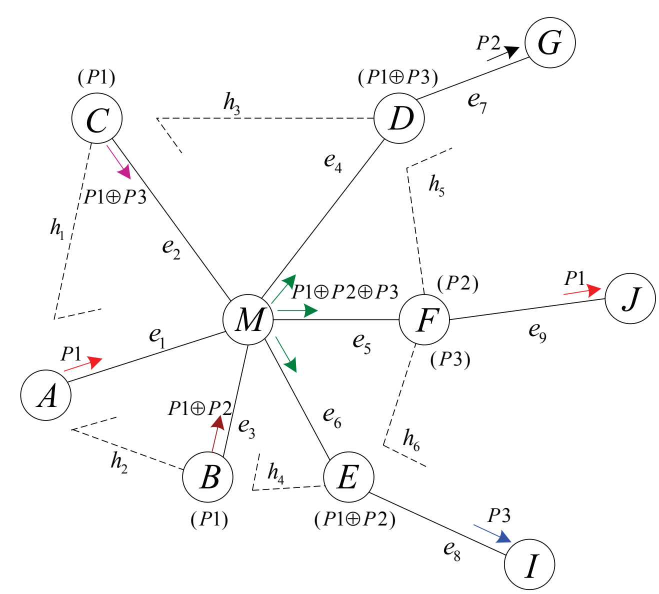
A. Coded-Overhearing and Radio Coverage Limitations

We introduce a new network coding scheme that uses coded-overhearing to overcome the geographical limitations of overhearing in wireless ad hoc networks. We explain our scheme using Fig. 1, which shows the packets to be transmitted, received and overheard at each node. We use parentheses ( ) to denote the packets to be overheard. We call nodes A, B, and C, which are the previous-hop nodes of the intersecting node M, *background nodes*. Similarly, we call nodes D, E, and F, which are the next-hop nodes of M, *foreground nodes*. We call the structure in Fig. 1 a *3-flow star-structure*, since there are 3 incoming flows at node M. An n-flow star-structure is defined as a structure comprised of an intersecting node, n background nodes and n foreground nodes, where every background (foreground) node is a one-hop neighbor node of another background (foreground) node.

Without overhearing, node M must transmit three single packets separately. As illustrated in Fig. 1(a), a conventional network coding scheme forwards only one XOR-ed packet $P1 \oplus P2 \oplus P3$ at node M. The operator, $\oplus$ is equivalent to XOR in the binary field, $GF(2)$. This scheme assumes that the nodes D, E and F can overhear packets $(P1, P3)$, $(P1, P2)$ and $(P2, P3)$, respectively. The nodes D, E and F



(a) Conventional network coding scenario.



(b) New network coding scenario with coded-overhearing.

Fig. 1. Illustration of network coding scenarios.

can then decode the corresponding packet that each node has to forward to the next node by using $P1 \oplus P2 \oplus P3$ received from node M, and the overheard packets, $(P1, P3)$, $(P1, P2)$ and $(P2, P3)$, respectively. Unfortunately, full overhearing is not possible in a practical network due to radio coverage limitations. For example, in Fig. 1(a), nodes D, E and F may not overhear packets $P1$, $P1$ and $(P2, P3)$, respectively, due to radio coverage limitations. Fig. 1(b) depicts a somewhat more realistic scenario than Fig. 1(a) considering such radio coverage limitations. In Fig. 1(b), we assume that each node can overhear neighbors only within a one-hop distance. That is, nodes D and E can overhear nodes C and B, respectively, while node F is not able to overhear any background nodes. To overcome this sort of radio coverage limitation, we propose node collaboration to forward suitable information to the foreground nodes D and E, which can overhear the background nodes C and B, respectively. We call this strategy *coded-overhearing* for the reason that the background nodes, which are the neighbors of any foreground node, perform XOR-ing on their packet to be sent with the packet overheard from another background node. Notice that this coded packet has more information and is more helpful to the foreground node for decoding the target packet from $P1 \oplus P2 \oplus P3$.

Referring to Fig. 1(b), the nodes C and B transmit $P1 \oplus P3$ and $P1 \oplus P2$ to node M, respectively, after overhearing $P1$ from node A. Node M transmits $P1 \oplus P2 \oplus P3$ by XOR-ing the three packets from nodes A, B and C. In this scenario, nodes D and E are able to overhear $P1 \oplus P3$ and $P1 \oplus P2$ instead of $P3$ and $P2$, respectively, as in the conventional network coding scheme. After nodes D and E receive $P1 \oplus P2 \oplus P3$ from node M, they are able to decode their target packets $P2$ and $P3$, respectively. Nodes D and E can transmit their target packets to the next nodes, and at this time, node F can overhear the two packets, $P2$ and $P3$. In this manner, node F can decode $P1$ from $P1 \oplus P2 \oplus P3$, which was received from node M, and can forward $P1$ to node J. Notice in our scheme that, even though a radio coverage limitation exists, the intersecting node can forward three packets to three different foreground nodes by using a single transmission of the all-coded packet. The coding gain of the scheme is 1.5 (6/4), and a detailed analysis is provided in Sect. II-C.

B. Multi-channel, Multi-interface Network Coding

In this section, we employ our network coding scheme within a multi-channel/interface environment. From now on, we assume that 12 different frequency channels are supported in the network, and each node has 4 interfaces by default. We illustrate the required interfaces at each node in a 3-flow star-structure by using Fig. 1. If an interface is shared by more than one communication link, there can be transmission delay especially in areas of traffic saturation. Further, when an interface is assigned an overhearing link, it should continuously listen to the node to be overheard, since it is unknown when the node to be overheard will actually transmit a packet. For these reasons, it is preferred that each link connected to a node be assigned to a distinct interface, provided that a sufficient number of interfaces are available. In Fig. 1, a dotted line with the label h_x represents an overhearing link, while a solid line with the label e_x denotes a transmitting/receiving link. Each dotted line is linked to only one end node, because each overhearing link requires only one interface. The foot of each L-shaped dotted link lays parallel to the link that is being overheard. We further explain the notation by referring to Fig. 1(b). For example, node C has one interface assigned to link e_2 and another interface assigned to link h_1 which overhears link e_1. In contrast to node C, node A does not need to assign an interface to overhear node C. Under the assumption that there are 12 different frequency channels and each node has 4 interfaces, each distinct link that is connected to a node can be assigned a distinct interface. The only exception is that links e_4, e_5 and e_6 require only one interface in node M, since $P1 \oplus P2 \oplus P3$ is transmitted to nodes D, E and F simultaneously.

As shown in Fig. 1(b), among the three foreground nodes, D, E and F, only node F needs 4 interfaces, while nodes D and E each need 3 interfaces. In contrast, for the conventional network coding scheme in Fig. 1(a), nodes D, E and F each need 4 interfaces. According to our scheme in Fig. 1(b), nodes B and C each need one additional interface to overhear node A, which is the price for reducing the number of interfaces needed at nodes D and E by one. In this manner, the complexity at the foreground nodes D and E in terms of the number of required interfaces is reduced by distributing the complexity to the background nodes B and C. Thus, our proposed scheme provides not only more fairness and efficiency to the star-structure, but greater flexibility in terms of aggregate throughput when the maximum number of interfaces at each node is limited.

For the channel assignment shown in Fig. 1(b), the transmitting/receiving and overhearing links can be divided into the following groups:

$$g_{\text{Inter},M} = \{e_4, e_5, e_6\}, \tag{1}$$

$$g_{\text{Back},A} = \{e_1, h_1, h_2\}, \tag{2}$$

$$g_{\text{Back},B} = \{e_3, h_4\},\ g_{\text{Back},C} = \{e_2, h_3\}, \tag{3}$$

$$g_{\text{Fore},D} = \{e_7, h_5\},\ g_{\text{Fore},E} = \{e_8, h_6\},\ g_{\text{Fore},F} = \{e_9\}, \tag{4}$$

where all links in the same group are assigned the same channel. For example, $g_{\text{Back},A}$ needs one transmitting link, e_1, and nodes B and C have to overhear the channel assigned to e_1. Hence, they need overhearing links h_2 and h_1, respectively. Group $g_{\text{Inter},M}$ contains three links, e_4, e_5 and e_6, which are used for transmitting the same XOR-ed packets simultaneously using a single channel in a manner similar to multicasting. In this manner, all groups in (1)–(4) are defined. Groups $g_{\text{Back},A}$, $g_{\text{Back},B}$ and $g_{\text{Back},C}$ are for network coding at the background nodes A, B and C, respectively, and $g_{\text{Fore},D}$, $g_{\text{Fore},E}$ and $g_{\text{Fore},F}$ are for collaboration between the foreground nodes. Group $g_{\text{Inter},M}$ is a multicast link group for $P1 \oplus P2 \oplus P3$. Notice that the grouping for the channel assignment in (1)–(4) considers only a single star-structure to illustrate our approach for multi-channel/interface network coding, and the comprehensive channel assignment algorithm is described in Sect. III. At this point we emphasize that 4 interfaces and 4 channels are sufficient for node M to forward streams of packets without packet delays in our network coding scheme. However, without network coding, node M would require 6 interfaces and 6 channels to forward streams of packets without packet delays. This saving of 2 channels reduces the co-channel interference within node M's interference area.

When the maximum number of interfaces at each node is reduced from 4 to 3, we should change the interface assignment only at nodes M and F in Fig. 1(b), inasmuch as 3 interfaces are sufficient for the other nodes. For the conventional scheme in Fig. 1(a), nodes M, D, E and F each require 4 interfaces. As such, reducing the maximum number of interfaces from 4 to 3 has a greater effect and causes a larger throughput degradation than our scheme, even when radio coverage limitations are ignored in the conventional scheme. We can easily modify the groups in (1)–(4) for a 3-interface scenario as:

$$g_{\text{Inter},M} = \{e_4, e_5, e_6\}, \tag{5}$$
$$g_{\text{Back},A \text{ and } C} = \{e_1, e_2 = h_1, h_2, h_3\}, \tag{6}$$
$$g_{\text{Back},B} = \{e_3, h_4\}, \tag{7}$$
$$g_{\text{Fore},D \text{ and } E} = \{e_7, e_8, h_5 = h_6\},\ g_{\text{Fore},F} = \{e_9\}. \tag{8}$$

Groups $g_{\text{Back},A}$ and $g_{\text{Back},C}$ are merged into one group, $g_{\text{Back},A \text{ and } C}$, due to the limit on the maximum number of interfaces, since node M has 3 interfaces and should be assigned only 3 channels. Similarly, $g_{\text{Fore},D}$ and $g_{\text{Fore},E}$ are combined into $g_{\text{Fore},D \text{ and } E}$, since node F overhears nodes D and E with only one interface available for overhearing. In $g_{\text{Back},A \text{ and } C}$, e_1 and e_2 are assigned the same channel, and since node C can overhear node A with the interface assigned to e_2 we have $e_2 = h_1$. Merging the two groups in (5)–(8) introduces packet delays since both e_1 and e_2 or both e_7 and e_8 cannot be active in the same time slot. Nonetheless, with a 3-interface limitation, the proposed network coding scheme would outperform the conventional one in terms of the number of channels that each node can maximally use and, hence, the aggregate throughput, as will be described later in this section.

In a similar fashion, we can divide all links in a 4-interface conventional network coding scenario in Fig. 1(a) into the following groups:

$$g_{\text{Inter},M} = \{e_4, e_5, e_6\}, \tag{9}$$
$$g_{\text{Back},A} = \{e_1, h_1, h_2\}, \tag{10}$$
$$g_{\text{Back},B} = \{e_3, h_4, h_6\},\ g_{\text{Back},C} = \{e_2, h_3, h_5\}, \tag{11}$$
$$g_{\text{Fore},D} = \{e_7\},\ g_{\text{Fore},E} = \{e_8\},\ g_{\text{Fore},F} = \{e_9\}. \tag{12}$$

For a 3-interface conventional network coding scenario in Fig. 1(a), the groups are:

$$g_{\text{Inter},M} = \{e_4, e_5, e_6\},\ \ g_{\text{Fore},D} = \{e_7\}, \tag{13}$$
$$g_{\text{Back},A \text{ and } C} = \{e_1, h_1, h_2, e_2, h_3, h_5, e_8\}, \tag{14}$$
$$g_{\text{Back},B} = \{e_3, h_4, h_6, e_9\}. \tag{15}$$

Here, the nodes D, E and F should each have two channels for transmitting/receiving, and two channels for overhearing other nodes, but can be assigned at most 3 channels, owing to the 3-interface limitation. For this reason, e_8 and e_9 are included, respectively, in $g_{Back,A\ and\ C}$ and $g_{Back,B}$. Comparing (5)–(8) with (13)–(15), we emphasize that our scheme can exploit 5 channels, and outperform a conventional network coding scheme that can use a maximum of 4 channels even ignoring radio coverage limitations. The improvement of our scheme in the number of channels that the intersecting node can use and, hence, the aggregate throughput comes from the strategy that distributes foreground nodes' loads in terms of the required interfaces to the background nodes. A detailed analysis will be provided in Sect. II-C.

C. Analysis for the Aggregate Throughput

This section presents a detailed analysis for our multi-channel/interface network coding scheme. We consider the same scenario as Fig. 1(b) with 4 interfaces, and assume that each of the background nodes A, B and C have n continuous equal-size packets to be sent to node M. We do not consider packet losses so as to concentrate on the achievable aggregate throughput, but from Sect. II-D onwards, we will account for packet losses in the average rate of received packets. Table I summarizes all packets that are transmitted, received, and overheard at each node. In Table I, [ ] and ( ) refer to received packets by protocol and overheard packets, respectively. Packets without [ ] or ( ) in the first line of each time index are the transmitted packets from the corresponding nodes. Based on Table I, we adapt the following notation for analytical convenience. The background nodes A, B and C have sequences of packets, $p_a(x)$, $p_b(x)$ and $p_c(x)$, respectively, that are transmitted to the node M. Let

$$p_a(x) = \sum_{i=0}^{n-1} a_i x^i,\ \ p_b(x) = \sum_{i=0}^{n-1} b_i x^i,\ \ p_c(x) = \sum_{i=0}^{n-1} c_i x^i, \tag{16}$$

where a_i, b_i and c_i are packets corresponding to the packet number i and the time index is denoted by the exponent of x. Further, we define XOR operation in the polynomial domain as

$$p_a(x) \oplus p_b(x) = \left(\sum_{i=0}^{n-1} a_i x^i\right) \oplus \left(\sum_{i=0}^{n-1} b_i x^i\right) \triangleq \sum_{i=0}^{n-1} (a_i \oplus b_i)\, x^i. \tag{17}$$

Using (16)–(17), the packets sent from nodes A, B and C to node M are expressed as follows:

$$p_{a,\text{sent}}(x) = p_a(x), \tag{18}$$
$$\begin{aligned} p_{b,\text{sent}}(x) &= x p_a(x) \oplus x p_b(x) \\ &= \sum_{i=0}^{n-1} (a_i \oplus b_i) x^{i+1} = x\left\{p_a(x) \oplus p_b(x)\right\}, \end{aligned} \tag{19}$$
$$\begin{aligned} p_{c,\text{sent}}(x) &= x p_a(x) \oplus x p_c(x) \\ &= \sum_{i=0}^{n-1} (a_i \oplus c_i) x^{i+1} = x\left\{p_a(x) \oplus p_c(x)\right\}, \end{aligned} \tag{20}$$

where $p_{b,\text{sent}}(x)$ and $p_{c,\text{sent}}(x)$ are XOR-coded packets with the original packets and $p_a(x)$ as indicated in (19) and (20). Notice that nodes B and C need one time-unit of delay to overhear packets sent from node A. Node M receives $p_{a,\text{sent}}(x)$, $p_{b,\text{sent}}(x)$ and $p_{c,\text{sent}}(x)$, and transmits the XOR of these three packets with appropriate delays to the foreground nodes, D, E and F. That is,

$$\begin{aligned} p_{m,\text{sent}}(x) &= x^2 p_{a,\text{sent}}(x) \oplus x p_{b,\text{sent}}(x) \oplus x p_{c,\text{sent}}(x) \\ &= x^2\left\{p_a(x) \oplus p_b(x) \oplus p_c(x)\right\}. \end{aligned} \tag{21}$$

In a similar fashion, node D sends

$$\begin{aligned} p_{d,\text{sent}}(x) &= x p_{d,\text{decoded}}(x) \\ &= x\left\{x p_{c,\text{sent}}(x) \oplus p_{m,\text{sent}}(x)\right\} = x^3 p_b(x), \end{aligned} \tag{22}$$

where there is only a three time-unit delay. Likewise, we can express $p_{e,\text{sent}}(x)$ as

$$\begin{aligned} p_{e,\text{sent}}(x) &= x p_{e,\text{decoded}}(x) \\ &= x\left\{x p_{b,\text{sent}}(x) \oplus p_{m,\text{sent}}(x)\right\} = x^3 p_c(x). \end{aligned} \tag{23}$$

Finally, the foreground node F hears the transmission channel of nodes D and E to obtain packets $p_{d,\text{sent}}(x)$ and $p_{e,\text{sent}}(x)$,

TABLE I
TRANSMITTED, RECEIVED AND OVERHEARD PACKETS AT EACH NODE.

Node / Time index	A	B	C	M	D	E	F
0	a_0 [none] (none)	none [none] (a_0)	none [none] (a_0)	none [a_0] (none)	none [none] (none)	none [none] (none)	none [none] (none)
1	a_1 [none] (none)	$a_0 \oplus b_0$ [none] (a_1)	$a_0 \oplus c_0$ [none] (a_1)	none [$a_1, a_0 \oplus b_0, a_0 \oplus c_0$] (none)	none [none] ($a_0 \oplus c_0$)	None [none] ($a_0 \oplus b_0$)	none [none] (none)
2	a_2 [none] (none)	$a_1 \oplus b_1$ [none] (a_2)	$a_1 \oplus c_1$ [none] (a_2)	$a_0 \oplus b_0 \oplus c_0$ [$a_2, a_1 \oplus b_1, a_1 \oplus c_1$] (none)	none [$a_0 \oplus b_0 \oplus c_0$] ($a_1 \oplus c_1$)	none [$a_0 \oplus b_0 \oplus c_0$] ($a_1 \oplus b_1$)	none [$a_0 \oplus b_0 \oplus c_0$] (none)
3	a_3 [none] (none)	$a_2 \oplus b_2$ [none] (a_3)	$a_2 \oplus c_2$ [none] (a_3)	$a_1 \oplus b_1 \oplus c_1$ [$a_3, a_2 \oplus b_2, a_2 \oplus c_2$] (none)	c_0 [$a_1 \oplus b_1 \oplus c_1$] ($a_2 \oplus c_2$)	b_0 [$a_1 \oplus b_1 \oplus c_1$] ($a_2 \oplus b_2$)	none [$a_1 \oplus b_1 \oplus c_1$] ($b_0$, c_0)
4	a_4 [none] (none)	$a_3 \oplus b_3$ [none] (a_4)	$a_3 \oplus c_3$ [none] (a_4)	$a_2 \oplus b_2 \oplus c_2$ [$a_4, a_3 \oplus b_3, a_3 \oplus c_3$] (none)	c_1 [$a_2 \oplus b_2 \oplus c_2$] ($a_3 \oplus c_3$)	b_1 [$a_2 \oplus b_2 \oplus c_2$] ($a_3 \oplus b_3$)	a_0 [$a_2 \oplus b_2 \oplus c_2$] ($b_1$, c_1)
5	a_5 [none] (none)	$a_4 \oplus b_4$ [none] (a_5)	$a_4 \oplus c_4$ [none] (a_5)	$a_3 \oplus b_3 \oplus c_3$ [$a_5, a_4 \oplus b_4, a_4 \oplus c_4$] (none)	c_2 [$a_3 \oplus b_3 \oplus c_3$] ($a_4 \oplus c_4$)	b_2 [$a_3 \oplus b_3 \oplus c_3$] ($a_4 \oplus b_4$)	a_1 [$a_3 \oplus b_3 \oplus c_3$] ($b_2$, c_2)
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
n-1	a_{n-1} [none] (none)	$a_{n-2} \oplus b_{n-2}$ [none] (a_{n-1})	$a_{n-2} \oplus c_{n-2}$ [none] (a_{n-1})	$a_{n-3} \oplus b_{n-3} \oplus c_{n-3}$ [$a_{n-1}, a_{n-2} \oplus b_{n-2}, a_{n-2} \oplus c_{n-2}$] (none)	⋮	⋮	⋮
n	none [none] (none)	$a_{n-1} \oplus b_{n-1}$ [none] (none)	$a_{n-1} \oplus c_{n-1}$ [none] (none)	$a_{n-2} \oplus b_{n-2} \oplus c_{n-2}$ [$a_{n-1} \oplus b_{n-1}, a_{n-1} \oplus c_{n-1}$] (none)	c_{n-3} [$a_{n-2} \oplus b_{n-2} \oplus c_{n-2}$] ($a_{n-1} \oplus c_{n-1}$)	b_{n-3} [$a_{n-2} \oplus b_{n-2} \oplus c_{n-2}$] ($a_{n-1} \oplus b_{n-1}$)	a_{n-4} [$a_{n-2} \oplus b_{n-2} \oplus c_{n-2}$] ($b_{n-3}$, c_{n-3})
n+1	none [none] (none)	none [none] (none)	none [none] (none)	$a_{n-1} \oplus b_{n-1} \oplus c_{n-1}$ [none] (none)	c_{n-2} [$a_{n-1} \oplus b_{n-1} \oplus c_{n-1}$] (none)	b_{n-2} [$a_{n-1} \oplus b_{n-1} \oplus c_{n-1}$] (none)	a_{n-3} [$a_{n-1} \oplus b_{n-1} \oplus c_{n-1}$] ($b_{n-2}$, c_{n-2})
n+2	none [none] (none)	none [none] (none)	none [none] (none)	none [none] (none)	c_{n-1} [none] (none)	b_{n-1} [none] (none)	a_{n-2} [none] (b_{n-1}, c_{n-1})
n+3	none [none] (none)	none [none] (none)	none [none] (none)	none [none] (none)	none [none] (none)	none [none] (none)	a_{n-1} [none] (none)

respectively. Thus, we have

$$\begin{aligned} p_{f,\mathrm{sent}}(x) &= x p_{f,\mathrm{decoded}}(x) \\ &= x \left\{ x p_{m,\mathrm{sent}}(x) \oplus p_{d,\mathrm{sent}}(x) \ \oplus p_{e,\mathrm{sent}}(x) \right\} \\ &= x^4 p_a(x). \end{aligned} \tag{24}$$

We note that $p_{f,\mathrm{sent}}(x)$ has only four time-unit delays from the time when node A starts to send packets to node M.

The coding gain can be defined as the ratio of the number of transmissions required by the no-coding approach, to the number of transmissions used by the proposed network coding scheme to deliver the same set of packets [6]. Thus, as the coding gain increases, the aggregate throughput and energy saving also increase. Our scheme's coding gain at node M is 1.5 (6/4), and node D (E) and F can forward its target packets continuously to nodes G (I) and J after only 3 and 4 time-unit delays, respectively. If n is sufficiently large, we can ignore the delay of 4 time-units. Hence, the aggregate throughput is 3 packets per time-unit. In the case of no network coding, the aggregate throughput in a 3-flow star-structure is 2 packets per time-unit, since a maximum of 4 channels can be assigned to the 6 links of the intersecting node M. Further, we can conclude that our network coding scheme decreases the energy consumption at node M.

With a 3-interface limit, our network coding scheme shows greater flexibility and performance than conventional network coding in coping with the aggregate throughput degradation due to the 3-interface limit, even if radio coverage limitations are ignored in the latter. With a 3-interface limitation, based on (5)–(8), our our network coding scheme leads to:

$$p_{d,\mathrm{sent}}(x) = \sum_{i=0}^{n-1} b_i x^{i+3} = x^3 p_b(x), \tag{25}$$

$$p_{e,\mathrm{sent}}(x) = \sum_{i=0}^{n-1} c_i x^{2i+4} = x^4 p_c(x^2), \tag{26}$$

$$p_{f,\mathrm{sent}}(x) = \sum_{i=0}^{n-1} a_i x^{2i+4} = x^4 p_a(x^2). \tag{27}$$

Ignoring radio coverage limitations, the conventional coding scheme that encodes all 3 packets with the channel assignment in (13)–(15) and a 3-interface limitation leads to:

$$p_{d,\text{sent}}(x) = \sum_{i=0}^{n-1} b_i x^{i+3} = x^3 p_b(x), \tag{28}$$

$$p_{e,\text{sent}}(x) = \sum_{i=0}^{n-1} c_i x^{3i+3} = x^3 p_c(x^3), \tag{29}$$

$$p_{f,\text{sent}}(x) = \sum_{i=0}^{n-1} a_i x^{3i+3} = x^3 p_a(x^3). \tag{30}$$

In (25)–(30), $x^m p_{node}(x^n)$ means the first packet gets to this stage from the original source node after an m time-unit delay, and the time duration between successive packets in a stream of packets is scaled by the factor of n. Thus, n significantly impacts the aggregate throughput. From (25)–(30), we see that with a 3-interface limitation, the aggregate throughput of the conventional network coding case and our network coding case are 1.66 and 2, respectively. Further, the aggregate throughput of the no-network coding case is 1.5, since, node M must assign 3 interfaces to the distinct 6 links that need interfaces for those links to be active at the same time slot. Note that the proposed scheme maintains the best aggregate throughput, when the maximum number of interfaces is reduced from 4 to 3, even if radio coverage limitations are ignored in the conventional network coding scheme.

D. Waiting Time for Coding Opportunity

The improvement from our scheme is significant, but it will be less than expected in a practical wireless network due to the outage of coding opportunities. Although the original source nodes of the background nodes A, B and C in Fig. 1(b) have consecutive packets, these packets may not arrive at nodes A, B and C successively, if the network is saturated. The reason is that co-channel interference will exist outside of the 3-flow star-structure, or between the outside and inside of it, and packet delays happen accordingly. Hence, coding opportunities at node M do not always happen when packets from nodes A, B or C arrive at node M. In Fig. 1(b), we assume that nodes A, B and C receive packets, which are to be sent to node M with the average receiving rates, R_A, R_B and R_C, respectively, from the corresponding previous-hop nodes. We also consider packet delays caused by co-channel interference. In the proposed scheme, node M needs all three packets $P1$, $P1 \oplus P2$ and $P1 \oplus P3$ to form $P1 \oplus P2 \oplus P3$. We derive the waiting time of packet $P1$ at node M to form $P1 \oplus P2 \oplus P3$, and define it as the waiting time for coding opportunity of $P1 \oplus P2 \oplus P3$. First, we define the probability of arrival, $p_{\text{arrival},A}$ at node M from node A through link l_{A-M}, as

$$\begin{aligned} &p_{\text{arrival},A} \\ &= \text{Prob}[\text{ node } A \text{ has a packet to send to node } M\ ] \times \\ &\quad \text{Prob}[\ l_{A-M} \text{ occupies channel } C_1 \text{ assigned to } l_{A-M} \mid \\ &\qquad \text{node } A \text{ has a packet to send to node } M\ ] \\ &= \left(\frac{R_A}{C_{ch}}\right) \times \left(\frac{f_{l_{A-M}}}{\sum_{l' \in I_{C_1}(l_{A-M})} f_{l'}}\right), \end{aligned} \tag{31}$$

where $I_{C_1}(l_{A-M})$ is the set of links within the interference area of l_{A-M} that are assigned the same channel C_1 that is assigned to l_{A-M}, C_{ch} is the channel capacity, and $f_{l_{A-M}}$ and $f_{l'}$ are the average traffic rates at links l_{A-M} and l', respectively. R_A is usually less than C_{ch}, since the channel assigned to the link between node A and its previous node should be shared with other links assigned the same channel within the interference area of that link. Thus, (R_A/C_{ch}) can be regarded as the probability that node A has the packet sent by the previous node, in a statistical sense. We call $\left(f_{l_{A-M}} \Big/ \sum_{l' \in I_{C_1}(l_{A-M})} f_{l'}\right)$ the effective channel share (ECS), as in [3], to denote the available bandwidth share, and it can be regarded as the probability that link l_{A-M} occupies the same channel assigned to some of the other links within the interference area of link l_{A-M}. In a similar manner, we can express $p_{\text{arrival},B}$ and $p_{\text{arrival},C}$ as follows:

$$p_{\text{arrival},B} = \left(\frac{R_B}{C_{ch}}\right) \times \left(\frac{f_{l_{B-M}}}{\sum_{l' \in I_{C_2}(l_{B-M})} f_{l'}}\right), \tag{32}$$

$$p_{\text{arrival},C} = \left(\frac{R_C}{C_{ch}}\right) \times \left(\frac{f_{l_{C-M}}}{\sum_{l' \in I_{C_3}(l_{C-M})} f_{l'}}\right). \tag{33}$$

Using (31)–(33), we derive the expected waiting time for the 3-packet coding opportunity as:

$$\begin{aligned} &\mathrm{E}\left[t_{\text{wait}}\right] = \sum_{i=1}^{\infty} i \Big[\\ &\left\{p_{\text{arrival},B}(1-p_{\text{arrival},B})^{i-1}\right\}\left\{1-(1-p_{\text{arrival},C})^{i-1}\right\} + \\ &\left\{p_{\text{arrival},C}(1-p_{\text{arrival},C})^{i-1}\right\}\left\{1-(1-p_{\text{arrival},B})^{i-1}\right\} + \\ &p_{\text{arrival},B}(1-p_{\text{arrival},B})^{i-1} \cdot p_{\text{arrival},C}(1-p_{\text{arrival},C})^{i-1}\Big]. \end{aligned} \tag{34}$$

The first term in (34) is the probability that the packet $P1 \oplus P2$ from B arrives at node M exactly on the i-th subsequent slot since packet $P1$'s arrival, and the packet $P1 \oplus P3$ from node C arrives at node M on any slot between the first and the $(i-1)$-th subsequent slot since packet $P1$'s arrival. The second term in (34) can be interpreted in a similar manner with nodes B and C replaced by each other. Finally, the third term in (34) is the probability that both the packets from nodes B and C arrive at node M exactly on the i-th subsequent slot since packet $P1$'s arrival.

Node M can forward subsequent packets to the next-hop node without waiting for a coding opportunity, while previous packets are waiting for their coding opportunity. In this case, the total number of coding opportunities, $N_{\text{coding opportunities}}$, is:

$$\begin{aligned} N_{\text{coding opportunities}} = \min\Bigg\{ &\frac{N_A}{\mathrm{E}[t_{\text{wait}}] \cdot p_{\text{arrival},A}}, \\ &\frac{N_B}{\mathrm{E}[t_{\text{wait}}] \cdot p_{\text{arrival},B}}, \frac{N_C}{\mathrm{E}[t_{\text{wait}}] \cdot p_{\text{arrival},C}}\Bigg\}, \end{aligned} \tag{35}$$

where N_A, N_B and N_C are the number of packets to be sent to node M from nodes A, B and C, respectively. As $p_{\text{arrival},B}$ or $p_{\text{arrival},C}$ decreases, $\mathrm{E}[t_{\text{wait}}]$ increases, and the number of possible coding opportunities decreases since the terms $\mathrm{E}[t_{\text{wait}}] \cdot p_{\text{arrival},A}$, $\mathrm{E}[t_{\text{wait}}] \cdot p_{\text{arrival},B}$, and $\mathrm{E}[t_{\text{wait}}] \cdot p_{\text{arrival},C}$

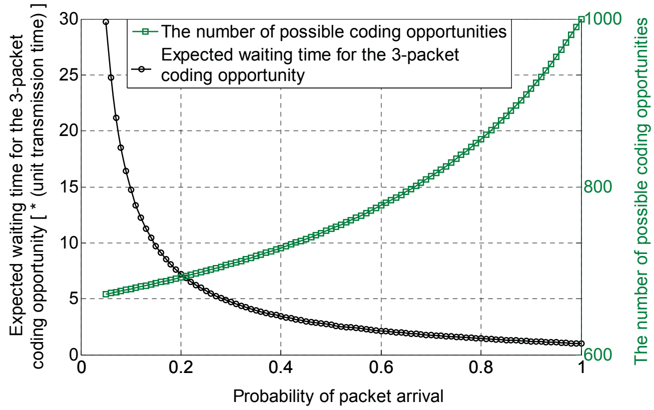


Fig. 2. Expected waiting time and the number of possible opportunities for 3-packet coding in a 3-flow star-structure.

increase. It is possible to attain a reasonable waiting time by a slight amendment of the protocols in a way similar to [6]. We provide graphs of $\mathrm{E}[t_{\text{wait}}]$ and $N_{\text{coding opportunities}}$ for $p = p_{\text{arrival},B} = p_{\text{arrival},C}$ and $N = N_A = N_B = N_C = 1000$ in Fig. 2.

Based on the above development, we propose two strategies: one for the network coding scheme, and the other for the channel assignment algorithm. First, we advocate that each intersecting node needs to set a different waiting time, based on the expected waiting time derived from the probability of packet arrival measured at each intersecting node. Second, in order to have a short expected waiting time, we must set a threshold for ECS, Th_{ECS}, and assign channels such that any link between the background nodes and their intersecting node has an ECS greater than Th_{ECS}.

III. Coding-aware Channel Assignment

We now propose a novel channel assignment algorithm that supports the proposed network coding scheme in a multi-channel/interface environment.

A. Prioritizing Metrics for Channel Assignment

The basic information needed for channel assignment is the network topology and average incoming and outgoing traffic rate of each link connected to each node. Regarding the network topology, every node is assumed to know its one-hop and two-hop neighbor nodes. This information is used to discover possible star-structures as defined in Sect, II-A. From this information, we can calculate the metrics presented in this section. The coding efficiency at the intersecting node M is defined as:

$$\eta_c^M = \sup\left[\sum_{l=1}^{k}\left[\left(\left|F_c^M(l)\right| - 1\right)\cdot \min\left\{F_c^M(l)\right\}\right]\right], \quad (36)$$

where

$$F_c^M(l) \subseteq F_{in}^M(l), \quad (37)$$
$$F_{in}^M(l+1) = \Big\{x : \left[\left(x + \min F_c^M(l)\right) \in F_c^M(l) \text{ and } x \neq 0\right] \text{ or } x \in F_{in}^M(l) \setminus F_c^M(l)\Big\}, \quad (38)$$

and $F_{in}^M(1)$ is the set of all original incoming traffic rates at node M. Subset $F_c^M(l)$ is an arbitrary subset of $F_{in}^M(l)$, the set of remaining average incoming rates, which can be partially or fully combined by XOR-ing at the intersecting node M. The term $\min\{F_c^M(l)\}$ is the average traffic rate which can be maximally combined together via XOR-ing in $F_c^M(l)$. Note that sup is included in (36) to account for the arbitrary way of determining $F_c^M(l)$ and, hence, $F_{in}^M(l+1)$ from $F_{in}^M(l)$.

The parameter η_c^M can be regarded as the maximum average traffic rate that can be saved by our network coding scheme. We define the weighted coding efficiency (WCE) as:

$$\mathrm{WCE}^M = \alpha\, \eta_c^M + (1-\alpha)\, f_{\max}^M \ . \quad (39)$$

Here, $f_{\max}^M$ is the maximum average traffic rate at a link between one background node and an intersecting node; α is a weight tunable from 0 to 1. We can view (39) as a tradeoff between the performance of the entire network and that of a local path. If we emphasize the second term, the throughput of paths that traverse this maximum average traffic rate link will be increased. On the other hand, if we give a higher weight to the first term, the coding efficiency becomes a more important factor, which improves the aggregate throughput.

In addition to the WCE, we define another metric to consider loads at foreground nodes. We define the average available interface capacity (AAIC) of the foreground nodes at a star-structure with intersecting node M as:

$$\mathrm{AAIC}_{\text{Fore}}^M = \sum_{s\in S_f} C_{A,\text{interface}}^s \Big/ |S_f|, \quad (40)$$

$$C_{A,\text{interface}}^s = \min\left\{N_{\text{interface}}^s, N_{\text{outflow}}^s\right\}\cdot C_{ch} - \sum f_{\text{out}}^s, \quad (41)$$

where $C_{A,\text{interface}}^s$ is the available interface capacity (AIC) at node s, and $N_{\text{interface}}^s$ and N_{outflow}^s are the number of interfaces and the number of outgoing flows at node s, respectively. Further, S_f is the set of all foreground nodes, and $\sum f_{\text{out}}^s$ is the summation of the average outgoing traffic rates at node s. A low $\mathrm{AAIC}_{\text{Fore}}^M$ means that the links for foreground cooperation should be assigned more available channels so that the foreground nodes can immediately occupy the assigned channels when their busy interfaces become available.

B. Declaration of Star-structures and the Dominant Set

To obtain high efficiency, it is vital to determine which parts of a given network are to be declared meaningful star-structures, based on traffic patterns. We identify a star-structure when the incoming flow from any background node to an intersecting node has an average traffic rate greater than half the channel capacity, and the difference of the average traffic rates between any two incoming flows from background nodes to an intersecting node does not yield an average traffic rate that is greater than a quarter of the channel capacity. These threshold values can also be adjusted. In addition, any single link that has an average traffic rate greater than the minimum WCE of selected star-structures can be identified. With such single links and star-structures, we compose the dominant set,

S_D, as:

$$S_D = S_{D,\ \mathrm{star-structure}} \bigcup S_{D,\ \mathrm{single\ link}}\ , \tag{42}$$

$$\begin{aligned} &S_{D,\ \mathrm{star-structure}} \\ &\quad = \Big\{ S : f_{l_{X-M}} < \frac{1}{2}C_{ch}, \forall X, M \in S \text{ s.t. } X \text{ is a} \\ &\qquad \text{background node. } \& \ \left|f_{l_{Y-M}} - f_{l_{Z-M}}\right| \le \frac{1}{4}C_{ch}, \\ &\qquad \forall\, Y, Z \in S \text{ s.t. } Y, Z \text{ are background nodes.} \Big\}, \\ &S_{D,\ \mathrm{single\ link}} = \Big\{ L : \exists S \in S_{D,\ \mathrm{star-structure}} \text{ s.t.} \\ &\qquad f_l \ge \mathrm{WCE}^M \text{ for } l \in L, M \in S \Big\}, \end{aligned}$$

where M is an intersecting node and $f_{l_{X-M}}$, $f_{l_{Y-M}}$ and $f_{l_{Z-M}}$ are the average traffic rates at links l_{X-M}, l_{Y-M} and l_{Z-M}, respectively. Notice that an element of S_D is the set composed of all links and nodes in a star-structure, or the set of a single link and its two end-nodes.

C. Coding-Aware Channel Assignment Algorithm

Our channel assignment algorithm is basically a centralized one, but it can be applied to a local star-structure in a distributed manner. Table II summarizes the entire algorithm, and additional points are presented in this section.

The preparation for transmitting coded packets is completed via background node cooperation, and foreground node cooperation is merely used to forward decoded packets more efficiently. For this reason, channel assignment for background node collaboration is much more important than that for foreground node collaboration. Hence, the foreground nodes are assigned channels in Step 2-c after the background nodes, intersecting nodes and single links are assigned channels in Step 2-b. In (1)–(4), $g_{\mathrm{Inter},M}$ is assigned first, and then $g_{\mathrm{Back},A}$, $g_{\mathrm{Back},B}$ and $g_{\mathrm{Back},C}$ are assigned in the order of outgoing traffic to node M through links e_1, e_3 and e_2, respectively.

For the whole channel assignment algorithm, the problem as to which channel should be assigned to a given group of links is important. The most appropriate channel is selected based on the available channel capacity at the transmitting link in each group as follows:

$$C_g = \begin{cases} \underset{C \in S_{ch}}{\arg\max} \left\{ C_{ch,C} - \sum_{l \in I_C(g)} f_l \right\}, \\ \qquad \text{if } \exists\ c \in S_{ch} \text{ s.t. } \left(C_{ch,C} - \sum_{l \in I_C(g)} f_l \right) \ge 0. \\ \underset{c \in S_{ch}}{\arg\max} \left\{ f_g \Big/ \sum_{l \in I_C(g)} f_l \right\}, \ \text{otherwise.} \end{cases} \tag{43}$$

Here S_{ch}, C_g and $C_{ch,C}$ are the set of all channels, the channel that will be assigned to all elements in group g and the capacity of channel C, respectively. Parameters $I_C(g)$, f_g and f_l are the set of links assigned to the same channel C as group g within the interference area of any element of group g, the sum of the average traffic rates of all transmitting links in group g, and the average traffic rate of link l in $I_C(g)$, respectively. Notice that f_g is also included in $\sum_{l \in I_C(g)} f_l$. We refer to $\left(C_{ch,C} - \sum_{l \in I_C(g)} f_l \right)$ as the remaining available channel capacity (RACC). If any channel is not overloaded after additionally assigning it to group g, we expect that this channel can support all traffic flows within the interference area of g. We also select C_g such that its ECS is greater than Th_{ECS} only in Step 2-b, as mentioned in Sect. II-D. If some channels have a tie, the channel used in the corresponding star-structure has the lowest priority, and the one assigned to other star-structures outside the interference area has the highest priority. The rationale for this policy is that we can save the available capability of the other channels for the remaining neighbors of other star-structures.

TABLE II
CODING-AWARE CHANNEL ASSIGNMENT ALGORITHM.

Step 1: Declare star-structures and the dominant set S_D. (described in III.B)
Step 2: Assign channels to all the links in S_D. a. Evaluate the WCE and prioritize all elements of S_D: The element with a larger WCE has the higher priority for channel assignment. b. Assign channels to the background nodes and intersecting node of each star-structure, and each single link, according to the priority. c. Assign channels to the foreground nodes of star-structures in the order from the lowest to the highest $\mathrm{AAIC}^M_{\mathrm{Fore}}$. d. Assign additional interfaces/channels to links that are already overhearing links, if there is traffic in the links.
Step 3: Cluster by assigning channels to one-hop and then two-hop neighbors of S_D in the order from the lowest to the highest $\mathrm{AIC}^s_{\mathrm{All}}$.
Step 4: Assign channels to all remaining links in the order from the lowest to the highest $\mathrm{AIC}_{\mathrm{All}}$.

In Step 2-c, groups $g_{\mathrm{Fore},D}$, $g_{\mathrm{Fore},E}$ and $g_{\mathrm{Fore},F}$ in (1)–(4) are assigned channels in the order of outgoing traffic to nodes G, I and J through links e_7, e_8 and e_9, respectively. Step 2-d assigns additional interfaces/channels to all remaining links at star-structures. It includes overhearing links where there is traffic other than the traffic to be overheard. If a link is already determined to be an overhearing link, it has a higher priority than non-overhearing links. If no additional interfaces exist to be assigned to an overhearing link, then the link shares an overhearing channel. The priorities of star-structures are in the order of the WCE as in Step 2-a and, in turn, all remaining links in a one star-structure are prioritized comparing their $\mathrm{AAIC}_{\mathrm{Fore}}$. This prioritizing rule is also applied to Step 3. We define AIC for all traffic at a given node, s, as follows:

$$\mathrm{AIC}^s_{\mathrm{All}} = \min\left\{ N^s_{\mathrm{interface}}, N^s_{\mathrm{non-zero\ link}} \right\} \cdot C_{ch} - \sum_{l \in L(s)} f^s_l \tag{44}$$

where node s has $N^s_{\mathrm{interface}}$ interfaces and $N^s_{\mathrm{non-zero\ link}}$ links each of which has non-zero average traffic rates, f^s_l, for link l, and $L(s)$ is the set of all links connected to node s. A small $\mathrm{AIC}_{\mathrm{All}}$ means that the remaining available capacity that interfaces can support is low.

A star-structure is the area where many flows are gathered from and dispersed to its neighbors, resulting in high traffic in many of its neighbors. To exploit coding gain efficiently, these neighbors should provide the star-structure with high traffic. Accordingly, Step 3 is separated from Step 4, and has a higher priority. We can extend Step 3 to 3 or 4-hop neighbors depending on the assumption of the interference distance, defined as the distance from a node within which other nodes cannot use the channel assigned to that node in the same time slot due to co-channel interference.

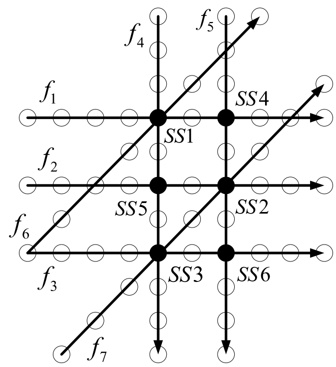


Fig. 3. Evaluation Scenario with seven flow, three 3-flow star-structures, and three 2-flow star-structures.

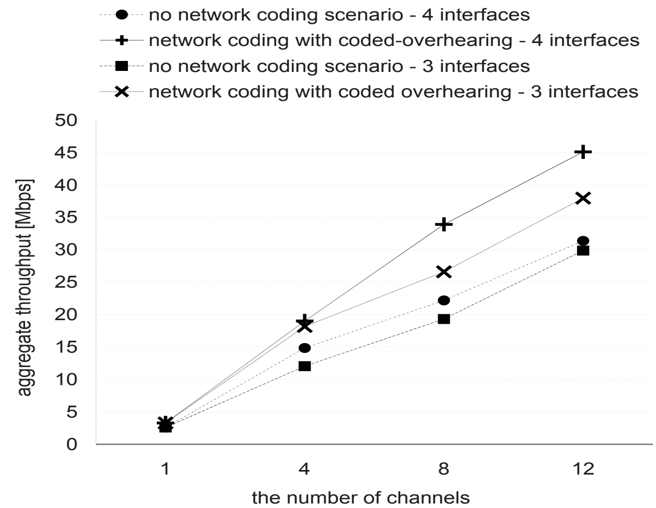


Fig. 4. Aggregate throughput in the no-coding scenario and the network coding with the coded-overhearing scenario.

IV. Performance Evaluation

A. Evaluation Scenario

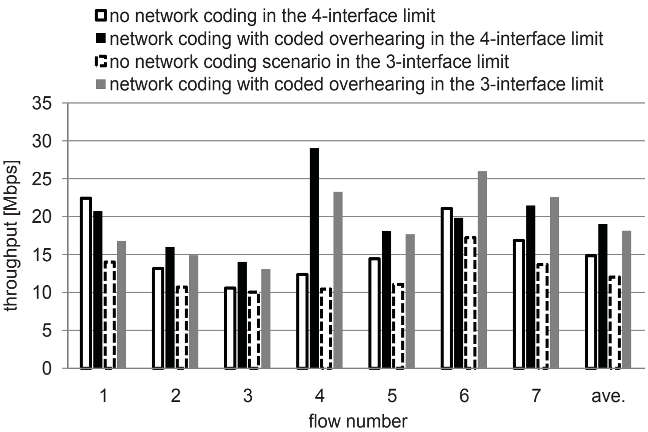
We verify that our network coding and channel assignment schemes can achieve substantial improvement in aggregate throughput via simulation. Although our simulations are based on only one example network topology and simulation results will vary with the network topology and routing, our example network topology is representative of a traffic saturation area such as the nodes around the gateway in wireless mesh networks for last-mile connectivity. Future work may consider arbitrary network topologies and new routing algorithms matched to our network coding scheme.

In the simulation, the proposed channel assignment algorithm is first applied to the network. In the baseline, no-coding scenario applies the channel assignment algorithm in [3], which is one of the most efficient known algorithms. We assume 54 Mbps channel capacity, two-hop interference distance and one-hop communication distance in the square grid network in Fig. 3. It is also assumed that any one-hop and two-hop neighbors of both a transmitting and receiving node cannot simultaneously use the channel with which packets are being sent from the transmitting to the receiving node. The simulation considers delays and packet losses from co-channel interference. We use almost the same protocols and modified packet headers as in [6]. In Fig. 3, every node except those at the outermost periphery can have eight neighbors. We set $\alpha = 0.5$, and $Th_{\mathrm{ECS}} = 1$ for 8- and 12- channel scenarios, and Th_{ECS} = 0.1 for the 4-channel scenario, since 4 channels is not sufficient to have a high ECS. Both 4- and 3-interface limits are considered. In Fig. 3, there are 7 flows from 6 source nodes to 7 destination nodes, 3 intersecting nodes of 3-flow star-structures, $SS1$, $SS2$ and $SS3$, and 3 intersecting nodes of 2-flow star-structures, $SS1$, $SS2$ and $SS3$. We varied the number of channels supported by the network with 1, 4, 8, and 12 channels, and set the number of packets at each node proportional to the average traffic information.

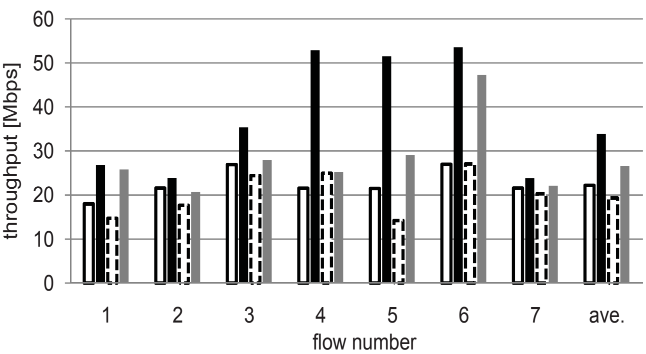
We emphasize that we considered different waiting times, varying from 1 to 7 transmission times at each intersecting node of 3-flow star-structures, and chose the best results. The best results on the 4-interface limitation are obtained when the waiting time sets are $\{3, 7, 1\}$, $\{2, 6, 6\}$ and $\{5, 6, 2\}$ in 4, 8 and 12-channel scenarios, respectively. The waiting time set means $\{\text{waiting time at } SS1, \text{waiting time at } SS2, \text{ waiting time at } SS3\}$ in the order named, and the unit of each element in a waiting time set is the unit packet transmission time. Within a 3-flow star-structure, the expected waiting time can be derived analytically as (34). However, in a set of several star-structures such as Fig. 3, where star-structures are connected to one another, the waiting time at a star-structure affects the waiting time at other star structures. In such cases, distributed algorithms can be used to assign channels and adjust waiting time at each independent node with the estimated average packet receiving rates in (31)–(33). However, this issue is outside of the scope and contribution of this paper.

B. Simulation Results

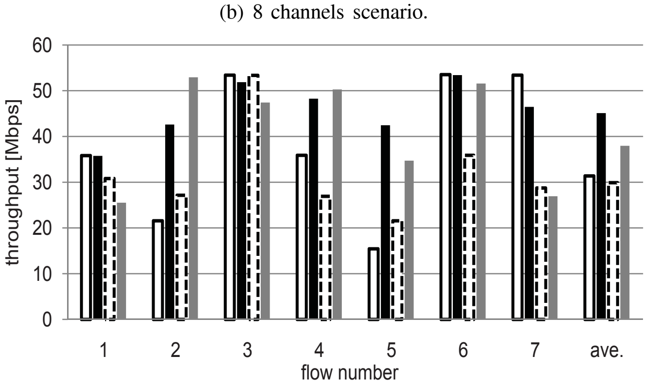
Fig. 4 shows aggregate throughput for all scenarios, against the number of channels and interface limits. In the 4-interface limit, our scheme increases the aggregate throughput over the no-coding scheme by 26%, 28%, 52%, and 43%, for the case of 1, 4, 8, and 12 channels, respectively. In the case of the 3-interface limit, these improvements are 26%, 50%, 37%, and 27%, respectively. Notice that our algorithm with a 3-interface limit outperforms the no-coding scheme with a 4-interface limit. Further, for the 4-interface limit, our scheme with 8 channels shows better aggregate throughput than a no-coding scheme with 12-channels. As the number of channels increases, the difference between the aggregate throughput of our network coding scheme and the no-coding scenario grows larger. However, the aggregate throughput also depends the number of interfaces. As mentioned in Sect. II-B, based on (1)–(4) and (5)–(8), in the case of our network coding scheme with a 3-flow star-structure and 4 and 3-interface limits, we can use a maximum of 7 and 5 channels, respectively, to mitigate packet delays. For this reason the ratio of the aggregate throughput in our network coding scenario to that of the no-coding scenario is the highest at 8-channels for the 4-interface case (52%) and at 4-channels for the 3-interface case (50%), which are near the maximum number of channels that can be used, i.e., 7 and 5 in each case.



(a) 4 channels scenario.



(b) 8 channels scenario.



(c) 12 channels scenario.

Fig. 5. Throughput for each flow in the different scenarios in terms of interface limitation and the number of channels.

We present the throughput of each flow for every scenario in Fig. 5. With 4 channels, which are not sufficient to avoid serious co-channel interference, and a 3-interface limit, every flow experiences significant improvement (Fig. 5(a)). In Fig. 5(b), when there are 8 channels, flows f_4, f_5 and f_6 have much improvement since f_4 and f_5 pass through 3 intersecting nodes so that the impact of the proposed network coding scheme is high, and f_6 passes only 1 intersecting node $SS1$, where all the incoming flows have not spent time waiting coding opportunities at the intersecting nodes before those flows arrive at $SS1$. The other two flows exceed a satisfactory rate, such as above 33 Mbps, in the 4-interface limit. Further, in the 3-interface limit, the flows which had showed unsatisfactory throughput of around 15 Mbps without our algorithm, increased by up to approximately 25 Mbps, thus increasing the aggregate throughput by up to 37%. In Fig. 5(c), we can see that having 4 interfaces and 12 channels, all flows are above the satisfactory level of traffic rate and the aggregate throughput is improved by 52%.

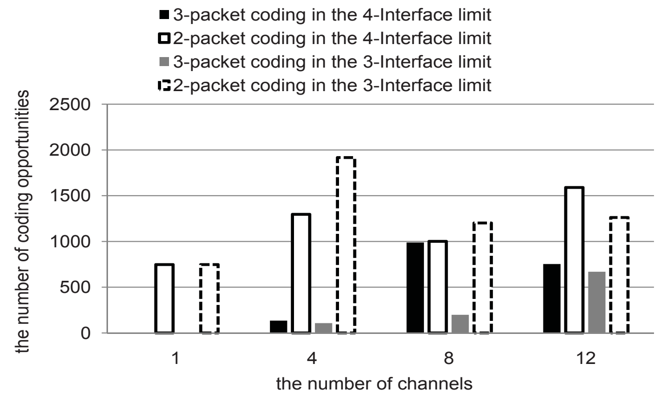


Fig. 6. The total number of coding opportunities at 3-flow star structures.

Fig. 6 summarizes the total number of coding opportunities that occur at 3-flow star-structures whose intersecting nodes are $SS1$, $SS2$ and $SS3$. As we examined in Sect. II-A, taking into account the radio coverage limitations, 3-packet coding opportunities in Fig. 6 are rare in conventional network coding schemes, but they happen frequently with coded-overhearing. In the 4-interface limit, 3-packet coding opportunities with 8 and 12 channels are about 100% and 50% greater than 2-packet coding opportunities, respectively. In the case of 12 channels, during the waiting time for 3-packet coding, 2-packet coding with the subsequent packets happens more frequently than in 8-channel scenario. Thus 3-packet coding opportunities are less than that in 8-channel scenario. The additional gain from 3-packet coding is attributed to our new collaboration scheme of network coding and channel assignment.

V. Conclusions

We proposed a novel scheme of multi-channel/interface network coding collaboration. Our analysis and evaluation proved that the combination of our network coding scheme and the coding-aware channel assignment algorithm is capable of achieving substantial improvement in the achievable aggregate throughput. Potential future research directions are: (1) more general multi-channel/interface collaborative network coding schemes, which take into account traffic patterns and directions; and (2) distributed channel assignment algorithms that cope with traffic variations.

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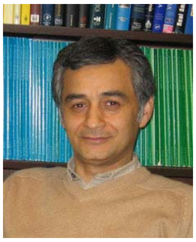

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