

# High-Throughput Routing with Superposition Coding and Successive Interference Cancellation

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**Abstract**—Network coding aware routing protocols have been an interesting research topic in recent years. In this paper, we explore similar routing gains with physical layer coding techniques. A source routing protocol S3 is proposed to be implemented with a routing metric called iETT. By extending the traditional ETT measurement, iETT provides a simple way to make the routing protocol interference-aware. To further enable superposition coding and successive interference cancellation, S3 uses iETT to explore physical layer coding opportunities and measure potential gains in network throughput. Experimental evaluations confirm the effectiveness of iETT and S3. Significant improvements in network throughput are observed in both single-path and multi-path routing scenarios.

**Index Terms**—Wireless mesh networks, source routing, superposition coding, successive interference cancellation.

## I. INTRODUCTION

Superposition coding (SC) and successive interference cancellation (SIC) are well-known physical layer techniques [10]. The former enables simultaneous unicast transmissions from a single sender to multiple receivers, and the latter enables simultaneous unicast transmissions from multiple senders to a single receiver. More specifically, signals are mixed on the physical layer, either due to the single sender performing the superposition coding, or the multiple senders transmitting simultaneously. When receivers receive the signal, they apply successive interference cancellation to decode information destined for them. Interested readers are referred to [10], [33], [21] for more details.

A measurement study [18] has shown that, in a typical wireless mesh network (WMN), due to the device placement and environmental diversity, even with equal transmission power, the quality of the resulting channel may vary a lot. According to the Shannon capacity formula, the capacity  $C(\cdot)$  of the additive white Gaussian noise channel with noise variance  $N_0$  is defined as

$$C\left(\frac{P}{N_0}\right) = B \log_2\left(1 + \frac{P}{N_0}\right), \quad (1)$$

where  $B$  is the bandwidth,  $P$  is the power of the transmitted signal, and the ratio  $P/N_0$  represents the SNR which determines the channel capacity. The difference of channel quality

in terms of SNR then leads to the different capacity of these channels.

On the one hand, in a 802.11-based wireless mesh network, the data rates only consist of several discrete values, ranging from 6 Mbps to 54 Mbps.<sup>1</sup> Under the condition of fixed transmission power, each device tries its best to utilize the limited resource and adopts a data rate as high as possible. However, if the transmission power exceeds the level for the highest achievable data rate, but is not enough for the next higher rate, the excess amount of resource is wasted. This inspires the work of applying superposition coding to WMNs to greedily improve the network throughput [19]. We call this approach *downlink superposition coding*, where the single sender splits its transmission power into two parts, for simultaneous transmission to two different receivers. The receivers then decode the signal destined for them by successive interference cancellation.

On the other hand, there is the case when two senders are sending traffic to the same receiver, over channels of different quality. In the traditional 802.11 MAC protocol, both senders share the airtime and transmit in turn. This strategy greatly restricts the throughput of the whole network. A better approach would be allowing both senders to transmit simultaneously, and enabling the receiver to decode both signals using successive interference cancellation. We call this approach *uplink successive interference cancellation*.

To briefly sum up, channel diversity makes both downlink superposition coding and uplink successive interference cancellation applicable. However, each of them has a different requirement: downlink superposition coding requires good allocation of transmission power, while uplink successive interference cancellation requires good synchronization. While there have been previous work in communication theory community [10], [33] on the fundamentals of SC and SIC, and in networking community [21], [19] on some heuristic applications for improving network performance, we aim to provide a missing piece to closely tie the two directions together. We present a systematic design of end-to-end routing metric as well as routing protocol, to truly reap the benefit of both techniques.

The remainder of this paper is organized as follows. Section II discusses a routing metric based on a simple extension

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<sup>1</sup>In this paper, we only consider the 802.11a, b, g standards.

of the expected transmission time (ETT) [13]. Section III elaborates on the routing protocol design that includes three steps to create coding opportunities in both uplink and downlink manners. Following that, Section IV discusses the implementation of the proposed protocol on GNU radio platform. Experimental results in both single-path and multi-path routing scenarios are also included. Section V reviews the literature and Section VI concludes the whole paper.

## II. ROUTING METRIC DESIGN: iETT

In this and next sections, we discuss our design considerations. For each aspect, we will also include motivating examples, where the potential improvement of adopting downlink superposition coding and uplink successive interference cancellation arises in common routing scenarios.

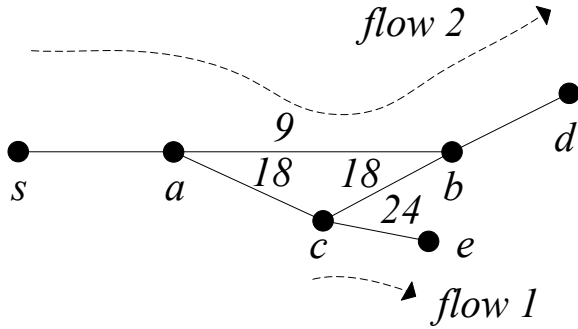


Fig. 1. An example network topology. The value over each link represents the achievable link rate.

Consider the network topology as shown in Fig. 1. Flow 1 is an existing active flow over link  $l_{ce}$ . The objective now is to find a good path for flow 2 that is from source node  $s$  to destination node  $d$ .

The normalized ETT [13] for a link  $l_j$  is computed as the inverse of the link rate

$$\text{ETT}(l_j) = \frac{1}{R_j}, \quad (2)$$

where  $R_j$  is the link rate of  $l_j$ .

In order to more accurately reflect the interfering neighborhood in a simple way, we extend ETT to include interference-awareness and refer this new metric as *interference aware ETT* (iETT). To roughly model the current 802.11 MAC, equal media access probability is assumed. Thus, the iETT value of link  $l_j$  is computed as

$$\text{iETT}(l_j) = \frac{1}{R_j} + \sum_q \sum_{l_k} \frac{\rho_k^q}{R_k^q}, \quad (3)$$

where  $q$  is an active node in the neighborhood,  $l_k$  is an interfering link adjacent to node  $q$ ,  $R_k^q$  is the link rate of  $l_k$ , and  $\rho_k^q$  denotes the fraction of link time occupied by the traffic from node  $q$  over  $l_k$ .

The essence of iETT is not to allow flows to use the channel resource simultaneously when they interfere with each other, in which case only time-sharing is allowed. For example, assuming flow 1 in Fig. 1 is infinitely backlogged,

then  $\rho_{ce}^c = 1$ . Therefore  $\text{iETT}(l_{ab}) = \frac{1}{9} + \frac{1}{24} = \frac{11}{72}$  and  $\text{iETT}(l_{ac}) = \text{iETT}(l_{cb}) = \frac{1}{18} + \frac{1}{24} = \frac{7}{72}$ .

Under this definition, the iETT value of a path  $L$  is calculated as

$$\text{iETT}(L) = \sum_{l_j \in L} \text{iETT}(l_j). \quad (4)$$

Note that this definition of iETT is a little conservative. For example, in Fig. 1, both  $\text{iETT}(l_{ac})$  and  $\text{iETT}(l_{cb})$  take into account the interference due to link  $l_{ce}$ . The sum of  $\text{iETT}(l_{ac})$  and  $\text{iETT}(l_{cb})$  thus double-counts the interference effect. As a result, this definition tends to penalize path  $a \rightarrow c \rightarrow b$  with more hops over path  $a \rightarrow b$ . However, this fact does have its advantage in practical networks, since longer paths are usually easily interfered and tend to have lower quality. Moreover, the routing protocol proposed in the following subsection could actually compensate this penalty, if superposition coding and successive interference cancellation are applicable.

## III. ROUTING PROTOCOL DESIGN: S3

The proposed routing protocol uses source routing, which allows a sender of a packet to specify the route the packet takes through the network. The routing protocol works in three steps to explore opportunities of enabling superposition coding and successive interference cancellation. We refer this routing protocol as the S3 (Source routing, Superposition coding, and Successive interference cancellation) routing protocol below.

**Step 1.** When the routing procedure begins, the source node  $s$  broadcasts route request (RREQ) packets. Each RREQ packet is modified so as to collect iETT of each link. Each node that receives RREQ inserts its ID and adds the iETT value of the incoming link into the packet. After that, it re-broadcasts the RREQ. After receiving the first RREQ packet, instead of extracting the path information immediately, the destination node  $d$  waits for a time period  $t_w$  to potentially allow other RREQ packets to arrive. After  $t_w$  expires,  $d$  picks up the RREQ packet with the least total iETT measurement. The path recorded in this packet is then extracted out as the chosen one for data packet forwarding.

In the example shown in Fig. 1, when both coding techniques are disabled, path  $a \rightarrow b$  with  $\text{iETT} = \frac{11}{72}$  is preferred over path  $a \rightarrow c \rightarrow b$  with  $\text{iETT} = \frac{7}{72} + \frac{7}{72} = \frac{14}{72}$ .

**Step 2.** During the routing procedure, when an upstream node that is aware of the possibility of adopting superposition coding receives the RREQ, it first inserts the iETT of the incoming link into the packet and re-broadcasts the RREQ normally. Then it calculates iETT for the part where superposition coding is applicable. If this could improve the throughput, it unicasts a special RREQ with the re-calculated iETT along the links which will potentially carry the superposed transmission. Upon receiving the unicast special RREQ, the recipient only inserts its ID and re-broadcasts the packet.

In the example shown in Fig. 1, when node  $c$  (the transmitter of the existing active flow) receives the RREQ from node  $a$ , it is aware of the possibility of adopting superposition coding along the links  $l_{ce}$  and  $l_{cb}$  to improve the performance. Therefore, it re-calculates the iETT value for  $\{l_{ac}, l_{cb}\}$  part. The calculation is carried out as follows.

Let the available power for each node be  $P$ . Without superposition coding,  $P$  is used for transmission at each link. Let  $\tau_1$ ,  $\tau_2$  and  $\tau_3$  be the active fraction in one unit of time for flows over  $l_{ac}$ ,  $l_{ce}$  and  $l_{cb}$  respectively. Define  $R_k(P/N_0) = C(P/N_0)$  to be the achievable data rate of link  $k$  when packets are transmitted with power  $P$ . The total end-to-end flow throughput over paths  $a \rightarrow c \rightarrow b$  and  $c \rightarrow e$  is then computed as

$$T = R_{l_{ac}} \left( \frac{P}{N_0} \right) \tau_1 + R_{l_{ce}} \left( \frac{P}{N_0} \right) \tau_2. \quad (5)$$

We also have the flow conservation condition

$$R_{l_{ac}} \left( \frac{P}{N_0} \right) \tau_1 = R_{l_{cb}} \left( \frac{P}{N_0} \right) \tau_3, \quad (6)$$

and the time conservation condition

$$\tau_1 + \tau_2 + \tau_3 = 1. \quad (7)$$

With superposition coding, let  $\tau'_1$ ,  $\tau'_2$  and  $\tau'_3$  be the active fraction in one unit of time for flows over  $l_{ac}$ ,  $\{l_{cb}, l_{ce}\}$  and  $l_{cb}$  respectively, where  $\{l_{cb}, l_{ce}\}$  denotes the links to carry the superposed transmission in which the transmission in  $l_{ce}$  is encoded as the first layer with power  $p$ . We want to maximize the total end-to-end throughput as

$$\begin{aligned} \max \quad & T' = R_{l_{ac}} \left( \frac{P}{N_0} \right) \tau'_1 + R_{l_{ce}} \left( \frac{p}{P-p+N_0} \right) \tau'_2, \\ \text{s.t.} \quad & R_{l_{ac}} \left( \frac{P}{N_0} \right) \tau'_1 = R_{l_{cb}} \left( \frac{P-p}{N_0} \right) \tau'_2 + R_{l_{cb}} \left( \frac{P}{N_0} \right) \tau'_3, \\ & \tau'_1 + \tau'_2 + \tau'_3 = 1, \\ & \tau'_1 \geq 0, \tau'_2 \geq 0, \tau'_3 \geq 0, \\ & 0 \leq p \leq P. \end{aligned} \quad (8)$$

The first constraint denotes the flow conservation over path  $a \rightarrow c \rightarrow b$ . The second constraint denotes the time conservation. We require that superposition coding is used only when the optimal value to the above program (8) is greater than the value computed by (5).

Due to the discrete transmission rates specified by the 802.11 standard, we can solve this optimization problem and compute the optimal  $\tau'_1$  by searching the optimal value of  $p$ . The details involve computing the SNR and looking up a table generated from [11]. Interested readers are referred to [21], [20].

Then the iETT with superposition coding is computed as

$$\text{iETT}(\{l_{ac}, l_{cb}\}) = \frac{1}{R_{l_{ac}} \left( \frac{P}{N_0} \right)} / \tau'_1. \quad (9)$$

In the example shown in Fig. 1, we could get  $R_{l_{ac}} \left( \frac{P}{N_0} \right) = 18$ ,  $R_{l_{cb}} \left( \frac{P-p}{N_0} \right) = 12$ ,  $\tau'_1 = 2/5$ ,  $\tau'_2 = 3/5$  and  $\tau'_3 = 0$  after solving the optimization problem. Then node  $c$  re-calculates the iETT value for  $\{l_{ac}, l_{cb}\}$  part as

$$\text{iETT}(\{l_{ac}, l_{cb}\}) = \frac{1}{18} / \frac{2}{5} = \frac{5}{36}. \quad (10)$$

When node  $b$  receives this special RREQ, it is aware of the  $\text{iETT}(\{l_{ac}, l_{cb}\})$  for the superposed transmission. Therefore,

node  $b$  does not add  $\text{iETT}(l_{cb})$  into the RREQ before re-broadcasting.

By taking advantage of downlink coding opportunity, path  $a \rightarrow c \rightarrow b$  with  $\text{iETT} = \frac{5}{36}$  is now preferred over path  $a \rightarrow b$  with  $\text{iETT} = \frac{11}{72}$  by the routing protocol.

**Step 3.** Similarly, during the routing procedure, when a downstream node becomes aware of the possibility of adopting uplink successive interference cancellation, it will first re-calculate the iETT value as in the previous step, and check whether there is a potential improvement. If so, this node broadcasts a special RREQ including the new iETT value for the superposed transmission. If finally this path with uplink coding opportunity is chosen by the routing protocol, this node sends a special SYNC request to the two upstream nodes and advises them to synchronize their transmissions.

The protocol is summarized in Algorithm 1.

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**Algorithm 1** The pseudo-code of S3 routing protocol.

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1: {Source node s;}
2: while no routing information is available do
3:   initiate RREQ packet, specifying source s and destination d
4:   broadcast RREQ to all neighbors and wait for RREP
5:   if receive RREP before timeout then
6:     extract routing information and enter forwarding stage
7:   end if
8: end while

9: {Intermediate node i;}
10: if receive RREQ from neighbor j and i ≠ d then
11:   if it is a normal RREQ (w/o coding) then
12:     insert i and iETT(lij) into the RREQ
13:   else
14:     insert i into the RREQ
15:   end if
16: broadcast RREQ to all neighbors
17: while there exists potential coding opportunities do
18:   re-calculate iETT value for the coding links
19:   if new iETT is better then
20:     unicast a special RREQ with the re-calculated iETT
       along the coding links
21:   end if
22: end while
23: end if

24: {Destination node d;}
25: if receive the first RREQ then
26:   start a timer tw and wait for subsequent RREQs
27:   select the RREQ with least total iETT
28:   extract route information and prepare RREP
29:   send RREP back via the chosen route
30: end if

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## IV. EXPERIMENTAL EVALUATIONS

### A. Implementation Setup

In this section, we describe the experimental evaluations. The testbed is built on GNU radio platform [2]. We modify the standard 802.11 packet format to include the support for superposition coding and successive interference cancellation. Similar to the implementation in [20], each data packet consists of a header with a 16-bit CRC and a 233-byte payload encoded with Reed-Solomon encoding at the rate of 233/255.

The transmitter modulates each packet with BPSK at a symbol rate of 62500 symbol/s, and transmits at a fixed power level. If downlink superposition coding is used, the transmitter splits the total power into two parts, which are used to transmit the first layer and second layer signals, respectively. The receiver samples at a rate of four times the symbol rate to process the received signal.

Due to limited number of devices, the evaluations are done on a small-scale basis. Several typical scenarios have been constructed for experiments. In each scenario, we perform 50 independent experiments with different channel conditions by changing the locations of the clients. In each experiment, we measure the throughput of two cases; one using the S3 protocol with iETT as the routing metric, while the other one using the dynamic source routing (DSR) [16] protocol with ETT [13] as the routing metric. For some scenarios, we will also discuss the results if the expected transmission count (ETX) [9] is used as the routing protocol. We examine the *throughput ratio* between the two cases. When the throughput ratio is greater than 1.0, it indicates that S3 achieves a higher throughput. The resulting throughput ratios from the 50 experiments in each scenario are presented as a cumulative distribution function (CDF), which depicts the distribution of throughput ratios.

Before conducting experiments in each scenario, we perform channel measurements in our indoor environment. Since packet headers are always transmitted with full power, we measure the received header amplitude to estimate the channel stability. Three tests are conducted, in each of which the transmitter sends 20 packets to the receiver. Between tests, there is a delay of a few seconds. We collect all the samples of the three tests together and calculate the statistics. The standard deviation normalized by the mean is about 0.3, which indicates the stability of the test environment.

In the following subsections, we describe the result of each evaluation scenario in detail.

### B. Single Access Point and Relay Point

In the first scenario, traffic is moving from the access point (AP) to two clients. This scenario corresponds to the situation when clients are performing download tasks. Downlink superposition coding is used for the pair of asymmetric links. The power split between the two layers is tuned to be as close to optimum as possible. Another scenario describes the situation when traffic is moving from clients to the AP. Uplink successive interference cancellation is used for the pair of asymmetric links. The third scenario consists of a single relay point and four clients. The four clients form two independent communication pairs, and all the traffics are relayed through the single relay point. Both uplink successive interference cancellation and downlink superposition coding are employed in this scenario.

Fig. 2 plots the CDFs of the throughput ratios of these scenarios. It can be seen that the throughput ratios are always greater than unity, hence S3 always outperforms DSR. Note that in all three scenarios, the maximum throughput ratio is above 1.9, which means a 90% of throughput increase can be achieved.

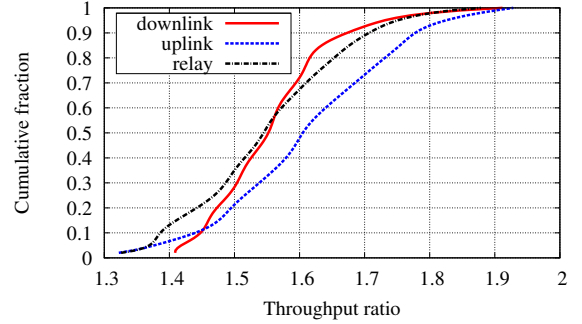


Fig. 2. CDF of the throughput ratio for non-routing cases.

### C. Single-Path Routing

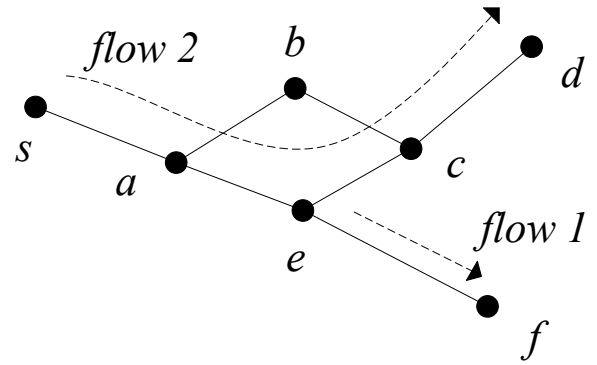


Fig. 3. Topology for single-path routing.

In this subsection, we investigate the effectiveness of iETT and S3 in a single-path routing scenario shown in Fig. 3. Before the path for routing flow 2 from node  $s$  to  $d$  is selected, there has already been another active flow originating from node  $e$  to node  $f$ . When using DSR, the top path  $s \rightarrow a \rightarrow b \rightarrow c \rightarrow d$  is preferred over the bottom path  $s \rightarrow a \rightarrow e \rightarrow c \rightarrow d$ , because the former has a smaller total ETT value. However, in the S3 protocol, node  $e$  re-calculates the iETT measurement for  $(l_{ae}, l_{ec})$  and unicasts it to node  $c$ . Note that since  $l_{sa}$  and  $l_{cd}$  are out of the transmission range of each other, both of them can be active simultaneously due to spatial reuse. Fig. 4 presents the CDF of the throughput ratio. It is obvious that the network throughput in the single-path routing scenario benefits from adopting S3.

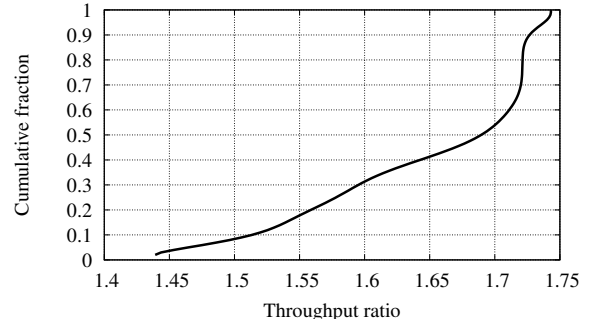


Fig. 4. CDF of throughput ratio for single-path routing.

#### D. Multi-path Routing

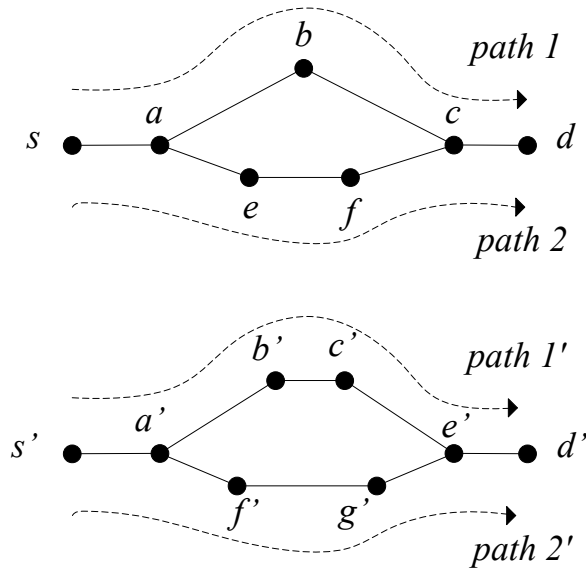


Fig. 5. Topology for multi-path routing.

Even without the existence of other flows in the neighborhood, we can use multi-path routing to create coding opportunities for routing a single flow. Two different cases shown in Fig. 5 are experimented. The network at the top shows a routing scenario in which a path between node  $s$  to node  $d$  is to be searched, while the network at the bottom shows another routing scenario in which a path between node  $s'$  to node  $d'$  is to be searched.

We carefully arrange the location of each node. As a result, in the first scenario, shortest path routing metrics such as ETX leads to path 1, while rate-aware routing metrics such as ETT leads to path 2. In S3, downlink superposition coding is used by  $a$  to simultaneously transmit to  $b$  and  $e$ , while uplink successive interference cancellation is used by  $c$  to receive simultaneous transmissions from  $b$  and  $f$ .

We also carefully arrange the location of each node in the second multi-path routing scenario, such that ETX and ETT cannot distinguish between path 1' and path 2'. In S3, downlink superposition coding is used by  $a'$  to simultaneously transmit to  $b'$  and  $f'$ , while uplink successive interference cancellation is used by  $e'$  to receive simultaneous transmissions from  $c'$  and  $g'$ . Different from the previous scenario, spatial reuse is utilized since link  $l_{b'c'}$  and  $l_{f'g'}$  are out of the interference range of each other. Therefore, both links are able to carry active flows simultaneously.

The throughput ratios of both scenarios are shown in Fig. 6. It is confirmed that higher throughput is always achieved by using S3 to create coding opportunities via multi-path routing. Note that the curve corresponding to “without spatial reuse” is always above of that corresponding to “with spatial reuse”. It means that, for a given throughput ratio value, there is a larger proportion of experimental results exceeding that value when spatial reuse is available. This observation indicates that, as expected, spatial reuse is beneficial to throughput improvement. The use of multi-path routing for better coding

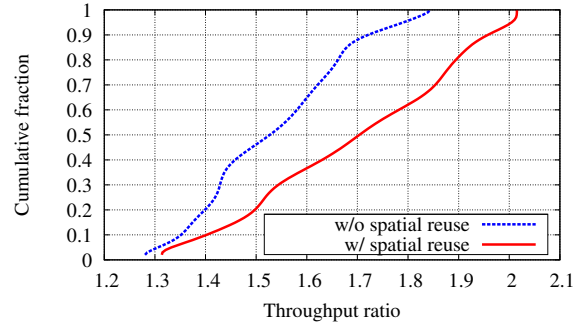


Fig. 6. CDF of throughput ratio for multi-path routing.

opportunities has further extended the applicability of iETT and the S3 protocol.

#### V. RELATED WORK

Routing is one of the central research areas that encompasses efforts from computer science, engineering, operations research, and even economics and social science. In general, people are interested in optimizing the routes to forward items, with respect to certain objective functions, and subject to some critical resource constraints. There are huge amount of literature related to routing, and we only discuss related routing problems in communication networks here. Some previous work [12], [13], [9] focus on increasing network throughput, subject to the constraints that network links have limited capacity and sometimes interfere with each other; while some research efforts [26], [23], [8], [27], [15], [31] are devoted to improve communication robustness, given that the underlying communication links have reliability issues; and some studies [24], [6], [7], [4], [34], [36], [32] aim for stimulating cooperation among participants, due to the fact that the network participants might be selfish and even malicious.

Network coding has been an active field of information theory and coding theory for years [3], [22], [35]. Traditionally, communication nodes only relay packets of information they receive. Network coding techniques instead allow nodes to take several packets and combine them together for transmission, such that maximum possible information flow in a network is obtained. Network coding techniques have been widely used in many areas, such as wireless mesh networks [17], [29], spatial sensor networks [5] and P2P file sharing applications [1].

Similar to network coding techniques, superposition coding and successive interference cancellation are well-known physical layer techniques [10], [33]. [14] discusses some implementation and experimental results of superposition coding on software radio. Previous studies on applying SC and SIC to WMNs include designing a simple MAC protocol with a greedy scheduler [19] and an opportunistic local two-hop rerouting algorithm [20]. These initial works have demonstrated the applicability of both techniques in WMNs. However, those heuristic mechanisms leave much room for improvement. Since each node ignores any potential application of both SC and SIC during the routing process, such reactive rerouting strategy only results in local optimal segments within

an end-to-end route. To truly reap the benefit of coding opportunities in the physical layer, a systematic design that is similar to [17], [29] in the network coding context is needed.

## VI. CONCLUSION

We present a routing metric iETT and a routing protocol S3 for WMNs, to take advantage of physical layer coding techniques for high network throughput. iETT includes the interference-awareness property and provides a simple way of measuring the potential gains of applying both techniques. The S3 protocol works in three steps to explore the coding opportunities. Experimental results based on GNU radio platform confirm the effectiveness of the proposed protocol. Significant improvements in network throughput are observed in both single-path and multi-path routing scenarios.

There are several related research problems. In particular, we find the following one quite interesting. We formulate the objective in the optimization problem (8) as to maximize the total end-to-end throughput. Sometimes it would be appropriate to maintain certain notion of fairness [28], [30], [25] among network flows. It would be interesting to study whether the optimization problems with such additional fairness constraints are still tractable - and if the answer is yes, what are the efficient algorithms to solve them.

Hopefully, the positive results presented in this work would inspire more work to further investigate and appreciate the potential advantage of physical layer coding techniques in the networking community.

## ACKNOWLEDGEMENT

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