Cross-layer Optimization for Multi-hop Wireless Networks with Successive Interference Cancellation

Canming Jiang, Yi Shi, *Senior Member, IEEE,* Xiaoqi Qin, *Student Member, IEEE,* Xu Yuan, *Member, IEEE,* Y. Thomas Hou, *Fellow, IEEE,* Wenjing Lou, *Fellow, IEEE,* Sastry Kompella, *Senior Member, IEEE,* and Scott F. Midkiff, *Senior Member, IEEE*

***Abstract*—The classical approach to interference management in wireless medium access is based on avoidance. Recently, there is a growing interest in exploiting interference (rather than avoiding it) to increase network throughput. This was made possible by a number of advances at the physical layer. In particular, the so-called *successive interference cancellation* (SIC) scheme appears very promising, due to its ability to enable concurrent receptions from multiple transmitters as well as interference rejection. Although SIC has been extensively studied as a physical layer technology, its research and advances in the context of *multi-hop* wireless network remain limited. In this paper, we aim to close this gap by offering a systematic study of SIC in a multi-hop wireless network. After gaining a fundamental understanding of SIC's capability and limitation, we propose a cross-layer optimization framework for SIC that incorporates variables at physical, link, and network layers. We use numerical results to affirm the validity of our optimization framework and give insights on how SIC behaves in a multi-hop wireless network.**

***Index Terms*—Interference avoidance, scheduling, interference exploitation, successive interference cancellation, optimization, multi-hop wireless networks**

I. INTRODUCTION

Interference is widely regarded as the fundamental impediment to throughput performance in wireless networks. In the wireless networking community, the classical and main stream approach to handle interference is to employ certain *interference avoidance* scheme, which can be done either through deterministic scheduling (e.g., TDMA, FDMA, or CDMA) or random access based schemes (e.g., CSMA, CSMA/CA). The essence of an interference avoidance scheme is to avoid any potential overlap among the transmitting signals. Although natural and easy to implement, an interference avoidance scheme, in general, cannot offer a performance close to network information theoretical limit [29].

Recently, there is a growing interest in exploiting interference (rather than avoiding it) to increase network throughput (see Section II for related work). In essence, such an *interference exploitation* approach allows overlap among transmitting signals and relies on some advanced physical (PHY) layer schemes to remove or cancel interference. In particular, the so-called *successive interference cancellation* (SIC) scheme appears very promising [1], [3], [8], [10], [16], [34] and has already attracted development efforts from industry (e.g., QUALCOMM's CSM6850 chipset for cellular base station [22]). Under SIC, a receiver attempts to decode concurrent signals from multiple transmitters iteratively, starting from the strongest signal. If the strongest signal can be decoded, it will be subtracted from the aggregate signal so that the signal to interference and noise ratio (SINR) for the remaining signals can be improved. Then the SIC receiver continues to decode the second strongest signal and so forth, until all signals are decoded, or terminates if the remaining signals are no longer decodable.

The beauty of SIC resides in its simplicity. It is a purely received-based interference management scheme and does not require sophisticated coordination with transmitters of other nodes. Although SIC has been extensively studied as a PHY layer technology, its performance and behavior in the context of *multi-hop* wireless networks remain unknown. In this paper, we will try to answer the following questions: (i) What are the fundamental limitations of SIC in a multi-hop wireless network? (ii) How to maximize the potential of SIC in a multi-hop wireless network? We show that the limitations of SIC come from its stringent constraints when decoding multiple signals. Specifically, in order to decode aggregate signals successively, an SIC receiver must meet a series of SINR constraints for its received signal powers. Further, due to these constraints, there exists a decoding limit for SIC in its abilities for concurrent receptions or interference rejection. Due to this limit, SIC alone is inadequate to handle all concurrent interference in a multi-hop wireless network. Judicious design of link layer scheduling remains critical to enable SIC to work smoothly in a multi-hop wireless network.

Due to the tight coupling of SIC with link layer scheduling and network layer routing, it is important to consider these layers holistically so as to optimize upper layer throughput performance. Such a cross-layer design approach is also necessary to maximize the full potential of SIC in a multi-hop wireless network. In this paper, we develop such a framework, with joint formulation of SIC at PHY layer, time-based scheduling at link layer, and flow routing at network layer. To the best of our knowledge, this optimization framework is the first effort that allows a systematic study of SIC in a multi-hop wireless network. To demonstrate the practical utility of this framework, we apply it to study a network throughput maxi-

Canming Jiang is with Shape Security, Mountain View, CA, USA. e-mail: jiangcanming@gmail.com.

Yi Shi, Xiaoqi Qin, Xu Yuan, Y. Thomas Hou, Wenjing Lou, and Scott F. Midkiff are with Virginia Polytechnic Institute and State University, USA. e-mail: {yshi,xiaoqi,xuy10,thou,wjlou,midkiff}@vt.edu

Sastry Kompella is with U.S. Naval Research Laboratory, Washington, DC, USA. e-mail: sastry.kompella@nrl.navy.mil.

Manuscript received Sept. 10, 2005; revised March 4, 2016; accepted May 14, 2016.

TABLE I
NOTATION.

Symbol	Definition
A_j	The maximum number of signals an SIC receiver j can decode
B	Channel bandwidth
C_{ij}	The maximum achievable rate on link $i \to j$
d_{ij}	Distance between nodes i and j
$d(f)$	Destination node of session $f \in \mathcal{F}$
$\mathcal{F}$	The set of user sessions in the network
g_{ij}	Channel gain from node i to node j
$\mathcal{I}_i$	The set of neighboring nodes of node i
$\mathcal{L}$	The set of links in the network
$\mathcal{N}$	The set of nodes in the network
$\mathcal{N}_j$	The set of transmitting nodes when j is receiving
P	The transmission power of each node
$P_j^{\max}$	$= \max_{i \in \mathcal{N}_j} P_{ij}$, the maximum power of all signals received at node j
P_{ij}	The received power at node j from node i
$r(f)$	Data rate of session $f \in \mathcal{F}$
$r_{ij}(f)$	Data rate that is attributed to session f on link $i \to j$
$s(f)$	Source node of session f
T	The number of time slots in a time frame
$x_{ij}[t]$	A binary indicator of weather the transmission on link $i \to j$ is successful or not in time slot t
$w(f)$	A weight associated with session f
R	The data rate of a successful transmission
β	The SINR threshold for successful decoding
γ	Path loss index
$\lambda_i[t]$	A binary indicator of weather node i is transmitting or not in time slot t
σ^2	The power level of ambient noise

mization problem. Our numerical results affirm the efficacy of this optimization framework and give us insights on how SIC be exploited to improve performance in a multi-hop wireless network.

The rest of this paper is organized as follows. Section II presents related work. Section III offers a primer on SIC and discuss its inherent limitations. In Section IV, we show how to circumvent SIC's limitation through joint SIC and link layer scheduling. In Section V, we develop a mathematical model for SIC in a multi-hop wireless network, with joint consideration of link and network layers. In Section VI, we refine our mathematical model through reformulation, which leads to an optimization framework for SIC in a multi-hop wireless network. In Section VII, we apply our optimization framework to a throughput maximization problem and present some insights via numerical results. Section VIII concludes this paper. Table I lists notation used in this paper.

II. RELATED WORK

At the PHY layer, a major reference on interference exploitation (cancellation) is the book by Verdu [31] and references therein. For more details and new advances of some important interference cancellation techniques, we refer readers to study SIC [5], [32], parallel interference cancellation [9], [30], iterative interference cancellation (turbo multiuser user detection) [13], [33], which all aim to enable a receiver to decode multiple signals at the same time and reject interference from other unintended transmitters. A recent review on how to apply interference cancellation for cellular systems was given in [1], which positioned SIC as one of the most promising techniques to mitigate interference due to its simplicity and effectiveness.

Note that the SIC considered in this paper differs from some new interference cancellation schemes such as analog network coding [14] and ZigZag decoding [19]. Both were proposed to resolve packet collisions, and they require knowledge of some bits in one of the colliding packets. SIC also differs from smart antenna-based interference cancellation schemes, such as Zero-Forcing Beam Forming (ZFBF) [2], [27], [35] in MIMO[1] and directional antennas [15], [23], [28].

There is a growing interest to exploit SIC at the PHY layer to improve performance at upper layers in a wireless network [3], [8], [10], [16], [17], [18], [34]. In [10], Halperin *et al.* built a ZigBee prototype of SIC based on [31, Ch. 7] using software radios and used experimental results to validate that SIC is an effective way to improve system throughput. In [16], Lv *et al.* studied a scheduling problem in an ad hoc network with SIC. To simplify network-layer problem, the authors considered fixed routes in the network (e.g., based on shortest path), and subsequently developed a greedy scheduling algorithm based on conflict set graph. Link scheduling problem for wireless networks with SIC was also studied in [17], [18], but the aggregate interference effect of the practical SINR model was not considered. In [8], Gelal *et al.* proposed a topology control framework to exploit SIC. They studied how to divide a network topology into a minimum number of sub-topologies where the set of links in each sub-topology can be active at the same time. In [34], Weber *et al.* studied asymptotic transmission capacity of one-hop ad hoc networks with SIC under a simplified model where all signals from transmitters within a specific radius can all be successfully decoded. More realistic SIC model for asymptotic transmission capacity was later explored by Blomer and Jindal in [3]. We also notice a paper by Sen *et al.* [25] claiming that the potential gain by SIC is marginal. This is in contrast to the state-of-the-art [3], [8], [10], [16], [17], [34] as well as our findings in this paper. A closer look at [25] shows that their SIC scheme did not fully exploit the benefits of SIC. The authors in [25] only considered a simple network with two links and compared the completion time required to transmit one packet on both links with and without SIC. When without SIC, the two links transmits data sequentially and the completion time is the sum of the time used on both links. With SIC, the two links can transmit data simultaneously and the completion time was defined as the maximum time used by these two links. Such a comparison is not quite fair, as the link that finishes its transmission first can start to transmit other packets instead of being idle.

To date, results on how to apply SIC in a *multi-hop* network remain very limited. Qu, He, and Assi [21] considered SIC in multi-rate multi-hop wireless networks. They formulated the optimization problem as a mixed integer linear program and solved it by a decomposition approach using column generation for very small size network instances. For medium or large size network instances, they developed one efficient

[1]Note that MIMO requires multiple antennas for interference cancellation, while SIC does not have such requirement. This paper considers SIC with a single antenna on each node.

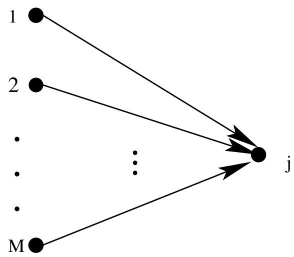


Fig. 1. A receiver with M concurrent transmitters.

greedy method but the obtained solution is not optimal. The goal of this paper is to fill this gap by providing the necessary mathematical foundation.

III. SIC: Capabilities and Limitations

We review SIC's capabilities in Section III-A and discuss its limitations in Section III-B.

A. SIC: A Primer

Under the classical information reception model in a wireless network, a receiver j treats all interfering signals from other concurrent (non-intended) transmissions as noise. For the signal coming from the intended transmitting node i, if its SINR at node j is greater than or equal to a threshold β, then the transmission is said to be successful (i.e., the signal from node i to j can be decoded successfully). Denote P_{ij} the power level of the signal from node i that is received by node j. Denote $\mathcal{N}_j$ the set of concurrent transmitting nodes that can be heard by node j. Then, under the classical model, a successful transmission from node i to node j occurs if

$$\frac{P_{ij}}{\sum_{k\in\mathcal{N}_j}^{k\neq i} P_{kj} + \sigma^2} \geq \beta ,$$

where constant σ^2 is power level of the ambient noise.

In contrast to the above classical paradigm, a receiver with SIC capability can decode a number of concurrent signals (including some interfering signals) rather than treating them blindly as noise [10], [31, Ch. 7], [34]. This is done by decoding concurrent signals in a *sequential* order and subtracting each successfully decoded signal before proceeding to decode the next signal. Figure 1 illustrates a communication scenario where a node j is receiving from M concurrent transmitters. Under SIC, receiver j first attempts to decode the strongest signal. If the strongest signal can be decoded successfully (i.e., the SINR of this signal is no less than the threshold β), then this signal will be subtracted from the aggregate signal (see Fig. 2). Then the receiving node j tries to decode the second strongest signal and so forth. The process continues until all the signals are successfully decoded or at some stage the SINR criterion for the underlying signal is no longer satisfied.

Without loss of generality, referring to Fig. 1, suppose that the power levels of the signals from the M transmitters received at node j are in nondecreasing order as $P_{1j} \leq P_{2j} \leq \cdots \leq P_{Mj}$. Receiving node j tries to decode the signals in the order of transmitting nodes $M, M-1, \cdots 1$. Then, the signal

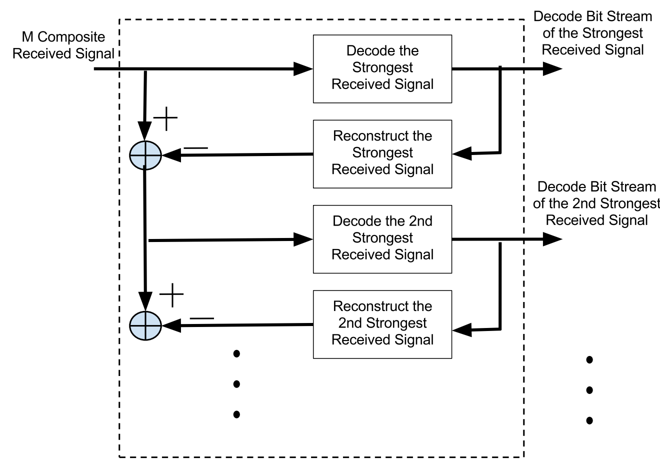


Fig. 2. A schematic of the SIC process.

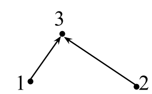


Fig. 3. An example of concurrent receptions from multiple transmitters.

with received power P_{ij} can be decoded successfully if and only if

$$\begin{aligned} &\text{Step 1} \quad \frac{P_{Mj}}{\sum_{k=1}^{M-1} P_{kj} + \sigma^2} \geq \beta , \\ &\text{Step 2} \quad \frac{P_{M-1,j}}{\sum_{k=1}^{M-2} P_{kj} + \sigma^2} \geq \beta , \\ &\quad \vdots \qquad\qquad \vdots \\ &\text{Step } (M-i+1) \quad \frac{P_{ij}}{\sum_{k=1}^{i-1} P_{kj} + \sigma^2} \geq \beta . \end{aligned} \tag{1}$$

As shown in (1), in order to decode the signal with received power P_{ij}, it is necessary to decode all the preceding stronger signals first. Note that we assume perfect cancellation of a successfully decoded signal in the iterative process. Similar to [8], [16], [17], we do not consider link rate adaptation in our model and assume that the data rate for each successful transmission is $R = B\log_2(1+\beta)$, where B is the channel bandwidth. We leave the more complex case with link rate adaption as future work.

There are two key benefits associated with SIC, namely, *concurrent receptions from multiple transmitters* and *interference rejection*. In the rest of this section, we elaborate these two benefits.

Concurrent Receptions from Multiple Transmitters. Note that under the classical reception model, only one intended transmitter is allowed to transmit; concurrent transmissions to the same receiver will lead to a collision and are considered wasteful of resource. In contrast, an SIC receiver is capable of receiving from multiple transmitters at the same time (if the criteria in (1) are met) and thus can substantially increase throughput in the network. As a simple example, consider Fig. 3, where both nodes 1 and 2 wish to transmit to node 3. Assume $P_{13} = 1$, $P_{23} = 2$, $\sigma^2 = 1$, and $\beta = 1$, where all units are normalized with appropriate dimensions. Under

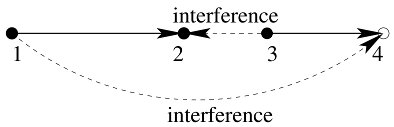


Fig. 4. An example for interference rejection.

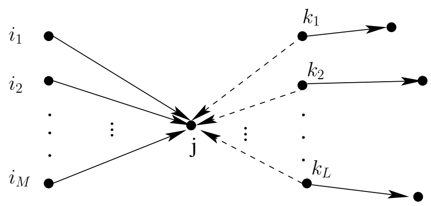


Fig. 5. The general case of concurrent reception and interference rejection at a receiving node j. A solid arrow represents intended transmission and a dashed arrow represents interference.

the classical interference avoidance model, nodes 1 and 2 cannot transmit to node 3 at the same time due to interference. Under SIC, receiver 3 can first decode the stronger signal from node 2 by treating the signal from 1 as interference. We have $\frac{2}{1+1} = 1 \geq \beta$. Next, receiver 3 subtracts the decoded signal from the aggregate signal. The SINR from node 1 is $\frac{P_{13}}{\sigma^2} = \frac{1}{1} = 1 \geq \beta$, which shows transmission from node 1 is also successful.

Interference Rejection. The ability to decode multiple received signals can also help the receiving node to reject interference from unintended transmitters. As a simple example, consider the two-transmitter two-receiver case in Fig. 4. Node 1 wishes to send data to node 2 while node 3 wishes to send data to node 4. Due to the broadcast nature of a wireless channel, the signal from node 3 will interfere with the reception at node 2 and likewise the signal from node 1 will interfere with the reception at node 4. Assume $P_{12} = 1$, $P_{14} = 0.5$, $P_{32} = 3$, $P_{34} = 1.6$, $\sigma^2 = 1$, and $\beta = 1$. Under the classical interference avoidance model, links $1 \to 2$ and $3 \to 4$ cannot be active at the same time. Under SIC, receiver 2 can first try to decode the stronger received signal, which is the signal from node 3. Since $\frac{P_{32}}{P_{12}+\sigma^2} = \frac{3}{1+1} = 1.5 \geq \beta$, such decoding is successful. Then, node 2 subtracts this decoded signal from the aggregate signal, and tries to decode the second stronger signal, which is from node 1. We have $\frac{P_{12}}{\sigma^2} = \frac{1}{1} = 1 \geq \beta$. So this decoding is again successful. Likewise, on node 4, it tries to decode the stronger received signal first, which is from node 3. Since $\frac{P_{34}}{P_{14}+\sigma^2} = \frac{1.6}{0.5+1} = 1.07 \geq \beta$, this decoding is successful.

Summary. Our discussion of the above two benefits can be generalized by Fig. 5. In this figure, a receiving node j tries to decode all the signals it receives, among which it tries to retain the desired bit streams from the M intended transmitters and reject the interfering bit streams from the L unintended transmitters.

B. Understanding the Limitations of SIC

To enable SIC to work, stringent constraints in (1) must be satisfied. As a consequence, we show that SIC can only decode a limited number of signals (either intended or unintended). Before we calculate this limit, we present the following property.

Property 1: **(Geometric Power Property)** *Denote P_{1j}, P_{2j}, $\cdots$, P_{Mj} as the received powers of the signals that can be successfully decoded at node j via SIC. Without loss of generality, suppose $P_{1j} \leq P_{2j} \leq \ldots \leq P_{Mj}$. Then, we have*

$$P_{ij} \geq \beta(1+\beta)^{i-1}\sigma^2, \text{ for } i = 1, \ldots, M \ .$$

Proof: Our proof is based on induction. First consider $i = 1$. Since all previous stronger interference are removed from the composite interference when decoding the weakest signal, the SINR for P_{1j} is $\frac{P_{1j}}{\sigma^2}$, which must be no less than β. Then, we have $\frac{P_{1j}}{\sigma^2} \geq \beta$, which is $P_{1j} \geq \beta\sigma^2$.

Next, suppose that

$$P_{ij} \geq \beta(1+\beta)^{i-1}\sigma^2, \ i = 1, \ldots, l \ . \tag{2}$$

We will prove that $P_{l+1,j} \geq \beta(1+\beta)^{l}\sigma^2$. We know that we still have all the interference from the weaker signals when we decode the signal from $P_{l+1,j}$. Then, we have $P_{l+1,j}/(\sum_{i=1}^{l} P_{ij} + \sigma^2) \geq \beta$, which gives us

$$\begin{aligned} P_{l+1,j} &\geq \beta\left(\sum_{i=1}^{l} P_{ij} + \sigma^2\right) \geq \beta\left[\sum_{i=1}^{l} \beta(1+\beta)^{i-1}\sigma^2 + \sigma^2\right] \\ &= \beta\left[1 + \beta\frac{(1+\beta)^l - 1}{(1+\beta)-1}\right]\sigma^2 = \beta(1+\beta)^l\sigma^2 \ , \end{aligned}$$

where the second inequality holds due to (2). ■

Now we are ready to calculate the limit on the number of signals that can be decoded. More formally, denote A_j an upper bound of the number of signals that receiver j can decode. Then we have the following lemma.

Lemma 1: Denote $P_j^{\max}$ the strongest possible received power at receiver j, i.e., $P_j^{\max} = \max_{i\in\mathcal{N}_j} P_{ij}$, where $\mathcal{N}_j$ is the set of all active concurrent transmitters. Then the number of successfully decoded signals at receiver j is no more than $A_j = 1 + \log_{\beta+1}(\frac{P_j^{\max}}{\beta\sigma^2})$.

Proof: Let $P_{1j} \leq P_{2j} \leq \ldots \leq P_{Mj}$ be any set of powers of the signals successfully decoded at receiver j, we have $P_j^{\max} \geq P_{Mj}$. Combining $P_j^{\max} \geq P_{Mj}$ with Property 1 gives us $P_j^{\max} \geq P_{Mj} \geq \beta(1+\beta)^{M-1}\sigma^2$, which gives us

$$M \leq 1 + \log_{\beta+1}\left(\frac{P_j^{\max}}{\beta\sigma^2}\right) = A_j \ .$$

That is, the number of successfully decoded signals at receiver j is upper bounded by A_j. ■

As an example of the sequential decoding limit, we assume that $P_j^{\max} = 10$, $\sigma^2 = 1$, and $\beta = 1$. Based on Lemma 1, we have $A_j = 1 + \log_{1+1}(\frac{10}{1\cdot 1}) = 4.32$. That is, only up to four signals can be successfully decoded at receiver j.

Remark 1: Note that A_j given in Lemma 1 is only an upper bound. The actual number of decodable signals may be much lower than this bound. This is because that the powers of decodable signals must also satisfy the sequential SINR constraints in (1). ■

IV. Joint SIC and Scheduling

Based on the discussion in Section III-B, SIC has some intrinsic limitations. To unleash its full potential in a multi-hop wireless network, it is necessary to incorporate a judicious design of scheduling at the link layer. This is true for both the sequential SINR constraints and sequential decoding limit. In particular, when the sequential SINR constraints are no longer satisfied at certain stage, one has to resort to scheduling (e.g., time slot assignment) to avoid interference so that different transmissions can be carried out successfully. Likewise, whenever the number of interfering transmissions exceeds the sequential decoding limit, one again has to employ scheduling to allocate these transmissions into different time slots such that the number of interfering transmissions in each time slot is within the decoding limit. In other words, it is necessary to have SIC work jointly with link layer scheduling to mitigate its limitations. In a multi-hop wireless network, SIC introduces several new challenges that we must address:

1) At the physical layer, under the classical SINR model, a receiving node treats all the other concurrent (unintended) interfering transmissions as noise when deciding whether or not the underlying intended transmission is successful. This itself is not a trivial problem as the set of interfering transmissions is usually coupled with upper layer scheduling and routing algorithms. In the context of SIC, not only one needs to deal with such coupling with upper layer algorithms, one also has to deal with multiple transmissions, in the sense that one has to decode those stronger signals before decoding its own signal (in a sequential order). This sequential decoding imposes significant difficulty in developing a tractable model for mathematical programming.

2) At the link layer, a scheduling algorithm (i.e., interference avoidance scheme) is needed to address the limitations of SIC at the physical layer. Note that such scheduling algorithm is also coupled with routing in a multi-hop network environment. How to design an optimal scheduling algorithm to fulfill certain network performance objective in this context is a new and non-trivial problem.

3) As discussed in Section III-A, SIC allows more concurrent transmissions in the network than traditional interference avoidance model. This offers many more available links for choosing a path at the network layer. Consequently, the design space at the network layer is much larger, leading to a more complex optimization problem.

To address these new challenges, we find it is necessary to develop a framework that jointly considers SIC at the PHY layer, scheduling at the link layer, and flow routing at the network layer.

V. SIC in Multi-hop Wireless Networks: A Mathematical Model

As a first step toward a formal optimization framework, we examine constraints across the PHY, link, and network layers for a multi-hop wireless network. Consider a network with a set of $\mathcal{N}$ nodes, with each node equipped with a single antenna. For scheduling at the link layer, we assume a frame is divided into T time slots, each of equal length. For simplicity, we do not consider power control of individual node and assume each node transmits at the same power P. Denote g_{ij} as the channel gain from node i to node j. Then, when node i is transmitting, the received power at node j is $P_{ij} = P \cdot g_{ij}$.

Scheduling Constraints. We first define a binary scheduling variable $x_{ij}[t]$ for link $i \to j$ in time slot t ($1 \leq t \leq T$).

$$x_{ij}[t] = \begin{cases} 1 & \text{if node } i \text{ transmits data to node } j \text{ successfully} \\ & \text{in time slot } t; \\ 0 & \text{otherwise.} \end{cases}$$

By "successfully," we mean that the intended transmission from node i can be decoded at node j via SIC, i.e., the sequential SINR constraints in (1) are satisfied for this signal. In the case of an "unsuccessful" transmission (i.e., the sequential SINR constraints in (1) are not satisfied for this signal), it is desirable to turn off the transmitter rather than having it transmit undecodable signals. Therefore, when $x_{ij}[t] = 0$, we will not have any transmission from node i to node j.

Denote $\mathcal{I}_i$ as the set of all neighboring nodes of node $i \in \mathcal{N}$. For unicast communication in the network, a node transmits data to only one node in a time slot, i.e.,

$$\sum_{j \in \mathcal{I}_i} x_{ij}[t] \leq 1 \quad (i \in \mathcal{N}, 1 \leq t \leq T) . \tag{3}$$

For reception, a node can receive data from multiple transmit nodes in a time slot. That is, for receiver j, we may have $\sum_{i \in I_j} x_{ij}[t] > 1$.

Assuming simple half-duplex at each node i, we have:

$$x_{ki}[t] + x_{ij}[t] \leq 1 \quad (i \in \mathcal{N}, k, j \in \mathcal{I}_i, 1 \leq t \leq T) . \tag{4}$$

That is, node i cannot transmit and receive at the same time.

Denote C_{ij} as the achievable link rate on link $i \to j$. Then, we have $C_{ij} = \frac{1}{T} \sum_{t=1}^{T} R \cdot x_{ij}[t]$.

Joint PHY-Link Constraints. We first give a definition for *residual SINR,* which characterize the SINR value in a sequential fashion under SIC. For a signal from node i to node j in time slot t (from either intended or unintended transmission), we define the residual SINR (or r-SINR) of this signal, r-SINR$_{(i,j)}[t]$, as

$$\begin{aligned} &\text{r-SINR}_{(i,j)}[t] \\ =&\frac{P_{ij}}{\sum_{k \neq i} \sum_{l \in \mathcal{I}_k} P_{kj} x_{kl}[t] - \sum_{k \neq i}^{P_{kj} > P_{ij}} \sum_{l \in \mathcal{I}_k} P_{kj} x_{kl}[t] + \sigma^2} \\ =&\frac{P_{ij}}{\sum_{k \neq i}^{P_{kj} \leq P_{ij}} \sum_{l \in \mathcal{I}_k} P_{kj} \cdot x_{kl}[t] + \sigma^2} . \end{aligned} \tag{5}$$

Note that $\sum_{k \neq i}^{P_{kj} \leq P_{ij}} \sum_{l \in \mathcal{I}_k} P_{kj} \cdot x_{kl}[t]$ is the residual interference when node j attempts to decode the signal from node i after subtracting all the stronger received signals.

To see the coupling of r-SINR with scheduling, note that when $x_{ij}[t] = 1$, we have a successful decoding for the signal from node i to node j under SIC. This implies that

- The r-SINR's of all stronger received signals at node j from other concurrent transmissions are no less than the SINR threshold β.
- The r-SINR of the signal from node i to node j is no less than the SINR threshold β.

More formally, we have following coupling constraints for PHY-Link layers.

$$\text{If } x_{ij}[t]=1, \text{ then r-SINR}_{(m,j)}[t] \geq \beta \quad (j \in \mathcal{N}, i \in \mathcal{I}_j, m \neq i, n \in \mathcal{I}_m, P_{mj} > P_{ij}, x_{mn}[t]=1, 1 \leq t \leq T) \quad (6)$$

$$\text{If } x_{ij}[t]=1, \text{ then r-SINR}_{(i,j)}[t] \geq \beta \; (j \in \mathcal{N}, i \in \mathcal{I}_j, 1 \leq t \leq T). \quad (7)$$

Flow Routing Constraints. Consider a set of unicast communication sessions $\mathcal{F}$. Denote $r(f)$ as the data rate of session $f \in \mathcal{F}$, $s(f)$ and $d(f)$ as the source and destination nodes of session $f \in \mathcal{F}$, respectively. Denote $r_{ij}(f)$ the amount of rate on link $i \to j$ that is attributed to session $f \in \mathcal{F}$. Then we have the following flow balance. If node i is the source node of session f, i.e., $i = s(f)$, then

$$\sum_{j \in \mathcal{I}_i} r_{ij}(f) = r(f) \quad (f \in \mathcal{F}, i = s(f)) \, . \quad (8)$$

If node i is an intermediate relay node for session f, i.e., $i \neq s(f)$ and $i \neq d(f)$, then

$$\sum_{j \in \mathcal{I}_i}^{j \neq s(f)} r_{ij}(f) = \sum_{k \in \mathcal{I}_i}^{k \neq d(f)} r_{ki}(f) \;\; (f \in \mathcal{F}, i \neq s(f), d(f)). \quad (9)$$

If node i is the destination node of session f, i.e., $i = d(f)$, then

$$\sum_{k \in \mathcal{I}_i} r_{ki}(f) = r(f) \quad (f \in \mathcal{F}, i = d(f)) \, . \quad (10)$$

Note that in the above flow balance equations, we allow flow splitting/merging inside the network, which is more general than single-path flow routing. Further, it can be easily verified that if (8) and (9) are satisfied, then (10) is also satisfied. As a result, it is sufficient to list only (8) and (9) in the optimization framework.

Since the aggregate flow rate on any link $i \to j$ cannot exceed the achievable link rate C_{ij}, we have

$$\sum_{f \in \mathcal{F}}^{s(f) \neq j, d(f) \neq i} r_{ij}(f) \leq C_{ij} = \sum_{t=1}^{T} \frac{R}{T} \cdot x_{ij}[t] \quad (j \in \mathcal{N}, i \in \mathcal{I}_j). \quad (11)$$

VI. Reformulation for Mathematical Optimization

Note that the two sets of constraints in (6) and (7) are stated in the form of sufficient conditions rather than in the form of mathematical programming that is suitable for problem solving.[2] Therefore, a reformulation of (6) and (7) is needed.

As the first step to reformulate (6), we move $x_{mn}[t] = 1$ out of the range in (6). By treating $x_{mn}[t] = 1$ as part of the sufficient condition, (6) can be re-stated as follows:

$$\text{If } (x_{ij}[t]=1 \text{ and } x_{mn}[t]=1), \text{ then r-SINR}_{(m,j)}[t] \geq \beta \quad (j \in \mathcal{N}, i \in \mathcal{I}_j, m \neq i, n \in \mathcal{I}_m, P_{mj} > P_{ij}, 1 \leq t \leq T). \quad (12)$$

[2]By "the form of mathematical programming," we mean that a constraint should be written in the form: $h(\mathbf{x}) \leq 0$ or $h(\mathbf{x}) = 0$, where $\mathbf{x}$ is the set of variables in the constraint and h is a function mapping $\mathbf{x}$ into real space.

To combine $x_{ij}[t] = 1$ and $x_{mn}[t] = 1$ into one condition, we can introduce a binary variable, $y_{(i,j)(m,n)}[t]$, as follows.

$$y_{(i,j)(m,n)}[t] = 1 \text{ if and only if } (x_{ij}[t] = 1 \text{ and } x_{mn}[t] = 1) \quad (j \in \mathcal{N}, i \in \mathcal{I}_j, m \neq i, n \in \mathcal{I}_m, P_{mj} > P_{ij}, 1 \leq t \leq T).$$

For time slot t, we note that binary variable y has subscripts for four node dimensions, i, j, m, n, which means the number of such y variables could be a very large number. Fortunately, we find that we can remove the last node dimension n and reduce the number of y variables based on the following lemma.

Lemma 2: Statement (12) is equivalent to the following statement:

$$\text{If } \left(x_{ij}[t]=1 \text{ and } \textstyle\sum_{n \in \mathcal{I}_m} x_{mn}[t]=1\right), \text{ then r-SINR}_{(m,j)}[t] \geq \beta \;\; (j \in \mathcal{N}, i \in \mathcal{I}_j, m \neq i, P_{mj} > P_{ij}, 1 \leq t \leq T) \, . \quad (13)$$

Note that the differences between (12) and (13) are that $x_{mn}[t] = 1$ in (12) is replaced by $\sum_{n \in \mathcal{I}_m} x_{mn}[t] = 1$ in (13) and that $n \in \mathcal{I}_m$ in the range of (12) disappears in that of (13).

Proof: We first show that if (12) holds, then (13) also holds. If $x_{ij}[t] = 1$ and $\sum_{n \in \mathcal{I}_m} x_{mn}[t] = 1$, then there must exists one node $\hat{n} \in \mathcal{I}_m$ such that

$$x_{m\hat{n}}[t] = 1 \, .$$

Combining $x_{ij}[t] = 1$ and $x_{m\hat{n}}[t] = 1$, based on (12), we have r-SINR$_{(m,j)}[t] \geq \beta$.

Next, we show that if (13) holds, then (12) also holds. If $x_{ij}[t] = 1$ and $x_{mn}[t] = 1$, we have

$$\sum_{n \in \mathcal{I}_m} x_{mn}[t] = 1$$

based on (3). Based on $x_{ij}[t] = 1$, $\sum_{n \in \mathcal{I}_m} x_{mn}[t] = 1$, and (13), we have r-SINR$_{(m,j)}[t] \geq \beta$. ■

To simplify (13), we introduce a new binary variable $\lambda_m[t]$ and define it as follows:

$$\lambda_m[t] = \sum_{n \in \mathcal{I}_m} x_{mn} \quad (m \in \mathcal{N}, 1 \leq t \leq T) \, . \quad (14)$$

Intuitively, $\lambda_m[t]$ can be regarded as a variable representing whether or not node m is transmitting in time slot t, regardless of to whom it is transmitting. Then, (13) becomes

$$\text{If } (x_{ij}[t] = 1 \text{ and } \lambda_m[t] = 1), \text{ then r-SINR}_{(m,j)}[t] \geq \beta \quad (j \in \mathcal{N}, i \in \mathcal{I}_j, m \neq i, P_{mj} > P_{ij}, 1 \leq t \leq T). \quad (15)$$

To combine both conditions $x_{ij}[t] = 1$ and $\lambda_m[t] = 1$ into just one condition, we introduce a binary variable $y_{(i,j)(m)}[t]$ as follows:

$$y_{(i,j)(m)}[t] = 1 \text{ if and only if } (x_{ij}[t] = 1 \text{ and } \lambda_m[t] = 1) \quad (j \in \mathcal{N}, i \in \mathcal{I}_j, m \neq i, n \in \mathcal{I}_m, P_{mj} > P_{ij}, 1 \leq t \leq T) \, . \quad (16)$$

Note that variable y only has three node dimensions, i, j, m, which shows that the number of variables in the optimization framework has been decreased. Combining (16) and (15), we have

$$\text{If } y_{(i,j)(m)}[t] = 1, \text{ then r-SINR}_{(m,j)}[t] \geq \beta \quad (j \in \mathcal{N}, i \in \mathcal{I}_j, m \neq i, P_{mj} > P_{ij}, 1 \leq t \leq T) \, . \quad (17)$$

Now, (6) is replaced by (14), (16) and (17). Although (16) and (17) are still not yet in the form of mathematical programming, they are ready to be reformulated into such form. In the rest of this section, we show how to reformulate (16), (17) and (7).

A. Revised PHY-Link Constraints

Based on the definition of new variable $\lambda_m[t]$, we can refine the earlier definition of residual SINR in (5) as follows.

Definition 1: (r-SINR). *For a signal from node i to node j in time slot t (from either intended or unintended transmission), the residual SINR (or r-SINR) of this signal is*

$$\textit{r-SINR}_{(i,j)}[t] = \frac{P_{ij}}{\sum_{k\neq i}^{P_{kj}\leq P_{ij}} P_{kj}\cdot\lambda_k[t]+\sigma^2} \,. \tag{18}$$

(i) Reformulation of (16)

Statement (16) is equivalent to the following two statements:

$$\text{If } (x_{ij}[t]=1 \text{ and } \lambda_m[t]=1), \text{ then } y_{(i,j)(m)}[t]=1 \quad (j\in\mathcal{N}, i\in\mathcal{I}_j, m\neq i, P_{mj}>P_{ij}, 1\leq t\leq T)\,. \tag{19}$$

$$\text{If } y_{(i,j)(m)}[t]=1, \text{ then } (x_{ij}[t]=1 \text{ and } \lambda_m[t]=1) \quad (j\in\mathcal{N}, i\in\mathcal{I}_j, m\neq i, P_{mj}>P_{ij}, 1\leq t\leq T)\,. \tag{20}$$

Statement (19) can be written as

$$y_{(i,j)(m)}[t]\geq x_{ij}[t]+\lambda_m[t]-1 \quad (j\in\mathcal{N}, i\in\mathcal{I}_j, m\neq i, P_{mj}>P_{ij}, 1\leq t\leq T)\,, \tag{21}$$

which means that when $x_{ij}[t]=1$ and $\lambda_m[t]=1$, we have $y_{(i,j)(m)}[t]=1$. Statement (20) can be written as

$$x_{ij}[t]\geq y_{(i,j)(m)}[t] \quad (j\in\mathcal{N}, i\in\mathcal{I}_j, m\neq i, P_{mj}>P_{ij}, 1\leq t\leq T), \tag{22}$$

$$\lambda_m[t]\geq y_{(i,j)(m)}[t] \quad (j\in\mathcal{N}, i\in\mathcal{I}_j, m\neq i, P_{mj}>P_{ij}, 1\leq t\leq T). \tag{23}$$

Inequalities (22) and (23) ensure that when $y_{(i,j)(m)}[t]=1$, we have $x_{ij}[t]=1$ and $\lambda_m[t]=1$.

Now statement (16) is reformulated as (21), (22), and (23), which are in the form of mathematical programming.

(ii) Reformulation of (17)

By substituting (18) to (17), (17) becomes

$$\text{If } y_{(i,j)(m)}[t]=1, \text{ then } \frac{P_{mj}}{\sum_{k\neq m}^{P_{kj}\leq P_{mj}} P_{kj}\cdot\lambda_k[t]+\sigma^2}\geq\beta \quad (j\in\mathcal{N}, i\in\mathcal{I}_j, m\neq i, P_{mj}>P_{ij}, 1\leq t\leq T)\,,$$

which is equivalent to

$$P_{mj}-\sum_{k\neq m}^{P_{kj}\leq P_{mj}}\beta P_{kj}\lambda_k[t]-\beta\sigma^2\geq\left(1-y_{(i,j)(m)}[t]\right)D_{ijm} \quad (j\in\mathcal{N}, i\in\mathcal{I}_j, m\neq i, P_{mj}>P_{ij}, 1\leq t\leq T), \tag{24}$$

where D_{ijm} is a lower bound of $P_{mj}-\sum_{k\neq m}^{P_{kj}\leq P_{mj}}\beta P_{kj}\lambda_k[t]-\beta\sigma^2$ (e.g., we can set $D_{ijm}=P_{mj}-\sum_{k\neq m}^{P_{kj}\leq P_{mj}}\beta P_{kj}-\beta\sigma^2$). We can verify that when $y_{(i,j)(m)}[t]=1$, (24) becomes $P_{mj}-\sum_{k\neq m}^{P_{kj}\leq P_{mj}}\beta P_{kj}\cdot\lambda_k[t]-\beta\sigma^2\geq 0$, which is r-SINR$_{(m,j)}[t]\geq\beta$; when $y_{(i,j)(m)}[t]=0$, (24) becomes $P_{mj}-\sum_{k\neq m}^{P_{kj}\leq P_{mj}}\beta P_{kj}\cdot\lambda_k[t]-\beta\sigma^2\geq D_{ijm}$, which holds by the definition of D_{ijm}.

(iii) Reformulation of (7)

Following the same token as that in reformulating (17) into (24), we can rewrite (7) as

$$P_{ij}-\sum_{k\neq i}^{P_{kj}\leq P_{ij}}\beta P_{kj}\cdot\lambda_k[t]-\beta\sigma^2\geq(1-x_{ij}[t])H_{ij} \quad (j\in\mathcal{N}, i\in\mathcal{I}_j, 1\leq t\leq T)\,, \tag{25}$$

where H_{ij} is a lower bound of $P_{ij}-\sum_{k\neq i}^{P_{kj}\leq P_{ij}}\beta P_{kj}\cdot\lambda_k[t]-\beta\sigma^2$ (e.g., we can set $H_{ij}=P_{ij}-\sum_{k\neq i}^{P_{kj}\leq P_{ij}}\beta P_{kj}-\beta\sigma^2$).

B. Revised Scheduling Constraints

Inspired by the λ-variable's ability to reduce the dimension of y-variable from four to three, we would like to use λ-variable to formulate constraints for half-duplex. We have

$$\frac{1}{\min\{A_j,|\mathcal{I}_j|\}}\sum_{i\in\mathcal{I}_j}x_{ij}[t]+\lambda_j[t]\leq 1 \; (j\in\mathcal{N}, 1\leq t\leq T), \tag{26}$$

where A_j is an upper bound of the number of signals that node j can decode (see Lemma 1) and $|\mathcal{I}_j|$ is the number of neighboring nodes of node j. If node j is receiving from some node, the first term of the Left-Hand-Side in (26) is greater than 0. Then, $\lambda_j[t]$ must be 0. If node j is transmitting to some node (i.e., $\lambda_j[t]=1$), then we must have $\frac{1}{|\mathcal{I}_j|}\sum_{i\in\mathcal{I}_j}x_{ij}[t]=0$, which means that node j is not receiving from any node. Comparing the new half-duplex constraints (26) (formulated by using λ-variable) to the previously formulated half-duplex constraints (4), we find that the number of constraints in (26) is much smaller.

Moreover, due to the definition of variable λ in (14) and the fact that λ is binary, constraints (3) are redundant and can be removed from the framework.

C. Summary

Now we have all the constraints needed in an optimization framework for SIC, scheduling, and flow routing in a multi-hop wireless network. Within this framework, (14) and (26) are scheduling constraints, (21), (22), (23), (24), and (25) are joint PHY-Link constraints, (8), (9), and (11) are flow routing constraints. A summary of this mathematical framework is given in Fig. 6.

VII. Application to A Throughput Maximization Problem

The goal of this section is twofold. First, we want to apply the optimization framework that we developed in the last section to solve a throughput maximization problem. Second, we want to gain more insight on how SIC actually works in a multi-hop wireless network.

A. A Throughput Maximization Problem

Consider a typical throughput maximization problem where we want to maximize the sum of weighted rates of active user sessions in a multi-hop wireless network.[3] We assume each session $f\in\mathcal{F}$ is associated with a weight $w(f)$. Then,

[3]Note that problems with objectives such as maximizing the minimum session rate among all sessions or maximizing a scaling factor of all session rates belong to the same class of problems and can be solved similarly.

Scheduling:

$$\lambda_m[t] = \sum_{n\in\mathcal{I}_m} x_{mn} \qquad (m\in\mathcal{N}, 1\le t\le T)$$

$$\frac{1}{\min\{A_j, |\mathcal{I}_j|\}}\sum_{i\in\mathcal{I}_j} x_{ij}[t] + \lambda_j[t] \le 1 \qquad (j\in\mathcal{N}, 1\le t\le T)$$

PHY-Link:

$$y_{(i,j)(m)}[t] \ge x_{ij}[t] + \lambda_m[t] - 1 \qquad (j\in\mathcal{N}, i\in\mathcal{I}_j, m\neq i, P_{mj} > P_{ij}, 1\le t\le T)$$

$$x_{ij}[t] \ge y_{(i,j)(m)}[t] \qquad (j\in\mathcal{N}, i\in\mathcal{I}_j, m\neq i, P_{mj} > P_{ij}, 1\le t\le T)$$

$$\lambda_m[t] \ge y_{(i,j)(m)}[t] \qquad (j\in\mathcal{N}, i\in\mathcal{I}_j, m\neq i, P_{mj} > P_{ij}, 1\le t\le T)$$

$$P_{mj} - \sum_{k\neq m}^{P_{kj}\le P_{mj}} \beta P_{kj}\lambda_k[t] - \beta\sigma^2 \ge \left(1 - y_{(i,j)(m)}[t]\right) D_{ijm} \qquad (j\in\mathcal{N}, i\in\mathcal{I}_j, m\neq i, P_{mj} > P_{ij}, 1\le t\le T)$$

$$P_{ij} - \sum_{k\neq i}^{P_{kj}\le P_{ij}} \beta P_{kj}\cdot\lambda_k[t] - \beta\sigma^2 \ge (1 - x_{ij}[t])H_{ij} \qquad (j\in\mathcal{N}, i\in\mathcal{I}_j, 1\le t\le T)$$

Flow routing:

$$\sum_{j\in\mathcal{I}_i} r_{ij}(f) = r(f) \qquad (f\in\mathcal{F}, i = s(f))$$

$$\sum_{j\in\mathcal{I}_i}^{j\neq s(f)} r_{ij}(f) = \sum_{k\in\mathcal{I}_i}^{k\neq d(f)} r_{ki}(f) \qquad (f\in\mathcal{F}, i\neq s(f), d(f))$$

$$\sum_{f\in\mathcal{F}}^{s(f)\neq j, d(f)\neq i} r_{ij}(f) \le \sum_{t=1}^{T} \frac{R}{T}\cdot x_{ij}[t] \qquad (j\in\mathcal{N}, i\in\mathcal{I}_j)$$

Fig. 6. An optimization framework for SIC, scheduling, and flow routing in a multi-hop wireless network.

our objective is to maximize $\sum_{f\in\mathcal{F}} w(f)\cdot r(f)$. Listing all the constraints summarized in Fig. 6, we have the following network throughput maximization problem (TMP).

$$\textbf{TMP:} \quad \max \sum_{f\in\mathcal{F}} w(f)\cdot r(f)$$
$$\text{s.t. All constraints in Fig. 6.}$$

TMP is a mixed integer linear program (MILP). Although the theoretical worst-case complexity to a general MILP problem is exponential [7], [24], there exist highly efficient optimality/approximation algorithms (e.g., branch-and-bound with cutting planes [26]) and heuristics (e.g., sequential fixing algorithm [6], [11], [12]) to solve it. Another approach is to apply an off-the-shelf solver (CPLEX [4]), which can successfully handle a moderate-sized network. Since the main goal of this paper is to advocate joint optimization of SIC with link and network layers, we will use CPLEX for this purpose. A customized solution to an MILP problem that exploits the physical relationships among the variables can be developed separately (see, for example [20]) and its discussion is beyond the scope of this paper. The proposed framework is centralized in nature. A natural approach to implement this framework is to employ a software-defined network (SDN)-like architecture, where a central controller collects information from all the nodes, computes the optimal solution, and then conveys the optimal solution to each node in the network. Note that the proposed framework may not be compatible with traditional 802.11 protocol, which is distributed in nature and cannot achieve our optimization objective.

B. A 20-node Network

In this section, we will use a 20-node 3-session network as an example to explain the details of our solution. Another set of results for a 50-node 5-session network will be provided in the next section. We ran the CPLEX solver on a Dell Precision T7600 workstation, which has dual Intel Xeon CPUE5-2687W CPUs (each with 8 cores) running at 3.1 GHz. The memory of the workstation is 64 GB and the OS is Windows 7 Professional. The results for the 20-node network can be obtained in less than an hour, and the results for the 50-node network can be obtained in less than three hours.

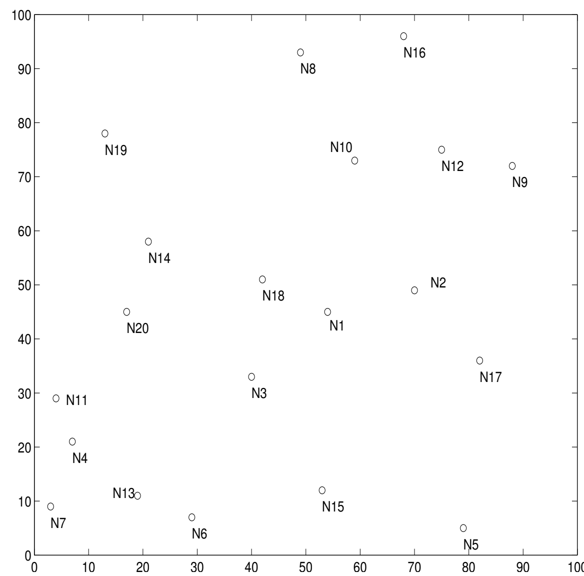


Fig. 7. The topology of a 20-node network.

TABLE II
SOURCE NODE, DESTINATION NODE, AND WEIGHT OF EACH SESSION IN THE 20-NODE NETWORK.

Session f	Source Node $s(f)$	Dest. Node $d(f)$	Weight $w(f)$
1	2	11	5.0
2	8	3	6.0
3	19	9	7.0

1) Simulation Setting: We consider a randomly generated multi-hop wireless network with 20 nodes, which are distributed in a 100×100 area. For generality, we normalize all units for distance, data rate, bandwidth, and power with appropriate dimensions. The topology of the network is shown in Fig. 7. There are three active sessions in the network, with each session's source node, destination node, and weight given in Table II.

The transmission power of each node is set to $P = 1$. For simplicity, we assume that channel gain g_{ij} only includes the path loss between nodes i and j and is given by $g_{ij} = d_{ij}^{-\gamma}$, where d_{ij} is the distance between nodes i and j, and $\gamma = 3$ is the path loss index. The power of ambient noise is $\sigma^2 = 10^{-6}$.

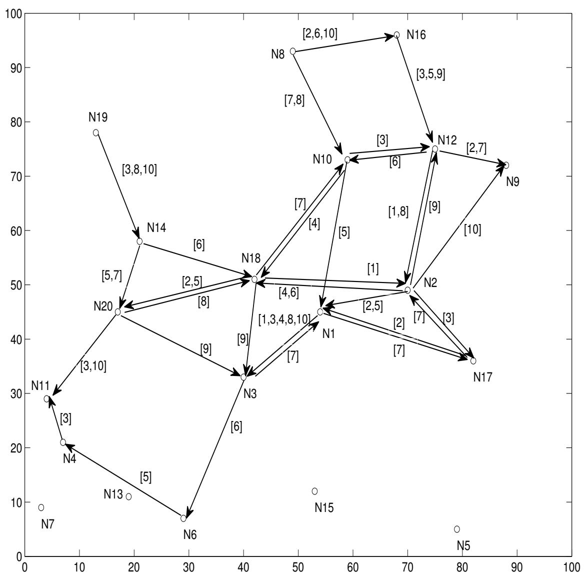


Fig. 8. Optimal routing and scheduling solution to TMP problem for the 20-node network.

TABLE III
ACTIVE LINKS IN EACH TIME SLOT IN THE OPTIMAL SOLUTION FOR THE 20-NODE NETWORK.

Time slot	Active links
1	$1 \to 3$, $12 \to 2$, $18 \to 2$
2	$2 \to 1$, $8 \to 16$, $12 \to 9$, $17 \to 1$, $18 \to 20$
3	$1 \to 3$, $2 \to 17$, $4 \to 11$, $10 \to 12$, $16 \to 12$, $19 \to 14$, $20 \to 11$
4	$1 \to 3$, $2 \to 18$, $10 \to 18$
5	$2 \to 1$, $6 \to 4$, $10 \to 1$, $14 \to 20$, $16 \to 12$, $18 \to 20$
6	$1 \to 17$, $2 \to 18$, $3 \to 6$, $8 \to 16$, $12 \to 10$, $14 \to 18$
7	$3 \to 1$, $8 \to 10$, $12 \to 9$, $14 \to 20$, $17 \to 2$, $18 \to 10$
8	$1 \to 3$, $8 \to 10$, $12 \to 2$, $19 \to 14$, $20 \to 18$
9	$2 \to 12$, $10 \to 1$, $16 \to 12$, $18 \to 3$, $20 \to 3$
10	$1 \to 3$, $2 \to 9$, $8 \to 16$, $19 \to 14$, $20 \to 11$

There are $T = 10$ time slots in each time frame. The SINR threshold for a successful transmission is $\beta = 1$. When a node i transmits to node j successfully in time slot t (i.e. $x_{ij}[t] = 1$), the achieved data rate is $R = 1$.

2) Results: For the 20-node network, we apply CPLEX solver for the TMP formulation. The optimal objective value (maximum weighted sum throughput) is 6.6, with respective data rates for sessions 1, 2 and 3 being 0.3, 0.5 and 0.3. Fig. 8 shows the optimal routing and scheduling in the solution, where the numbers in the brackets next to a link show the time slots in a frame when the link is active. For example, $[3, 8, 10]$ next to link $19 \to 14$ means that this link is active in time slots 3, 8, and 10.

Table III shows the set of active links in each time slot. Our solution divides different links which are used to support the end-to-end sessions into different time slots so that the set of links in each time slot can successfully coexist (i.e., all links in each time slot satisfy the sequential SINR constraints in (1)). We use scheduling to overcome the limitations of SIC (clearly, the links in Table III cannot be active in one single time slot). By exploiting the interference through SIC, we are able to activate as many links as possible in a time slot to maximize the network throughput. For example, in time slot 2, both nodes 2 and 17 transmit to node 1 simultaneously.

From Table III, we can validate the behavior of SIC quantitatively as follows. SIC allows a node to receive signals from multiple transmitters and reject the interference from other nodes in the same time slot. As an example, we look at the active links in time slot 1 in Table III. In this time slot, links $1 \to 3$, $12 \to 2$ and $18 \to 2$ are active simultaneously. For receiver 2, the signal from node 1 (transmitting to node 3) is an interference to receiver 2, while the signals from nodes 12 and 18 are intended signals. In this example, we will show that receiver 2 rejects the interference from node 1 and receives concurrent transmissions from nodes 12 and 18.

The received signal powers from nodes 1, 12 and 18 at node 2 are $P_{1,2} = 22.29 \times 10^{-5}$, $P_{12,2} = 5.39 \times 10^{-5}$ and $P_{18,2} = 4.52 \times 10^{-5}$, respectively. Receiver 2 first tries to decode the strongest signal, which is from node 1. Note that this is an interference signal. The r-SINR for decoding this signal is

$$\frac{P_{1,2}}{P_{12,2}+P_{18,2}+\sigma^2} = \frac{22.29 \times 10^{-5}}{(5.39+4.52+0.1)\times 10^{-5}} = 2.23 > \beta = 1,$$

which shows that the interference signal from node 1 can be successfully decoded at receiver 2. After subtracting the interference from node 1 from the composite signal (i.e., interference rejection), receiver 2 moves on to decode the second strongest signal, which is from node 12. For this intended signal, its r-SINR is

$$\frac{P_{12,2}}{P_{1,2}+P_{18,2}-P_{1,2}+\sigma^2} = \frac{5.39 \times 10^{-5}}{(4.52+0.1)\times 10^{-5}} = 1.17 > \beta = 1.$$

Thus, the signal from node 12 can be decoded successfully at receiver 2. Receiver 2 subtracts this signal from node 12 from the remaining composite signal and continues to decode the intended signal from node 18. The r-SINR for for decoding this signal is

$$\frac{P_{18,2}}{\sigma^2} = \frac{4.52 \times 10^{-5}}{10^{-6}} = 45.2 > \beta = 1 \ ,$$

which shows a successful decoding and reception.

3) Comparison to the Case without SIC: As a final part of our numerical results for this 20-node network, we compare our optimal result to the TMP problem to the optimal result when SIC is not employed. We call the problem formulation under this case (without SIC) as TMP-Pure. Here, only link layer scheduling is employed to avoid interference. The joint PHY-Link constraints will change. When decoding a signal from i to node j, we treat all the signals from other transmitting nodes as noise. Then, for a successful transmission from node i to node j in time slot t (i.e., $x_{ij}[t] = 1$), we need the following statement:

$$\text{If } x_{ij}[t] = 1, \text{ then } \frac{P_{ij}}{\sum_{k \neq i} P_{kj}\lambda_k[t] + \sigma^2} \geq \beta \quad (j \in \mathcal{N}, i \in \mathcal{I}_j, 1 \leq t \leq T) \ .$$

The above statement can be written as

$$P_{ij} - \sum_{k \neq i} \beta P_{kj}\lambda_k[t] - \beta\sigma^2 \geq (1 - x_{ij}[t])M_{ij} \quad (j \in \mathcal{N}, i \in \mathcal{I}_j, 1 \leq t \leq T) \ , \tag{27}$$

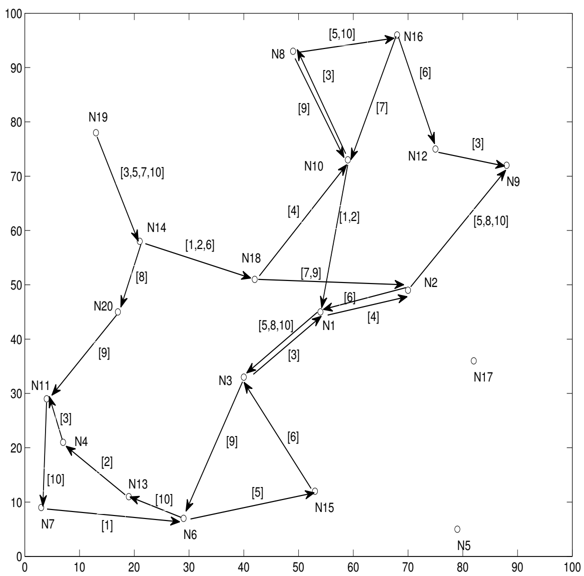


Fig. 9. The routing and scheduling results under the case when SIC is not used in the 20-node network.

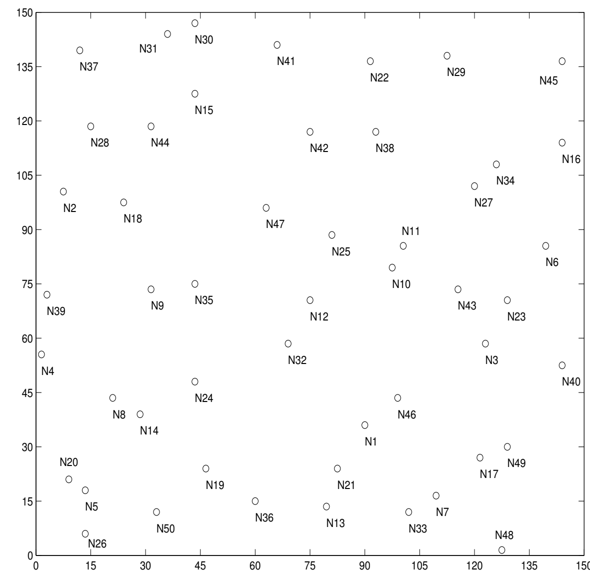


Fig. 10. The topology of a 50-node network.

TABLE IV
ACTIVE LINKS IN EACH TIME SLOT WHEN SIC IS NOT USED IN THE 20-NODE NETWORK.

Time slot	Active links
1	$7 \to 6$, $10 \to 1$, $14 \to 18$
2	$10 \to 1$,$13 \to 4$, $14 \to 18$
3	$3 \to 1$,$4 \to 11$,$10 \to 8$,$12 \to 9$,$19 \to 14$
4	$1 \to 2$, $18 \to 10$
5	$1 \to 3$, $2 \to 9$, $6 \to 15$, $8 \to 16$, $19 \to 14$
6	$2 \to 1$, $14 \to 18$, $15 \to 3$, $16 \to 12$
7	$16 \to 10$, $18 \to 2$, $19 \to 14$
8	$1 \to 3$, $2 \to 9$, $14 \to 20$
9	$3 \to 6$, $8 \to 10$, $18 \to 2$,$20 \to 11$
10	$1 \to 3$,$2 \to 9$, $6 \to 13$,$8 \to 16$

where M_{ij} is a lower bound of $P_{ij} - \beta \sum_{k \neq i} P_{kj} \lambda_k[t] - \beta\sigma^2$. Under this model, TMP-Pure has the same scheduling and flow routing constraints as that of problem TMP. Then, the formulation of TMP-Pure is as follows.

$$
\begin{aligned}
& \max \sum_{f \in \mathcal{F}} w(f) \cdot r(f) \\
& \text{s.t. Constraints } (8), (9), (11), (14), (26), (27) \\
& \quad x_{ij}[t], \lambda_i[t] \in \{0, 1\} \; (i \in \mathcal{N}, j \in \mathcal{I}_i, 1 \le t \le T) \\
& \quad r(f), r_{ij}(f) \ge 0 \quad (f \in \mathcal{F}, i \in \mathcal{N}, j \in \mathcal{I}_i)
\end{aligned}
$$

The formulated problem TMP-Pure is also a mixed integer linear program (MILP). Again, we use CPLEX to solve TMP-Pure for the same 20-node network.

The optimal objective value (maximum weighted sum of throughput) is now 4.5 (vs. 6.6 for TMP), with the data rates for the three sessions being 0.1, 0.2 and 0.4, respectively. In comparison, when SIC is employed, we have $\frac{6.6-4.5}{4.5} = 47\%$ increase in throughput.

The optimal routing and scheduling results are shown in Fig. 9. The active links in each time slot are given in Table IV. We now compare Fig. 9 and Table IV to Fig. 8 and Table III, respectively. It is clear that without SIC, fewer number of links are active in a pure interference avoidance solution.

TABLE V
SOURCE NODE, DESTINATION NODE, AND WEIGHT OF EACH SESSION IN THE 50-NODE NETWORK.

Session f	Source Node $s(f)$	Dest. Node $d(f)$	Weight $w(f)$
1	15	29	7.0
2	40	10	6.0
3	38	35	10.0
4	4	19	8.0
5	9	7	9.0

C. A 50-node Network

In this section, we consider a 50-node 5-session network which is distributed in a 150×150 area. The topology of the network is shown in Fig. 10. For the five active sessions, the source node, destination node, and weight of each session are given in Table V.

Again, we apply CPLEX solver for the TMP formulation. The optimal objective value (maximum weighted sum throughput) is 16.5, with respective data rates for sessions $1, 2, 3, 4$, and 5 being $0.2, 0.9, 0.3, 0.5$, and 0.3. Fig. 11 shows the optimal routing and scheduling in the solution. Table VI shows the set of active links in each time slot.

For comparison, we use CPLEX to solve TMP-Pure for the same 50-node network. The optimal objective value (maximum weighted sum of throughput) is now 11.5 (vs. 16.5 for TMP), with the data rates for the five sessions being $0.3, 0.4, 0.2, 0.4$, and 0.2, respectively. Comparing to the case when SIC is not used, we have $\frac{16.5-11.5}{11.5} = 43.5\%$ increase in throughput performance.

The optimal routing and scheduling results are shown in Fig. 12. The active links in each time slot are given in Table VII. Compare Fig. 12 and Table VII to Fig. 11 and

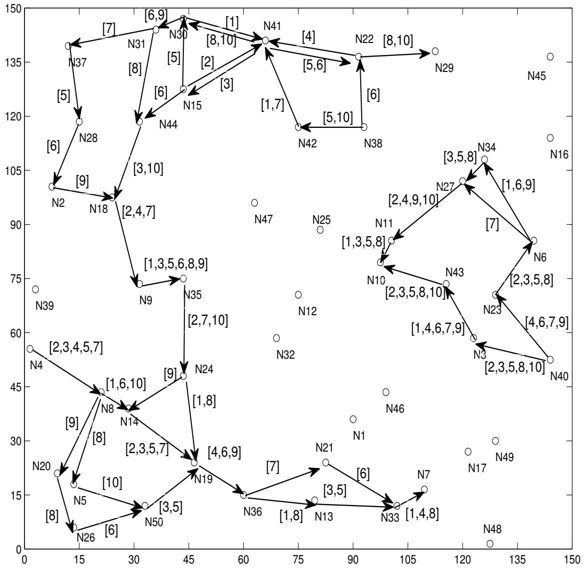


Fig. 11. Optimal routing and scheduling solution to TMP problem for the 50-node network.

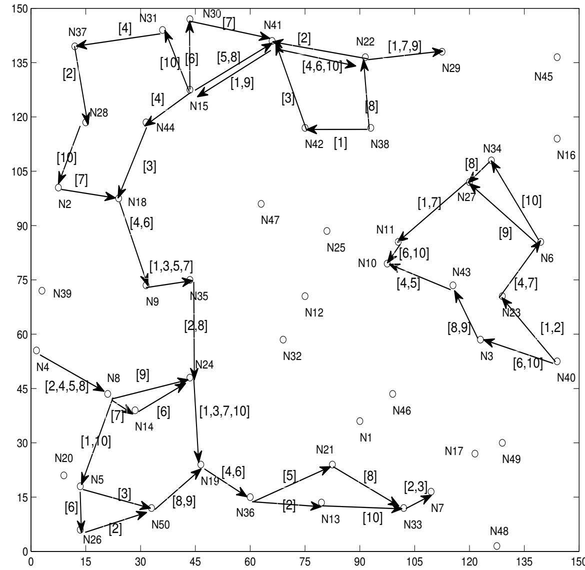


Fig. 12. The routing and scheduling results under the case when SIC is not used in the 50-node network.

TABLE VI
ACTIVE LINKS IN EACH TIME SLOT IN THE OPTIMAL SOLUTION FOR THE 50-NODE NETWORK.

Time slot	Active links
1	$3 \to 43$, $6 \to 34$, $8 \to 14$, $9 \to 35$, $11 \to 10$, $24 \to 19$ $30 \to 41$, $33 \to 7$, $36 \to 13$, $42 \to 41$
2	$4 \to 8$, $14 \to 19$, $15 \to 41$, $18 \to 9$, $23 \to 6$, $27 \to 11$ $35 \to 24$, $40 \to 3$, $43 \to 10$
3	$4 \to 8$, $9 \to 35$, $11 \to 10$, $13 \to 33$, $14 \to 19$, $23 \to 6$ $34 \to 27$ $40 \to 3$ $41 \to 15$ $43 \to 10$ $44 \to 18$ $50 \to 19$
4	$3 \to 43$, $4 \to 8$, $18 \to 9$, $19 \to 36$, $22 \to 41$, $27 \to 11$ $33 \to 7$, $40 \to 23$
5	$4 \to 8$, $9 \to 35$, $11 \to 10$, $13 \to 33$, $14 \to 19$, $15 \to 30$ $23 \to 6$, $34 \to 27$, $37 \to 28$, $38 \to 42$, $40 \to 3$, $41 \to 22$ $43 \to 10$, $50 \to 19$
6	$3 \to 43$, $6 \to 34$, $8 \to 14$, $9 \to 35$, $15 \to 44$, $19 \to 36$ $21 \to 33$, $26 \to 50$, $28 \to 2$, $30 \to 31$, $38 \to 22$, $40 \to 23$ $41 \to 22$
7	$3 \to 43$, $4 \to 8$, $6 \to 27$, $14 \to 19$, $18 \to 9$, $31 \to 37$ $35 \to 24$, $36 \to 21$, $40 \to 23$, $42 \to 41$
8	$8 \to 5$, $9 \to 35$, $11 \to 10$, $20 \to 26$, $22 \to 29$, $23 \to 6$ $24 \to 19$, $31 \to 44$, $33 \to 7$, $34 \to 27$, $36 \to 13$, $40 \to 3$ $41 \to 30$, $43 \to 10$
9	$2 \to 18$, $3 \to 43$, $6 \to 34$, $8 \to 20$, $9 \to 35$, $19 \to 36$ $24 \to 14$, $27 \to 11$, $30 \to 31$, $40 \to 23$
10	$5 \to 50$, $8 \to 14$, $22 \to 29$, $27 \to 11$, $35 \to 24$, $38 \to 42$ $40 \to 3$, $41 \to 30$, $43 \to 10$, $44 \to 18$

TABLE VII
ACTIVE LINKS IN EACH TIME SLOT WHEN SIC IS NOT USED IN THE 50-NODE NETWORK.

Time slot	Active links
1	$8 \to 5$, $9 \to 35$, $22 \to 29$, $24 \to 19$, $27 \to 11$, $38 \to 42$ $40 \to 23$, $41 \to 15$
2	$4 \to 8$, $22 \to 41$, $26 \to 50$, $33 \to 7$, $35 \to 24$, $36 \to 13$ $37 \to 28$, $40 \to 23$
3	$5 \to 50$, $9 \to 35$, $24 \to 19$, $33 \to 7$, $42 \to 41$, $44 \to 18$
4	$4 \to 8$, $15 \to 44$, $18 \to 9$, $19 \to 36$, $23 \to 6$, $31 \to 37$ $41 \to 22$, $43 \to 10$
5	$4 \to 8$, $9 \to 35$, $15 \to 41$, $36 \to 21$, $43 \to 10$
6	$5 \to 26$, $11 \to 10$, $14 \to 24$, $15 \to 30$, $18 \to 9$, $19 \to 36$ $40 \to 3$, $41 \to 22$
7	$2 \to 18$, $8 \to 14$, $9 \to 35$, $22 \to 29$, $23 \to 6$, $24 \to 19$ $27 \to 11$, $30 \to 41$
8	$3 \to 43$, $4 \to 8$, $15 \to 41$, $21 \to 33$, $34 \to 27$, $35 \to 24$ $38 \to 22$, $50 \to 19$
9	$3 \to 43$, $6 \to 27$, $8 \to 24$, $22 \to 29$, $41 \to 15$, $50 \to 19$
10	$6 \to 34$, $8 \to 5$, $11 \to 10$, $13 \to 33$, $15 \to 31$, $24 \to 19$ $28 \to 2$, $40 \to 3$, $41 \to 22$

Table VI, respectively. We can also see that without SIC, fewer number of links are active in the final solution.

VIII. CONCLUSIONS

SIC is a simple and powerful technique to mitigate interference. To date, most of research results on SIC were limited to simple network settings. This paper explored SIC for a multi-hop wireless network. After quantifying the fundamental limitations of SIC, we propose a joint optimization framework of SIC at PHY layer, link layer scheduling, and network layer routing for a multi-hop wireless network. Throughput rigorous mathematical development, we characterized an optimization framework through a set of constraints across the PHY, link, and network layers. To demonstrate the utility of this framework, we applied it to study a network throughout optimization problem. Our numerical results affirmed the efficacy of this framework and gave insights on the optimal operation of SIC in a multi-hope wireless network. The findings in this paper fill an important gap on how to optimally use SIC in a multi-hop wireless network.

We considered fixed modulation and coding and thus there is a single SINR threshold and a single rate. If adaptive modulation and coding (AMC) is used, we may formulate the problem by developing coupled constraints for SIC and AMC as follows. (i) The β in constraints (6) and (7) should be replaced by the smallest SINR threshold; and (ii) The R in constraint (11) should be the step function of r-SINR. Given that the step function is nonlinear, the new formulation will be more complex than the current one. We leave its solution as a future work.

Acknowledgments

This work was supported in part by NSF grants 1343222, 1064953, 1443889, and ONR Grant N00014-15-1-2926. Part of W. Lou's work was completed while she was serving as a Program Director at the NSF. Any opinion, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not reflect the views of the NSF. The work of S. Kompella was supported in part by the ONR. The authors thank Virginia Tech's Advanced Research Computing for giving them access to the BlueRidge computer cluster.

References

[1] J.G. Andrews, "Interference cancellation for cellular systems: A contemporary overview," *IEEE Wireless Commun. Magazine,* vol. 12, no. 2, pp. 19–29, April 2005.

[2] E. Aryafar, N. Anand, T. Salonidis, and E. Knightly, "Design and experimental evaluation of multi-user beamforming in wireless LANs," in *Proc. ACM MobiCom,* pp. 197–208, Chicago, IL, Sept. 20–24, 2010.

[3] J. Blomer and N. Jindal, "Transmission capacity of wireless ad hoc networks: Successive interference cancellation vs. joint detection," in *Proc. IEEE ICC,* 5 pages, Dresden, Germany, June 14–18, 2009.

[4] IBM ILOG CPLEX Optimizer, http://www-01.ibm.com/software/integration/optimization/cplex-optimizer/, accessed at May 26, 2016.

[5] P. Frenger, P. Orten, and T. Ottosson, "Code-spread CDMA with interference cancellation," *IEEE Journal on Selected Areas in Commun.,* vol. 17, no. 12, pp. 2090–2095, Dec. 1999.

[6] C. Gao, Y. Shi, Y.T. Hou, H.D. Sherali, and H. Zhou, "Multicast communications in multi-hop cognitive radio networks," *IEEE Journal on Selected Areas in Commun.,* vol. 29, no. 4, pp. 784–793, April 2011.

[7] M.R. Garey and D.S. Johnson, *Computers and Intractability: A Guide to the Theory of NP-Completeness,* W.H. Freeman and Company, New York, 1979.

[8] E. Gelal, K. Pelechrinis, T.S. Kim, I. Broustis, S.V. Krishnamurthy, and B. Rao, "Topology control for effective interference cancellation in multi-user MIMO networks," in *Proc. IEEE INFOCOM,* 9 pages, San Diego, CA, March 15–19, 2010.

[9] T.R. Giallorenzi and S.G. Wilson, "Suboptimum multiuser receivers for convolutionally coded asynchronous DS-CDMA systems," *IEEE Trans. on Commun.,* vol. 44, no. 9, pp. 1183–1196, Sept. 1996.

[10] D. Halperin, T. Anderson, and D. Wetherall, "Taking the sting out of carrier sense: Interference cancellation for wireless LANs," in *Proc. ACM MobiCom*, pp. 339–350, San Francisco, CA, Sept. 14–19, 2008.

[11] Y.T. Hou, Y. Shi, and H.D. Sherali, "Spectrum sharing for multi-hop networking with cognitive radios," *IEEE Journal on Selected Areas in Commun.,* vol. 26, no. 1, pp. 146–155, Jan. 2008.

[12] Y.T. Hou, Y. Shi, and H.D. Sherali, "Optimal base station selection for anycast routing in wireless sensor networks," *IEEE Trans. on Vehicular Technology,* vol. 55, issue 3, pp. 813–821, May 2006.

[13] P. Jung and M. Nasshan, "Results on Turbo-codes for speech transmission in a joint detection CDMA mobile radio system with coherent receiver antenna diversity," *IEEE Trans. on Vehicular Technology,* vol. 46, no. 4, pp. 862–870, April 1997.

[14] S. Katti, S. Gollakota, and D. Katabi, "Embracing wireless interference: Analog network coding," in *Proc. ACM SIGCOMM,* pp. 397–408, Kyoto, Japan, Aug. 27–31, 2007.

[15] X. Liu, A. Sheth, M. Kaminsky, K. Papagiannaki, S. Seshan, and P. Steenkiste, "Pushing the envelope of indoor wireless spatial reuse using directional access points and clients," in *Proc. ACM MobiCom,* pp. 209–220, Chicago, IL, Sept. 20–24, 2010.

[16] S. Lv, X. Wang, and X. Zhou, "Scheduling under SINR model in ad hoc networks with successive interference cancellation," in *Proc. IEEE GLOBECOM,* 5 pages, Miami, FL, Dec. 6–10, 2010.

[17] S. Lv, W. Zhuang, X. Wang, and X. Zhou, "Scheduling in wireless ad hoc networks with successive interference cancellation," in *Proc. IEEE INFOCOM,* pp. 1282–1290, Shanghai, China, April 10–15, 2011.

[18] S. Lv, W. Zhuang, X. Wang, and X. Zhou, "Link scheduling in wireless networks with successive interference cancellation," *Elsevier Computer Networks,* vol. 55, no. 13, pp. 2929–2941, Sept. 2011.

[19] S. Gollakota and D. Katabi, "Zigzag decoding: Combating hidden terminals in wireless networks," in *Proc. ACM SIGCOMM,* pp. 159–170, Seattle, WA, Aug. 17–22, 2008.

[20] X. Qin, X. Yuan, Y. Shi, Y.T. Hou, W. Lou, and S.F. Midkiff, "On Throughput Maximization for a Multihop MIMO Network," in *Proc. IEEE International Conference on Mobile Ad-hoc and Sensor Systems* (IEEE MASS 2013), pp. 37–45, Hangzhou, China, Oct. 14–16, 2013.

[21] L. Qu, J. He, and C. Assi, "Understanding the benefits of successive interference cancellation in multi-rate multi-hop wireless networks," *IEEE Transactions on Communications,* vol. 62, no. 7, pp. 2465–2477, July 2014.

[22] S. Sambhwani, W. Zhang, and W. Zeng, "Uplink interference cancelation in HSPA: Principles and practice," QUALCOMM Inc., San Diego, CA, White Paper, 2009.

[23] A.A. Sani, L. Zhong, and A. Sabharwal, "Directional antenna diversity for mobile devices: Characterizations and solutions," in *Proc. ACM MobiCom,* pp. 221–232, Chicago, IL, Sept. 20–24, 2010.

[24] A. Schrijver, *Theory of Linear and Integer Programming,* Wiley-Interscience, New York, NY, 1986.

[25] S. Sen, N. Santhapuri, R.R. Choudhury, and S. Nelakuditi, "Successive interference cancellation: A back-of-the-envelope perspective," in *Proc. Ninth ACM Workshop on Hot Topics in Networks (HotNets-IX),* Monterey, CA, Oct. 20–21, 2010.

[26] S. Sharma, Y. Shi, Y.T. Hou, H.D. Sherali, S. Kompella, and S.F. Midkiff, "Joint flow routing and relay node assignment in cooperative multi-hop networks," *IEEE Journal on Selected Areas in Commun.,* vol. 30, issue 2, pp. 254–262, Feb. 2012.

[27] Y. Shi, J. Liu, C. Jiang, C. Gao, and Y.T. Hou, "A DoF-based link layer model for multi-hop MIMO networks," *IEEE Transactions on Mobile Computing,* vol. 13, no. 7, pp. 1395–1408, July 2014.

[28] A.P. Subramanian, H. Lundgren, and T. Salonidis, "Experimental characterization of sectorized antennas in dense 802.11 wireless mesh networks," in *Proc. ACM MobiHoc,* pp. 259–268, New Orleans, LA, May 18–21, 2009.

[29] D.N.C. Tse and P. Viswanath, *Fundamentals of Wireless Communication,* Chapter 6, Cambridge Univ. Press, 2005.

[30] M.K. Varanasi and B. Aazhang, "Multistage detection in asynchronous code-division multiple access communications," *IEEE Trans. on Commun.,* vol. 38, no. 4, pp. 509–519, April 1990.

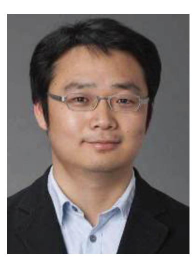
[31] S. Verdu, *Multiuser Detection,* Cambridge Univ. Press, 1998.

[32] A.J. Viterbi, "Very low rate convolutional codes for maximum theoretical performance of spread-spectrum multiple-access channel," *IEEE Journal on Selected Areas in Commun.,* vol. 8, no. 4, pp. 641–649, May 1990.

[33] X. Wang and H.V. Poor, "Iterative (Turbo) soft interference cancellation and decoding for coded CDMA," *IEEE Trans. on Commun.,* vol. 47, no. 7, pp. 1046–1061, July 1999.

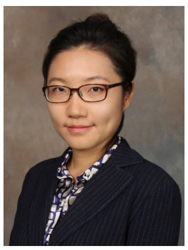
[34] S. Weber, J.G. Andrews, X. Yang, and G. de Veciana, "Transmission capacity of wireless ad hoc networks with successive interference cancellation," *IEEE Trans. on Information Theory,* vol. 53, no. 8, pp. 2799–2814, Aug. 2007.

[35] T. Yoo and A. Goldsmith, "On the optimality of multiantenna broadcast scheduling using zero-forcing beamforming," *IEEE Journal on Selected Areas in Commun.,* vol. 24, no. 3, pp. 528–541, March 2006.

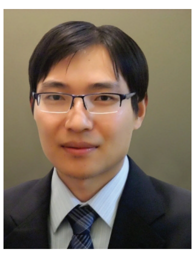


Canming Jiang received the B.E. degree from the Department of Electronic Engineering and Information Science, University of Science and Technology of China, Hefei, China, in 2004 and the M.S. degree from the Graduate School, Chinese Academy of Sciences, Beijing, China, in 2007. He earned his Ph.D. degree in computer engineering from Virginia Tech, Blacksburg, VA, in 2012. He is currently a Senior Software Development Engineer at Shape Security in Mountain View, CA.

Yi Shi (S'02–M'08–SM'13) is a Senior Research Scientist at Intelligent Automation Inc., Rockville, MD, and an Adjunct Assistant Professor at Virginia Tech. His research focuses on optimization and algorithm design for wireless networks and social networks. He has co-organized three IEEE and ACM workshops and has been a TPC member of many major IEEE and ACM conferences. He is an Editor of IEEE Communications Surveys and Tutorials. He authored one book, five book chapters and more than 110 papers on wireless network algorithm design and optimization. He was named an IEEE Communications Surveys and Tutorials Exemplary Editor in 2014. He was a recipient of IEEE INFOCOM 2008 Best Paper Award, IEEE INFOCOM 2011 Best Paper Award Runner-Up, and ACM WUWNet 2014 Best Student Paper Award.



Xiaoqi Qin (S'13) received her B.S. and M.S. degree in Computer Engineering from Virginia Tech, Blacksburg, VA, in 2011 and 2013, respectively. Since Fall 2013, she has been pursuing her Ph.D. degree in the same institution. Her current research interest are algorithm design and cross-layer optimization for wireless networks.



Xu Yuan (S'13–M'16) received his B.S. degree in Computer Science from Nankai University, Tianjin, China, in 2009. Since the Fall 2010, he has been pursuing his Ph.D. degree in the Bradley Department of Electrical and Computer Engineering at Virginia Tech, Blacksburg, VA. His current research interest focuses on algorithm design and optimization for spectrum sharing, coexistence, and cognitive radio networks.

Y. Thomas Hou (F'14) is the Bradley Distinguished Professor of Electrical and Computer Engineering at Virginia Tech, Blacksburg, VA. He received his Ph.D. degree from NYU Tandan School of Engineering (formerly Polytechnic Univ.). His current research focuses on developing innovative solutions to complex cross-layer optimization problems in wireless networks. He has published two graduate textbooks: *Applied Optimization Methods for Wireless Networks* (Cambridge University Press, 2014) and *Cognitive Radio Communications and Networks: Principles and Practices* (Academic Press/Elsevier, 2009). He is the Steering Committee Chair of IEEE INFOCOM conference and a member of the IEEE Communications Society Board of Governors.

Wenjing Lou (F'15) is a professor in the computer science department at Virginia Tech. She received her Ph.D. in Electrical and Computer Engineering from the University of Florida. Her research interests are in the broad area of wireless networks, with special emphases on wireless security and cross-layer network optimization. Since August 2014, she has been serving as a program director at the National Science Foundation. She is the Steering Committee Chair of IEEE Conference on Communications and Network Security (CNS).

Sastry Kompella (S'04–M'07–SM'12) received his Ph.D. degree in computer engineering from Virginia Tech, Blacksburg, Virginia, in 2006. Currently, he is the Head of Wireless Network Theory section, Information Technology Division at the U.S. Naval Research Laboratory (NRL), Washington, DC. His research focuses on complex problems in cross-layer optimization and scheduling in wireless and cognitive radio networks.

Scott F. Midkiff (S'82–M'85–SM'92) is Professor & Vice President for Information Technology and Chief Information Officer at Virginia Tech, Blacksburg, VA. From 2009 to 2012, Prof. Midkiff was the Department Head of the Bradley Department of Electrical and Computer Engineering at Virginia Tech. From 2006 to 2009, he served as a program director at the National Science Foundation. Prof. Midkiff's research interests include wireless and ad hoc networks, network services for pervasive computing, and cyber-physical systems.