Towards Coding-Efficient Link-Scheduling and Coding-Aware Routing in Wireless Networks

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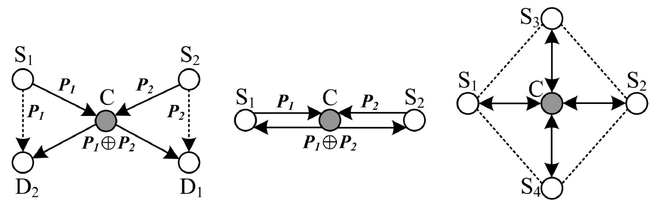
I. Motivation

Network coding has been shown to be able to improve the throughput of wireless networks. In [1], the authors propose the practical coding scheme as shown in Fig. 1. Consider the example in Fig.1(a), suppose node S_1 wants to transmit a packet P_1 to node D_1 via node C, while node S_2 wants to transmit P_2 to D_2 via node C. The dashed arrows $S_1 \dashrightarrow D_2$ and $S_2 \dashrightarrow D_1$ indicate that D_2, D_1 are within the transmission ranges of S_1, S_2 respectively. Therefore, D_1, D_2 can perform "*opportunistic listening*": when S_1 (S_2) transmits P_1 (P_2) to node C, node D_2 (D_1) can overhear the transmission of P_1 (P_2). Without network coding, node C needs to transmit P_1 and P_2 separately. However, when one uses the XOR coding scheme, node C can broadcast an encoded packet ($P_1 \oplus P_2$) to both D_1 and D_2, then D_1 can decode P_1 by performing $P_2 \oplus (P_1 \oplus P_2)$, while D_2 can decode P_2 by performing $P_1 \oplus (P_1 \oplus P_2)$. Therefore, node C delivers two packets worth of information using a single transmission so that $1/4$ of the bandwidth is saved. Another typical coding scenario is shown in Fig.1(b), where *no* opportunistic listening is required because each of the two source nodes are also destination nodes. Finally, Fig.1(c) shows a *hybrid form* of coding which combines the former two cases.



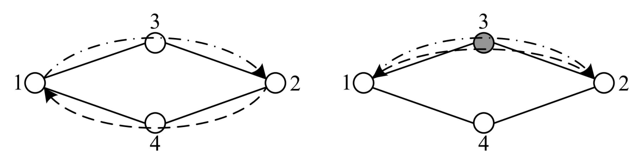
(a) Coding scenario with opportunistic listening. (b) Coding scenario without opportunistic listening. (c) Hybrid scenario.

Fig. 1. Basic scenarios of the coding scheme under idealized link-scheduling.

Essentially, the coding scheme utilizes the *broadcast nature* of wireless channel to conduct the *opportunistic listening* and *encoded broadcast*, such that the necessary number of transmissions for the coding node (i.e., node c in Fig. 1) can be reduced. The coding scheme in [1] works independently with the MAC and routing layer. However, the performance of the coding scheme is crucially dependent on the link-scheduler used and the routing decision, as we will discuss in the following.

To illustrate the effect of link-scheduling on the coding performance, let us consider Fig. 1(a) again. If the link-scheduling is such that the transmitters always transmit following the cycle of $S_1, S_2, C, \cdots$ (or $S_2, S_1, C, \cdots$), then node C can always encode two packets and maximize the total throughput. However, if the link-scheduling is $S_1, C, S_2, C, S_1, C, \cdots$, then node C can not encode any packets. In practice, most of the wireless link-scheduling algorithms are *probabilistic* in nature and *non-coding-oriented*, i.e., the potential coding opportunity may not be fully utilized.

To illustrate the effect of routing decision, let us consider Fig. 2 for an example. There are two flows, $1 \rightarrow 2$ and $2 \rightarrow 1$, to be routed. If we use a *load-aware* routing that finds disjoint paths, the traffic pattern may end up like Fig. 2(a). However, if we increase the coding opportunity by using the routes shown in Fig. 2(b), node 3 becomes a coding node and the total throughput can be increased. We define *coding-aware routing* to be the routing algorithm that takes into account of potential coding opportunities and maximizes end-to-end throughput for the flow to be routed.



(a) Routing without coding consideration. (b) Routing with network coding at node 3.

Fig. 2. An example showing the effect of routing decision on coding opportunity.

Inspired by the above two observations, we study how to incorporate coding consideration into the current link-scheduling and routing algorithms. There exists several interesting problems, e.g., can we quantify the performance of the practical coding scheme under random access link-scheduling? Do we need a "coding-oriented" link-scheduler? How to incorporate potential coding opportunity into the routing decision in a *distributed* way? More fundamentally, what is the throughput by the coding scheme for a network with general topology?

II. Our Approach

Our approach is as follows. For modeling the effect of random access link-scheduling, we define a key performance measure—"encoding number", which is equal to the number of packets that a coding node encodes in each transmission. We first (in Section II-A) give an upper bound on the encoding number in any possible coding structures, and then (in Section II-B) derive the average encoding number under a general class

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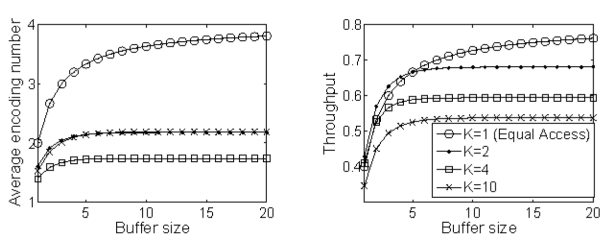
of random access mechanisms. In particular, we characterize the interplay of throughput, buffer size and the random access mechanism used. For the coding-aware routing, we (in Section II-C) propose a novel routing algorithm that combines the discovery processes for available paths and potential coding opportunities. Finally, in Section II-D, we provide a tight upper bound on the throughput gain by using the coding scheme for a general wireless network.

A. Physical Upper Bound of the Encoding Number

In a generic coding structure, there is one coding node and n coding flows whose packets can be encoded by the coding node. Clearly, the encoding number in this coding structure is at most n. In [1], the authors assume that n is unbounded because there can be infinite nodes surrounding the coding node. However, we show that due to physical limitations of the wireless channel and the geometrical constraints for proper decoding, n is indeed upper bounded by a small constant determined by the physical layer parameters. In particular, the upper bound is $O\big((r/\delta)^2\big)$ for 2D space, and $O\big((r/\delta)^3\big)$ for 3D space, where r is the "reliable transmission range" between the a transmitter and a receiver, and δ is the channel parameter such that the receiver with a distance larger than $r+\delta$ can only hear the transmission with a very low probability. For more details, please refer to [5].

B. Coding Performance under Random Access

We quantify how random access affects the throughput of the coding scheme, which is crucially dependent on the *"encoding number"*. The key insight in modeling the coding performance is that the encoding number is closely related to the *buffer status* of the coding node. We use a stochastic model to capture the dynamics of the coding node's buffer, and propose a methodology to calculate the capacity region of the coding structure. Please refer to [5] for details of the methodology. For the random access, we are particularly interested in two generic mechanisms: 1) "equal access", i.e., each node has equal channel access priority as in DCF of 802.11; 2) higher priority for the relay (coding) node. Surprisingly, we find that the simple "equal access" outperforms the more sophisticated "high priority" in most cases especially when the buffer size for each flow is relatively large (say greater than 10). For the saturated case, we use the model to calculate the average encoding number and total throughput of the coding structure. Fig. 3 shows an example of the results for 4 coding flows, where K indicates the priority of the coding node, and $K=1$ is simply the "equal access".



(a) Average encoding number. (b) Total throughput.

Fig. 3. Interplay of buffer size (M), encoding number, random access and throughput under saturation.

In addition, one may also consider letting the coding node hold transmission until it can encode more packets. We systematically define such scheduling method, and show via both analysis and simulation that such scheduling is *not* necessary for the coding scheme, and can perform even worse than the "equal access". Therefore, the simple "equal access" with moderate buffer size is surprisingly the *coding-efficient link-scheduler*.

C. Distributed Coding-Aware Routing

We briefly introduce the idea of distributed coding-aware routing as follows. We use a DSR-like on-demand routing, and let each node maintains a list of its one-hop neighbors. When a new flow is to be routed, the source node floods Routing Request (RREQ) into the network. Each sender of the RREQ piggybacks its one-hop neighbors into the RREQ, such that the information on "opportunistic overhearing" gradually gets accumulated as the RREQ travels through the network. Upon receiving the RREQ, the destination node sends Routing Reply (RREP) via the reverse path. When RREP reaches an intermediate node, the node can explore possible coding structures by using the path information and overhearing information. If there is coding opportunity, the node marks itself as "coding-possible" in the RREP packet. When all RREPs returns to the source node, a routing decision is made by choosing a path with maximum end-to-end throughput.

D. Fundamental Limits of the Coding Scheme

For a general wireless network, the coding scheme only brings *local improvement* and such improvement can be limited by other *non-coding* flows. We show that the throughput gain for the general wireless network is bounded by $2n/(n+1)$, where n is the maximum encoding number in one of its coding structures. Denoting M as the buffer size for each flow, the upper bound can be approximated as $2n/(n+\frac{M}{M+1})$ under equal access.

E. Future Work

We have established fundamental understanding on how the coding scheme works under a realistic physical layer and practical link-scheduling algorithms. In the future, we aim at a complete system solution to incorporate network coding into the MAC and routing protocols, which can achieve higher efficiency in using potential coding opportunities and provide higher throughput. Our results can serve as the prototype for future design of wireless networks embracing the network coding technology.

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