An Online Admission Control Algorithm for Dynamic Traffic in Underlay Coexistence Paradigm

Xu Yuan, *Member, IEEE,* Xiaoqi Qin, *Student Member, IEEE,* Feng Tian, *Member, IEEE,*
Brian Jalaian, *Member, IEEE,* Yi Shi, *Senior Member, IEEE,* Y. Thomas Hou, *Fellow, IEEE,*
Wenjing Lou, *Fellow, IEEE,* Wade Trappe, *Fellow, IEEE*

***Abstract*—Underlay is an aggressive spectrum sharing paradigm that allows secondary nodes to be active simultaneously with the primary nodes through interference cancelation (IC). In this paper, we design an online admission control algorithm to handle dynamic session arrival and departure in the underlay coexistence paradigm for multi-hop primary and secondary networks. For IC, we employ multiple antennas at each secondary node. Through distributed computation and degree-of-freedom (DoF) allocation at each secondary node, our algorithm ensures that all interference to/from the multi-hop primary network and interference within the multi-hop secondary network are canceled properly so that data transport is free of interference in both multi-hop primary and secondary networks. Further, we show that the DoF allocation by our algorithm is feasible (implementable) at the physical layer at all time. Through extensive performance evaluation, we find that our online admission control algorithm can offer competitive performance when compared to an offline centralized algorithm.**

KEYWORDS

Spectrum sharing, underlay coexistence, dynamic traffic, interference cancelation, MIMO.

I. INTRODUCTION

There has been extensive research on exploring coexistence between primary and secondary networks in recent years. In [6], Goldsmith *et al.* identified three coexistence paradigms, namely *interweave, underlay,* and *overlay.* The interweave paradigm follows the traditional interference avoidance, which refers to that the secondary nodes are allowed to use a spectrum allocated to the primary nodes only when the primary nodes do not use it (in time, frequency, or space) [5], [26]. In this way, interference is effectively avoided through *interweaving* spectrum access between primary and secondary nodes. On the other hand, the underlay paradigm refers to that the secondary nodes are allowed to be active simultaneously on the same spectrum with the primary nodes, as long as the interference produced by the secondary nodes are controlled properly (e.g., through effective interference cancelation [4], [11], [16], [23], [27], [30], [31]). Finally, the overlay paradigm refers to that there are some levels of cooperation between the primary and secondary nodes in data forwarding [9], [15], [21], [28].

One of the biggest challenges for all three paradigms is how to handle the dynamic changes for online traffic arrival and departure in both the primary and secondary networks. Typically, a secondary session arrives and departs over time and so does a primary session. The problem is particularly difficult in a distributed multi-hop network environment. This is because, when a new primary or secondary session arrives, one must quickly make an online decision on whether or not the new session can be admitted into the network. This problem is addressed differently under each of the three paradigms, each with its own unique challenges and solutions. In this paper, we attempt to address this problem for the underlay paradigm, which we believe is the most difficult one among the three. This is because unlike overlay, underlay does not allow active cooperation between the primary and secondary nodes and puts all burden related to interference management to the secondary nodes. Also, unlike interweave, underlay allows simultaneous activation of the secondary nodes with the primary nodes through interference cancellation (IC), which is more aggressive and complex than merely avoiding interference (under interweave).

There were active efforts to study efficient online admission control algorithms to handle traffic dynamics even in the old days for the telephone network. But the problems there were much simpler (e.g., wired network, no consideration of IC). For spectrum sharing in the interweave paradigm, there have been some recent studies on handling dynamic traffic (e.g., [2], [7], [13]). The focus there was mainly on utilizing spectrum holes efficiently and to avoid interference to the primary users (no active IC). In the overlay paradigm, there are also some studies addressing dynamic traffics (see, e.g., [3], [25]). The primary goal there was to identify optimal scheduling so that traffic could be successfully relayed from a source to its destination node. In the underlay paradigm, the problem becomes much harder as the goal is to enable

Manuscript received January 25, 2015; revised May 5, 2016, August 20, 2016 and September 28, 2016; accepted September 29, 2016.

X. Yuan was with Virginia Polytechnic Institute and State University, Blacksburg, VA 24061 USA. He is now with University of Toronto, Toronto, ON M5S 3G4, Canada. (e-mail: xuyuan@ece.utoronto.ca).

X. Qin was with Virginia Polytechnic Institute and State University, Blacksburg, VA 24061 USA. She is now Beijing University of Posts and Telecommunications, Beijing 102209, China. (e-mail: xiaoqi@vt.edu).

F. Tian is with Nanjing University of Posts and Telecommunications, Nanjing, Jiangsu 210003, China. (e-mail:tianf@njupt.edu.cn).

B. Jalaian was with Virginia Polytechnic Institute and State University, Blacksburg, VA 24061 USA. He is now with US Army Research Laboratory, Adelphi, MD 20783, USA. (e-mail: bran@vt.edu).

Y. Shi is with the Intelligent Automation Inc., Rockville, MD, 20855, USA. (e-mail: yshi@vt.edu).

Y.T. Hou and W. Lou are with Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, USA. (email: {thou, wjlou}@vt.edu).

W. Trappe is with Rutgers University, New Brunswick, NJ 08901, USA. (email: trappe@winlab.rutgers.edu).

aggressive (simultaneous) spectrum access by the secondary nodes through IC to the primary nodes. To date, some efforts (e.g., [4], [11], [16], [23], [27], [30], [31]) have worked on exploiting MIMO on secondary nodes to achieve the underlay paradigm. But none of them considered dynamic traffic in multi-hop primary and secondary networks. The novelty of this paper is that it offers the first study on admission control for dynamic traffic in the underlay paradigm where both the primary and secondary networks are multi-hop wireless networks.

The need of this research can be well justified by some real-world applications. It is well known that multi-hop ad hoc networks do not rely on any fixed infrastructure and are the primary means of communications for the military and emergency responders. As an example, consider a primary multi-hop network, which may come from one branch of the armed forces (e.g., Navy). To efficiently utilize the spectrum used by the primary network, a secondary (multi-hop) network from another branch of the armed forces (e.g., Marine Corps) can employ the underlay coexistence paradigm to achieve its communication needs without being disruptive to the primary network.

The goal of this paper is to design an online admission control algorithm to handle dynamic arrival and departure for sessions over multi-hop networks in the underlay paradigm. For IC, we consider employing multiple antennas on the secondary nodes. Since it takes time to configure the precoding/decoding vectors at a secondary node for spatial multiplexing (SM) and IC, per packet level dynamic traffic management [12] does not appear to be practical. Instead, our traffic management algorithm is to address session (flow) level dynamics, i.e., to determine if a new session can be admitted into the network and how to control the additional IC that comes with it. The novelty of this algorithm is that it can always adopt dynamic traffic changes with the time. Each secondary node only needs to perform local computation to achieve underlay coexistence with the primary network, and the feasibility at the PHY layer is always guaranteed at all nodes. In particular, our algorithm is designed with the following capabilities and features:

- When a new secondary session initiates, the algorithm is able to make a quick decision on whether or not it can join the network through distributed computation. If a secondary session is admitted into the network, then our algorithm will configure MIMO degree-of-freedom (DoFs) at each secondary node so that all interference to/from the primary nodes are properly canceled, as required for underlay coexistence.
- When a new primary multi-hop session enters the network, the algorithm is able to vacate any active secondary session that may be of hinderance. An active secondary session is allowed to be active only if it is able to cancel all interference to/from the primary nodes.
- At all time, our algorithm is able to guarantee that IC (as defined by MIMO DoF allocation) is feasible at the PHY layer for all MIMO transmitters and receivers. By "feasible" at the PHY layer, we mean that there exists a set of feasible precoding vectors at the secondary transmitters and a set of feasible decoding vectors at the secondary receivers so that all data in both multi-hop primary and secondary networks can be transported free of interference.
- Our online admission control algorithm is able to offer competitive performance when compared to an offline centralized algorithm.

The remainder of this paper is organized as follows. In Section II, we review the underlay coexistence paradigm and understand how interference is managed at the PHY layer. In Section III, we describe network setting and discuss the problem that we are going to study in this paper. In Section IV, we propose an online admission control algorithm to handle initiation and termination of primary/secondary sessions in the underlay coexistence paradigm. A proof of PHY layer feasibility of our algorithm is also given in Section V. Section VI presents performance evaluation of our algorithm. Section VII concludes this paper.

II. PRELIMINARIES: THE UNDERLAY COEXISTENCE PARADIGM

The underlay coexistence paradigm refers to that the secondary network is allowed to be active concurrently with the primary network in the same spectrum, as long as its interference to the primary network is negligible (e.g., kept at the noise floor) [6]. In contrast to interweave, which solely relies on interference avoidance, underlay relies on more powerful interference management techniques to enable concurrent activations of both the primary and secondary networks. In underlay, the primary nodes' behavior is *not* affected by the secondary nodes. The primary nodes may use the spectrum freely to serve their needs as if they were the only nodes that use the spectrum. On the other hand, to ensure their interference to the primary nodes is negligible, the secondary nodes must take appropriate measures in interference management during their transmissions. To ensure "underlay", all burdens (or actions) on interference management must rest solely on the secondary nodes and remain unnoticeable to the primary nodes.

There are many measures that the secondary nodes can take to control its interference to the primary network (e.g., UWB [33], MIMO). A very promising approach for the secondary nodes to control its interference is to exploit IC capabilities offered by multiple antennas at the node (i.e., MIMO). MIMO has already become pervasive in wireless communications (e.g., cellular, WiFi) and offers unprecedented capabilities in improving throughput, mitigating interference, and enhancing reliability [1], [24]. There have been some active efforts on exploiting MIMO on the secondary nodes in the underlay paradigm [4], [11], [16], [23], [27], [30], [31].

To understand how MIMO can help the secondary nodes achieve underlay coexistence paradigm, we consider the following simple example. In Fig. 1, we have a pair of primary transmit/receive nodes and a pair of secondary transmit/receive nodes. Suppose the primary transmit/receive nodes (m and k) are each equipped with a single antenna, while the secondary transmit/receive nodes (i and j) are each equipped with four

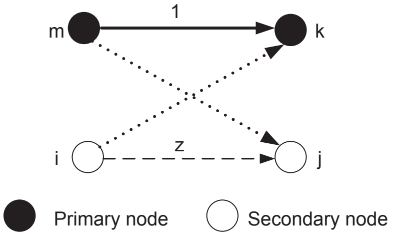

Fig. 1. Underlay coexistence of one secondary link with one primary link. A solid line represents a primary link, a dashed line represents a secondary link, and a dotted line represents interference.

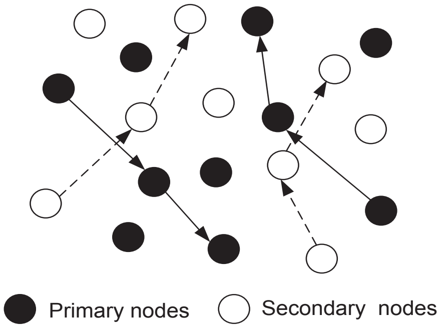

Fig. 2. An illustration of the multi-hop primary and secondary networks co-exist in the same area.

antennas. We assume the primary node m is transmitting one data stream to the primary receive node k. To allow concurrently transmission from secondary node i to node j, we must ensure that the interference from node i is canceled at primary receiver k so that k does not feel the presence of the secondary nodes. Further, at secondary receive node j, the interference from primary transmitter m must be canceled. Otherwise, node j will not be able to decode the signals from node i.

In this example (Fig. 1), we assume that secondary node i hopes to transmit z data streams to secondary receive node j. For data stream $a = 1, \cdots, z$, denote $\mathbf{u}_i^a$ as its 4×1 transmit vector at node i and $\mathbf{v}_j^a$ as a 4×1 receive vector at receive node j. For the data stream from primary transmit node m to receive node k, denote u_m and v_k as the weights at transmit node m and receive node k, respectively. Denote $\mathbf{H}_{(i,j)}$, $\mathbf{H}_{(i,k)}$, and $\mathbf{H}_{(m,j)}$ as the channel matrices between node i and j, i and k, and m and j, respectively. The dimensions of $\mathbf{H}_{(i,j)}$, $\mathbf{H}_{(i,k)}$, and $\mathbf{H}_{(m,j)}$ are 4×4, 4×1, and 1×4, respectively. We assume all channels are of full rank. To achieve underlay, secondary transmit node i must cancel its interference to primary receiver k. We have

$$(\mathbf{u}_i^a)^T \mathbf{H}_{(i,k)} v_k = 0 \ , \qquad (1 \le a \le z) \ . \tag{1}$$

In addition, to have secondary node j to receive from i free of the interference from primary transmit node m, secondary node j must cancel this interference. We have

$$u_m \mathbf{H}_{(m,j)} \mathbf{v}_j^a = 0 \ , \qquad (1 \le a \le z) \ . \tag{2}$$

After canceling all interference to the primary receiver and from the primary transmitter, the secondary transmit node i may transmit z data streams to its intended receive node j via spatial multiplexing (SM). We have:

$$(\mathbf{u}_i^a)^T \mathbf{H}_{(i,j)} \mathbf{v}_j^a = 1 \ , \qquad (1 \le a \le z) \ , \tag{3}$$

$$(\mathbf{u}_i^a)^T \mathbf{H}_{(i,j)} \mathbf{v}_j^b = 0 \ , \qquad (1 \le a \le z, 1 \le b \le z, a \ne b) \ . \tag{4}$$

If we can find a feasible solution to $\mathbf{u}_i^a$ and $\mathbf{v}_j^a$ for (1), (2), (3), and (4), then the secondary link (i to j) can be active simultaneously with the primary link and we can achieve underlay for the secondary link.

We now show that we can indeed find a feasible solution to $\mathbf{u}_i^a$ and $\mathbf{v}_j^a$ in (1), (2), (3), and (4). Let's consider the first data stream. In constraint (2), since u_m is a constant, $\mathbf{H}_{(m,j)}$ is a 1×4 constant matrix, one can always find z ($z \le 4$) feasible vectors $\mathbf{v}_j^1, \cdots, \mathbf{v}_j^z$ that satisfy this constraint. Now suppose we use one such set of feasible vectors, i.e., $\mathbf{v}_j^1, \cdots, \mathbf{v}_j^z$ are fixed. For precoding vector $\mathbf{u}_i^1$ (a 4×1 vector with 4 free variables), it is constrained by (1), (3), and (4), which has a total of $(1 + z)$ constraints. If $1 + z \le 4$, the number of constraints is no more than the number of variables, then there always exists a feasible precoding vector $\mathbf{u}_i^1$ satisfying (1), (3), and (4). That is, as long as $z \le 3$, we can find a feasible $\mathbf{u}_i^1$. The same arguments hold for $\mathbf{u}_i^2, \cdots, \mathbf{u}_i^z$. In summary, for $z \le 3$, we can construct a set of feasible precoding vectors $\mathbf{u}_i^1, \cdots, \mathbf{u}_i^z$ and decoding vectors $\mathbf{v}_j^1, \cdots, \mathbf{v}_j^z$ that achieve the desired IC (at nodes k and j) and SM (from i to j).

Instead of working with complex matrix representation, a simple model to quantify MIMO resources at a node is the so-called degree-of-freedom (DoF) [8], [24]. Simply put, the total number of DoFs at a node (no more than the number of antenna elements) represents the available resource at the node. A DoF can be used for either data transmission/receiption or IC. Typically, for SM, transmitting one data stream requires one DoF at the transmitter and one DoF at the receiver. For IC to the primary network, the number of DoFs required at a secondary transmitter is equal to the number of data streams that are received at the neighboring primary receivers. For IC from the primary network, the number of DoFs required at a secondary receiver for IC is equal to the number of data streams that are transmitting at the neighboring primary transmitters. The total number of the DoFs consumption (for SM and IC) cannot be more than the number of antennas. For the simple example in Fig. 1, the primary transmitter m uses 1 DoF to transmit 1 data stream to its receiver k. The secondary nodes i and j each has 4 DoFs. Secondary transmitter i uses 1 DoF to cancel its interference to primary receiver k (as k is receiving 1 data stream from m). Secondary receiver j uses 1 DoF to cancel the interference from primary transmitter m (as m is transmitting 1 data stream). Now node i and j each has 3 DoFs left and can transmit up to 3 data streams from i to j, which is consistent to our discussion by using the matrix model in the preceding paragraph.

III. PROBLEM DESCRIPTION

In this paper, we address underlay coexistence for the secondary users under dynamic traffic patterns. Consider a set of primary nodes $\mathcal{P}$ co-located with a set of secondary nodes $\mathcal{S}$ in the same geographical region. We consider multi-hop ad hoc network for both primary and secondary networks.

Within the primary network, new sessions arrive following a Poisson process.[1] Each new session consists of a source and a destination node and employs shortest path (unicast) routing (e.g., AODV [17], DSR [10]), as shown in Fig. 2. If the new primary session can be supported (through time slot scheduling), its holding time will follow certain distribution. Upon completing its holding time, the primary session will terminate and leave the network. Given that the primary nodes do not have any IC responsibility, we assume each primary node is equipped with a single antenna (just as in Fig. 1). For a new primary session, we assume it has a rate requirement of 1 data stream, which can be supported by a single antenna. We assume both the primary and secondary networks are based on TDMA system, where a time frame consists of several time slots. The time frame repeats itself and scheduling for the primary or secondary user is done for the entire frame (on every time slot). We suppose there are T time slots in a frame. The primary nodes can use this set of time slots freely as if they are the only nodes in the network (without any consideration of the secondary nodes). To ensure mutual and self interference are avoided, we need to have a feasible scheduling solution for all active primary sessions. If a new primary session is attempting to enter the network, it will try to find a feasible scheduling solution based on unused time slots along its path (without altering the current scheduling for the other active primary sessions). If such a feasible solution does not exist for a new session, it means that the network cannot support this additional primary session and it has to be dropped (lost).

For the secondary network $\mathcal{S}$, suppose its new session arrivals also follow a Poisson process. Each new secondary session consists of a source and a destination node and employs shortest path (unicast) routing. For IC, we assume each secondary node is equipped with multiple antennas (as in Fig. 1). Suppose each new secondary session has a rate requirement, which corresponds to a number of data streams in MIMO. To enter the network, the new session must ensure that in each time slot along its path: (i) its interference to the primary receivers is canceled; and (ii) the interference from the primary transmitters to the secondary receivers is canceled. The interference in (i) and (ii) is known as inter-network interference. In addition, the new session must also take care of potential mutual interference and self interference within its own secondary network (also known as intra-network interference). Only if the new session can take care of both inter- and intra-network interference successfully can it be admitted into the network. If the new secondary session can be supported (underlay coexistence), its holding time will follow certain distribution. Upon completing its holding time, the secondary session terminates and leaves the network. If the new session cannot be supported for any reason, it has to be dropped (lost).

The above network setting and session behavior reflect the dynamic traffic patterns of primary and secondary sessions in an operational environment. The goal of this paper is to develop an online admission control algorithm for the secondary network to handle such traffic dynamics. In particular, we want our online admission control algorithm to meet the following objectives:

- When a new secondary session initiates, the algorithm must be able to make a fast decision on whether or not it can join the network. Such decision must be made through distributed computation based on information stored locally at the nodes along the path of the new session. An "admit" decision for a new secondary session must successfully address inter- and intra-network interference that is required for underlay coexistence.
- When a new primary session enters the network, existing secondary sessions must make a quick assessment on its impact and formulate a plan on how to accommodate this new primary session. This includes allocation of addition DoFs (if available) for IC. In the extreme case, one (or more) secondary sessions may need to exit the network as the primary session always has pre-emptive priority in terms of spectrum access.
- At all time, our online admission control algorithm must ensure that IC is feasible at the PHY layer at all nodes. By feasible at the PHY layer, we mean that there exist a feasible set of precoding vectors at the secondary transmitters and a feasible set of decoding vectors at the secondary receivers so that all data (in both primary and secondary networks) can be transported free of interference.
- For performance, we hope our online admission control algorithm can offer a competitive performance when compared to an offline centralized algorithm. Although the latter is not practical for implementation in an online dynamic network environment, it offers a benchmark for comparison and can be used to measure the quality of our online admission control algorithm.

IV. AN ONLINE ADMISSION CONTROL ALGORITHM

In this section, we present our design of an online admission control algorithm to handle dynamic arrival/departure of the primary and secondary sessions in the underlay coexistence paradigm. The crux of the algorithm is distributed resource allocation (DoFs on the secondary nodes for SM and IC) and the use of local information to accomplish traffic management. With dynamic traffic arrival/departure, the online algorithm must achieve underlay coexistence at all time, i.e., the primary nodes do not feel the presence or activities of the secondary nodes.

There are four types of events that constitute traffic dynamics: initiation of a new secondary session, termination of an existing secondary session, initiation of a new primary session, termination of an existing primary session. Among these four types of events, the initiation of a new secondary or primary session needs most considerations. When a new secondary session initiates in the network, the online algorithm should make a link-by-link based decision on whether or not

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[1] We do not mention stationarity for session arrivals and departures. We considered Poisson arrival and exponential holding time traffic model as an example to evaluate the performance of our online algorithm. It should be clear that the behavior of our online algorithm is independent of the specific arrival/departure process (whether stationary or not). That is, it works for any traffic arrival/departure model.

at each node along the path there are enough DoFs (over T time slots) to support SM and intra/inter-network IC. When a new primary session arrives, the secondary nodes must take immediate actions to ensure that they will not interfere with the new primary session. Since our algorithm is online and distributed in nature, many race conditions (possible concurrent events) must be addressed. Finally, we must ensure that the DoF allocations at the secondary nodes for SM and IC are indeed feasible at the PHY layer at all time. That is, we must guarantee that one can come up with feasible precoding/decoding vectors at each secondary node to support the proposed DoF allocations.

In this section, we present a distributed algorithm to address the above problems. In Section IV-A, we define the set of local information that needs to be maintained at each secondary node. In Sections IV-B to IV-E, we present the details of our algorithm to handle the four types of traffic dynamics, with emphasis on new secondary and primary sessions arrivals. In Section IV-F, we show how to solve different race conditions that may occur.

A. Information Maintained at Secondary Nodes

Recall that the secondary nodes have full responsibility in canceling interference to/from the primary network to achieve underlay coexistence. This is a very challenging objective for an online admission control algorithm, particularly when the primary network is not required to communicate directly with the secondary network in the underlay paradigm. To address these challenges, we make the following assumptions and provide necessary justifications.

- *(i) Network topology.* We assume the primary network and the secondary network are each fully connected on its own. That is, any primary node can reach another primary node via single or multiple primary relay nodes. The same also holds true for any secondary node.
- *(ii) Node location information.* We assume that each secondary node has precise information about its location. This can be made possible by the widely available of GPS capability in mobile devices.
- *(iii) Eavesdropping.* We assume the secondary nodes can listen to all communications among the primary nodes. This is important for the secondary nodes to sense the activities of the primary sessions and their transmission/reception behaviors in each time slot.
- *(iv) Control channel.* We assume there is a separate control channel available for the secondary nodes to exchange control information. Control information for the secondary network may propagate one or more hops to reach other secondary nodes..
- *(v) Primary session activity.* For flow (session) level traffic management, we assume there is an explicit link-by-link initiation (set-up) and termination (tear down) phase for each primary session. This assumption will allow DoF allocation (configuration of precoding/decoding vectors) on the secondary nodes to be performed on a feasible time scale.

Among the five assumptions, the eavesdropping assumption is the strongest. The goal of this assumption is to have at least one secondary node to overhear the transmission of each primary node. This assumption is necessary in the development of our online admission control algorithm. Based on these assumptions, some important issues can be addressed. For example, the location of each primary node can be derived, through many available methods in the literature (e.g., [18]).

We now describe the set of local information that needs to be maintained at each secondary node. Our online admission control algorithm will use this local information to make flow management decisions. At each secondary node i, we maintain the following information:

- $\lambda_i^{\mathrm{SM}}(t)$ and $\lambda_i^{\mathrm{RM}}(t)$: $\lambda_i^{\mathrm{SM}}(t)$ is the number DoFs used for SM (either as a transmitter or a receiver) at node i in time slot t. $\lambda_i^{\mathrm{RM}}(t)$ is the remaining available DoFs at node i.
- $\mathcal{X}_i(t)$ and $\mathcal{Y}_i(t)$: These two sets are used to handle inter-network interference to/from the primary nodes. $\mathcal{X}_i(t)$ is the set of node i's neighboring primary transmitters that are active in time slot t, while $\mathcal{Y}_i(t)$ is the set of i's neighboring primary receivers that are active in time slot t. Based on our assumption, the secondary nodes can overhear the primary nodes activities, including all control messages. Together with the derived location information of the primary nodes, the secondary nodes can deduce the set of primary nodes that fall in $\mathcal{X}_i(t)$ and $\mathcal{Y}_i(t)$.
- $\alpha_i^j(t), \beta_i^j(t)$ and $\eta_i^j(t)$: These variables are used to handle intra-network interference among the secondary nodes. $\alpha_i^j(t)$ is the number of DoFs being transmitted in time slot t by a secondary transmitter j that is a neighboring node of i. $\beta_i^j(t)$ is the number of DoFs being received in time slot t by a secondary receiver j that is a neighboring node of i. $\eta_i^j(t)$ is a binary indicator (0 or 1) to denote whether node i is responsible for IC to/from secondary node j in time slot t. $\alpha_i^j(t)$ and $\beta_i^j(t)$ are relatively easy to obtain under our five assumptions.
- Channel state information (CSI): The secondary nodes need to have CSI to perform IC (to/from the primary nodes and within the secondary nodes). To estimate CSI between a secondary node and its neighboring primary nodes, there are two scenarios. First, if the signal from the primary node can be successfully decoded at the secondary node, then the secondary node can estimate CSI by comparing the decoded signal and the actually received one. On the other hand, if the signal from the primary node cannot be successfully decoded at this secondary node, then based on Assumption *(iii)*, there is another secondary node that is in the neighborhood of the primary node can hear and decode the same signal and broadcast this information to other secondary nodes. Again, by comparing the received (but unable to decode) copy of the signal and the successfully decoded copy of the same signal, the secondary node can estimate CSI. In either case, based on the reciprocity property of a wireless channel [22], we can derive CSI in the reverse direction as well. To control the overhead of CSI, we can limit such estimate only during the period when the primary

nodes are active and perform such estimates periodically (instead of continuously). The estimation of CSI within the secondary nodes are much easier as it is independent of the primary nodes. Given that the secondary nodes can share control information, we could employ a commonly known pilot signal sequence at a secondary transmitter for CSI estimation. The neighboring secondary receivers can compare the received copy of the pilot signal sequence with its known version and derive the CSI.

B. Initiation of a New Secondary Session

We first consider how to handle a new secondary session attempting to enter the network. As discussed, the routing path can be found by standard ad hoc routing protocol (e.g., AODV). Denote f as this new session and its source and destination nodes as s_f and d_f, respectively. Suppose that the new session wants to send R data streams from s_f to d_f. We assume the number of antennas at each node is A. For each node i along the path, it stores its previous node ($i.prev$) and next node ($i.next$) information along the path.

To determine whether the new secondary session can be supported while achieving underlay coexistence, we perform hop-by-hop examination/update on each link (more precisely, the two nodes of each link) along the path. We denote Tx and Rx as the transmit and receive nodes of this link, respectively. We start with the first link. Given that there are T time slots in a frame, we begin with the first time slot ($t = 1$).

- For inter-network IC, the Tx node of this link must use its available DoFs to cancel all interference in $\mathcal{Y}_{\text{Tx}}(t)$. Likewise, the Rx node of this link must use its available DoFs to cancel all interference from $\mathcal{X}_{\text{Rx}}(t)$.
- For intra-network IC, the Tx node of this link must use its (remaining) available DoFs to cancel its interference to all active secondary receivers in time slot t, which is $\beta^{j}_{\text{Tx}}(t)$ for each neighboring receive node j. Likewise, the Rx node of this link must use its (remaining) available DoFs to cancel the interference from all active neighboring transmit nodes in time slot t, which is $\alpha^{k}_{\text{Rx}}(t)$ for each neighboring transmit node k.
- After DoFs are allocated at this link (on Tx and Rx) for inter- and intra-network IC, we check how many (remaining) DoFs are available at Tx and Rx. If both nodes have at least R DoFs available, then all R data streams can be supported in this time slot; otherwise, we stuff as many data streams as possible in this time slot and we move on to the next time slot, until all R data streams can be supported or we conclude that the R data streams cannot be supported on this link over T time slots.

If the first link can accommodate R data streams for this new secondary session f over T time slots, then the Tx and Rx nodes of this link send the proposed new scheduling information (i.e., $\lambda^{\text{SM}}_{\text{Tx}}(t)$ and $\lambda^{\text{SM}}_{\text{Rx}}(t)$) and their transmission status (i.e., transmitter or receiver) to the transmit and receive nodes of the second link. Both the transmit and receive nodes of this link can obtain the new proposed scheduling information for Tx and Rx. Now we are done with the first link and can move on to the second link. Then both the transmit and receive nodes of the second link first update their local information on α and β based on the messages they received, and then follow the same process as the first link. Note here the second link could not select the same time slots that have been used by the first link due to the half-duplex capability at the intermediate node. If the second link can accommodate R data streams for this new secondary session f over T time slots, then the Tx and Rx nodes of this second link send their proposed new scheduling information (i.e., $\lambda^{\text{SM}}_{\text{Tx}}(t)$ and $\lambda^{\text{SM}}_{\text{Rx}}(t)$) and their transmission status together with the first link's information on each time slot to the transmit and receive nodes of the next link. Note that there is no need to propagate this new scheduling information to upstream nodes as the scheduling decisions there have already been done. The link-by-link scheduling process continues until either it is successful for all links or unsuccessful at some link. In the event of end-to-end successful scheduling, the destination secondary node will broadcast scheduling and resource allocation information on behalf of all nodes on the route to other nodes in the secondary network (in the dedicated control channel). The neighboring secondary nodes will update α and β in their local information upon receiving the broadcast information. After broadcasting, the destination node will return a positive ACK message toward its source indicating that underlay coexistence is achievable along the entire path. Upon receiving this positive ACK in the reverse direction, each node along the path will configure its precoding and decoding vectors at the PHY layer based on the proposed DoF allocation for SM and IC. When the source node receives this positive ACK, it can start transmitting R data streams. On the other hand, if any link fails to support R data streams over its T time slots, then the Tx node of that link will generate a negative ACK message and send it in the reverse direction toward the source. Each upstream node along the reversed route will discard the proposed DoF allocation and erase any proposed updates. Each node along the reverse path will simply continue its current operation without making any updates on the control plane. Upon receiving the negative ACK, the source node will drop the new incoming secondary session (lost). The idea of our algorithm is shown in Fig. 3.

Overhead Analysis and Computation Complexity For overhead, we count the total number of control messages involved in the process. Recall that all control messages in the secondary network are supported on a separate control channel without any interference to the primary network. When a link on the path can support the R data streams over T time slots, the transmit and receive nodes of this link will each generate a message and pass on to the next link. This requires 2 messages. Since the number of links along the route is no more than $(S-1)$, the number of such control message is no more than $2(S-1)$. When the admission test is successful at the last link, the destination node will broadcast a message containing each node's scheduling information to all nodes in the secondary network. The number of messages involved in this broadcast is no more than S. The destination node also sends a positive ACK on the reverse path toward the source node, which requires relaying this message for at most

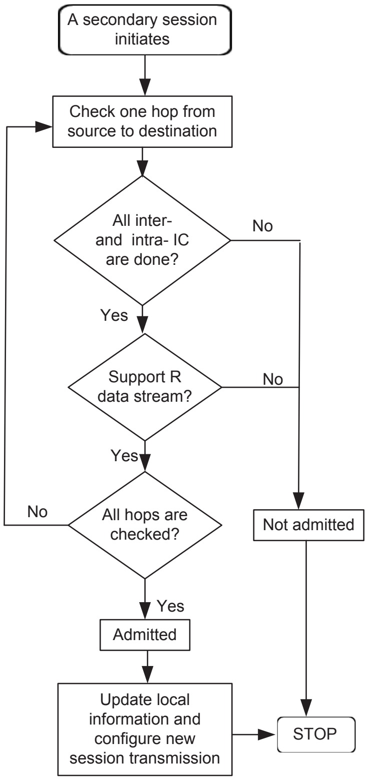


Fig. 3. A flowchart of the online admission control algorithm with the initiation of a new secondary session.

$S-1$ times. So the total number of control messages is $O(2(S-1))+O(S)+O(S-1)=O(S)$.

For each node along the path in a time slot, its total number of DoFs is A. So the number of allocations of DoFs for IC and SM is no more than A times. Since there is a total of T time slots in a frame, the complexity at each node is $O(TA)$. Since the number of nodes on the path is no more than S, the total computational complexity is $O(TAS)$.

C. Termination of a Secondary Session

When a secondary session f decides to terminate, it can cease transmission immediately on the data plane. On the control plane, an explicit link-by-link tear-down process is needed to release DoFs used for IC and SM. We start from the first link. Both the transmit node Tx and receive node Rx of this link will send their updated transmission information for this session (i.e., how the R data streams are removed over T time slots) to the transmit and receive nodes of the next link along the path. This is done in the control channel. This information will eventually propagate link-by-link toward the destination. The Tx and Rx nodes of the first link will check T time slots and release the DoF allocation for SM and IC on this link, and update their scheduling and resource allocation information in corresponding time slots. For example, the source node will release its DoF allocation for SM and IC in each time slot t that is used to support the R data streams, update its $\lambda_{\text{Tx}}^{\text{SM}}(t)$ and $\lambda_{\text{Rx}}^{\text{RM}}(t)$, and set binary variable $\eta_{\text{Tx}}^{j}(t)=0$ for IC to each neighboring receive node j. The receive node Rx will release its DoF allocation for SM and IC in time slot t, update its scheduling $\lambda_{\text{Rx}}^{\text{SM}}(t)$ and $\lambda_{\text{Rx}}^{\text{RM}}(t)$, and set binary variable $\eta_{\text{Rx}}^{k}(t)=0$ for IC for each neighboring transmit node k. Note that the release of DoFs at a transmit or receive node corresponds to freeing up the variables in the precoding or decoding vectors for SM and IC at the node. Given the variables are freed up here, it is always feasible at the PHY layer. Once these updates are completed for the first link, we move on to the second link. The transmit and receive nodes of the second link will send their updated transmission status in each time slot, along with the information received from the first link, to the transmit and receive nodes of the next link (third link). Both the transmit node Tx and receive node Rx of the second link will send their transmission information for this session (i.e., how the R data streams are supported over T time slots) to the transmit and receive nodes of the next link along the path. The Tx and Rx nodes of the second link will then release the DoFs allocated for SM and IC for the session on this link, and update their scheduling and resource allocation information in corresponding time slots. Once we are done with the second link, we move on to the third link and so forth. This process continues until reaching the destination node. The destination node has the aggregated transmission information for this session from all the nodes on this route. It broadcasts this information to all other nodes in the secondary network (in the dedicated control channel), announcing the termination of this session. Note that the termination operation is done only from source to destination (in contrast to a round trip for session initiation). The neighboring nodes that previously used DoFs to cancel interference to/from the terminated session will update α, β, and η in their local information upon receiving the broadcast message, and release the DoFs for IC to those nodes in the terminated session.

Following a similar analysis as in Section IV-B, we find that the total control messages and the complexity involved in a secondary session's termination are $O(S)$ and $O(TS)$, respectively [29].

D. Initiation of a New Primary Session

We now consider how to handle the network scenario where a primary session initiates in the network. The primary node can use whatever routing protocol it prefers to find a route. In underlay coexistence paradigm, the primary nodes do not notice the activities of the secondary nodes. They only need to concern other active primary nodes in the network. The primary nodes can use whatever scheduling algorithm to decide whether the new session can be admitted without any concern of the presence of secondary sessions. Since we do not mandate a specific scheduling algorithm for the primary nodes, the discussion of scheduling algorithm for the primary nodes is beyond the scope of this paper. We are only interested in how the secondary nodes respond when a new primary session initiates so as not to interfere with any of the primary nodes (underlay).

The main technical challenge here is that, in a time slot, how a secondary transmit node can cease its transmission when a primary node starts to transmit in the same time slot?

This is a fundamental problem in spectrum sharing. In the context of underlay coexistence, we propose the following solution. We divide each time slot for a secondary node into two parts: a small interval (on the order of several bits) for spectrum sensing and the remaining part for actual transmission [7]. During the spectrum sensing interval, if the secondary transmitter finds that there is change in neighboring primary transmitter's scheduling behavior (e.g., becoming active in this time slot), then the secondary node ceases to transmit in the remaining interval in this time slot. Based on our eavesdropping assumption, the secondary node can listen and decode the control information (in the packet header) of the primary transmitter. It will broadcast the activation of this new primary session to all other secondary nodes in the network (in the dedicated control channel for the secondary network). Given that the primary session has multiple nodes along its path, all neighboring secondary nodes will need to broadcast the change of scheduling behavior of the primary nodes along the path. This may incur considerable overhead in the number of control messages. So some aggregation method for the control messages at the secondary nodes is needed. We will discuss the the complexity of this operation shortly.

Upon hearing the activation of a new primary session, all secondary nodes that have interference with the primary session will immediately freeze their transmissions. They will also notify the source nodes of those involved secondary sessions (on control channel), who must immediately suspend transmission for these sessions. Upon hearing that the primary session is successfully admitted into the primary network, the neighboring secondary nodes will update their local information for $\mathcal{X}$ and $\mathcal{Y}$, based on the new scheduling behavior at the primary nodes. If the new primary session cannot be admitted into the primary network, then there is an explicit negative ACK message returning to the source node. Upon hearing this negative ACK message, the secondary nodes that have frozen their transmissions will generate a RESUME message back toward their source nodes so that those suspended secondary sessions can resume their activities.

After the new primary session is admitted into the network, those secondary sessions that are impacted by the new primary session will need to go through a re-admission process. The re-admission process for each session is the same as that in Section IV-B, except that we need to address the race condition of multiple such secondary sessions. In Section IV-F, we employ token passing to solve the race problem so that competing secondary sessions are handled one at a time. Such sequential handling of re-admission processes of concurrent secondary sessions is critical to achieve IC feasibility at the PHY layer. After going through a re-admission process, the impacted secondary session can either be admitted to re-enter the network or be terminated (due to the lack of resources on the path). The idea of our algorithm is shown in Fig. 4.

The total control messages involved in a primary session's initiation are between $\Omega(S)$ and $O(S^2)$. The complexity is $O(FTAS)$, where F is the number of secondary sessions that are impacted by the new primary session. The detailed analysis is given in [29] and is omitted here.

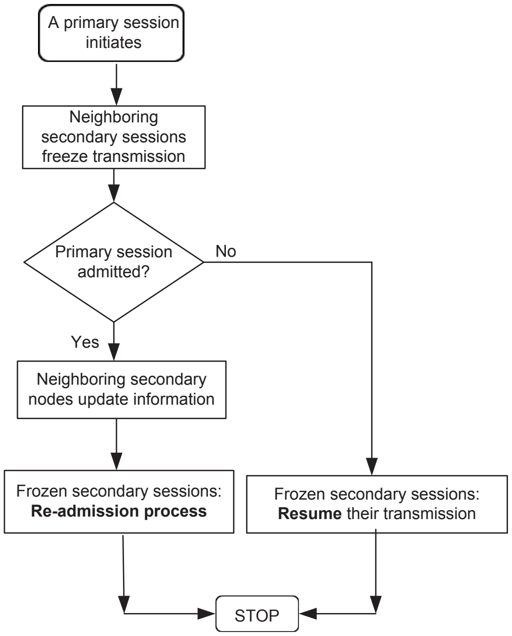


Fig. 4. A flowchart of the online admission control algorithm with the initiation of a primary session.

E. Termination of a Primary Session

Based on assumption *(v)*, the termination of a primary session employs an explicit link-by-link tear-down process. Upon hearing this control message along the path of a primary session, the neighboring secondary nodes will broadcast the change of scheduling behavior of the primary nodes along the path.

Note that the termination of a primary session will not affect the current transmission behavior of active secondary sessions. Each secondary node can still use its current scheduling for its own transmission (SM). But the IC responsibilities on the neighboring secondary nodes will change. Upon receiving the broadcast messages, a secondary node will release the DoF allocation (freeing up the variables in the precoding/decoding vectors) for IC to/from the primary nodes on the terminated primary session, and update their locally maintained information $\mathcal{X}$ and $\mathcal{Y}$.

The total number of messages involved in a primary session's termination is between $\Omega(S)$ and $O(S^2)$. The worse case complexity is $O(TS)$. The detailed analysis is given in [29] and is omitted here to conserve space.

F. Solving Race Problem

A major challenge in our design of online admission control algorithm is to address race condition. For example, the processing of a new secondary session arrival may take one round trip time to travel across network diameter. During this time, another new secondary session arrival may also occur. Since the IC responsibilities on the nodes in the latter session may depend on the first session, a blind processing of the latter session concurrently with the first one may result in infeasible DoF allocation at the PHY layer.

There are two approaches to address this race condition, both employs token passing. The first approach is similar to token ring, where a token is passed cyclically among the secondary nodes. A new secondary session is allowed to start its link-by-link DoF test only when the token is passed to the source node of the session. Once the source node holds the token, the corresponding session is the only new session that is under link-by-link DoF examination. Upon its completion, the source node will pass the token to the next node in the cycle and so forth. The advantage of this approach is that it is fully distributed. A lost token may be recovered through timeout. But the disadvantage is that the cycle time (for a token to travel around all secondary nodes) may be long (i.e., $O(S)$).

To speed up token passing time, the second approach employs a dedicated secondary node to serve as a token controller. This can be done through the distributed *leader election* algorithm [14], which has a message overhead of $O(S\log(S))$ but only needs to be done once. Each secondary node in the network has a unique identifier (UID). The token controller is assigned with the largest UID. Each secondary node will need to maintain a route from itself toward the token controller. When a new secondary session arrives, its source node will send a token request to the token controller node, requesting for a token. The token controller will grant a token only if it currently holds the token (not taken by another secondary source node). Otherwise, the new token request will be queued until the token returns to the token controller. This token passing approach will effectively handle secondary-secondary race condition. Although this approach relies on a dedicated secondary node (as token controller), it offers faster passing among the secondary nodes. To cope single point failure, another secondary node (with the second largest UID among the nodes [14]) may be used as a back up token controller (similar to DNS infrastructure). We adopt this approach to resolve secondary-secondary race condition.

Note that there is no race condition when a secondary session leaves the network (termination). When a secondary session decides to terminate, it can cease data transmission immediately. As discussed in Section IV-C, the session tear-down process is done on a link-by-link basis by releasing DoF allocation for SM and IC. This process continues until reaching the destination node. To minimize control overhead, only the destination node broadcasts the tear-down of the path (and all nodes involved) to other nodes in the secondary network. Upon receiving this tear-down broadcast, those relevant nodes can release their DoF allocation for IC to the nodes on the session's route. Since reconfiguring precoding/decoding vectors at a secondary node to release DoFs is guaranteed to be feasible, any concurrent operation involving a secondary session's departure is not considered a race condition.

When a new primary session initiates, a race condition may occur when a new secondary session also arrives. This is easy to handle as we assume the secondary nodes can eavesdrop the control channel (in-band or out-of-band) of the primary network. Upon identifying a new primary session's initiation, any new secondary session initiation activity will freeze until the new primary session is processed.

V. PHYSICAL LAYER FEASIBILITY

In Sections IV-B to IV-E, we have taken every step to ensure underlay coexistence for the primary and secondary multi-hop sessions under various traffic dynamics. In this section, we show that the PHY layer feasibility is maintained at each secondary node at all time. By PHY layer feasibility, we mean that there exist feasible precoding/decoding vectors at each secondary node to implement the desired DoF allocation for SM and IC.

A secondary session initiates When a new secondary session is admitted into the network, we perform the link-by-link operation to allocate DoF for SM and IC. To achieve underlay coexistence, the nodes in the new secondary session must perform inter-network and intra-network IC. Note that the IC responsibilities on the existing secondary sessions do not change. For nodes along the path of the new secondary session, we start with the first link (containing source node) and work our way toward the last link (containing the destination node). For each node, its DoF allocation for IC follows a sequential order from the source node to the current node. That is, IC to/from those nodes that are after this node along the path of the new secondary session is not the responsibility of this node. Such interference will be taken care of when we consider those nodes later. This sequential accounting of IC responsibility is the basis of our construction of precoding/decoding vectors at each node along the path (from source node toward destination node).

Lemma 1: After a new secondary session is successfully admitted into the network, there exists a set of feasible precoding/decoding vectors at each secondary node along the path based on the DoF allocation for SM and IC in the admission process.

Proof: Our proof is based on construction. We construct a set of feasible precoding/decoding vectors at each node starting from the source. For the first link, denote Tx as the source node and Rx as the receive node. Based on the DoF allocation for SM and IC in time slot t in the admission process, we now show that we can construct a feasible set of precoding vectors at Tx in the same time slot. At node Tx, its local information $\mathcal{Y}_{\mathrm{Tx}}(t)$ contains the neighboring primary receivers in time slot t, while β^{j}_{Tx} is the number of data streams being received at at neighboring secondary receiver j. The secondary node Tx needs to construct its precoding vectors to cancel all interference to these receivers. Denote the set of these neighboring secondary receivers as $\mathcal{B}$. Suppose that Tx transmits $z_{(\mathrm{Tx},\mathrm{Rx})}$ data streams to Rx in time slot t. Denote $\mathbf{u}^{a}_{\mathrm{Tx}}$ as an $A\times 1$ transmit vector at Tx for each data stream a ($1\le a\le z_{(\mathrm{Tx},\mathrm{Rx})}$), and $\mathbf{v}^{a}_{\mathrm{Rx}}$ as an $A\times 1$ receive vector at Rx to receive data stream a.

Denote $\mathbf{H}_{(\mathrm{Tx},j)}$ as the $A\times A$ channel matrix between nodes Tx and j ($j\in\mathcal{B}$), and denote $\mathbf{H}_{(\mathrm{Tx},k)}$ as the $A\times 1$ channel matrix between Tx and the primary receive node k ($k\in\mathcal{Y}_{\mathrm{Tx}}(t)$). We assume all channels $\mathbf{H}_{(\mathrm{Tx},j)}$ and $\mathbf{H}_{(\mathrm{Tx},k)}$ are of full rank. To transmit $z_{(\mathrm{Tx},\mathrm{Rx})}$ data streams from node Tx to Rx while achieving underlay coexistence, transmit node Tx must cancel its interference to neighboring primary receivers in $\mathcal{Y}_{\mathrm{Tx}}(t)$ and neighboring secondary receivers in $\mathcal{B}$.

Then, we should have the following constraints:

$$(\mathbf{u}_{\mathrm{Tx}}^{a})^{T}\mathbf{H}_{(\mathrm{Tx},\mathrm{Rx})}\mathbf{v}_{\mathrm{Rx}}^{a} = 1\ , \quad (1 \le a \le z_{(\mathrm{Tx},\mathrm{Rx})}), \tag{5}$$

$$(\mathbf{u}_{\mathrm{Tx}}^{a})^{T}\mathbf{H}_{(\mathrm{Tx},\mathrm{Rx})}\mathbf{v}_{\mathrm{Rx}}^{b} = 0\ , \quad (1 \le a \le z_{(\mathrm{Tx},\mathrm{Rx})},\ 1 \le b \le z_{(\mathrm{Tx},\mathrm{Rx})}, a \ne b), \tag{6}$$

$$(\mathbf{u}_{\mathrm{Tx}}^{a})^{T}\mathbf{H}_{(\mathrm{Tx},k)}v_{k} = 0\ , \quad (1 \le a \le z_{(\mathrm{Tx},\mathrm{Rx})}, k \in \mathcal{Y}_{\mathrm{Tx}}(t)), \tag{7}$$

$$(\mathbf{u}_{\mathrm{tx}}^{a})^{T}\mathbf{H}_{(\mathrm{Tx},j)}\mathbf{v}_{j}^{q} = 0\ , \quad (1 \le a \le z_{(\mathrm{Tx},\mathrm{Rx})}, j \in \mathcal{B},\ 1 \le q \le z_{(i,j)}), \tag{8}$$

where i is the transmit node that transports $z_{(i,j)}$ data streams to secondary receive node j. Since each primary receiver has only a single antenna and can only receive one data stream, v_k is a constant for each $k \in \mathcal{Y}_{\mathrm{Tx}}(t)$.

The number of constraints in (5) and (6) is $(z_{(\mathrm{Tx},\mathrm{Rx})})^2$. The number of constraints in (7) is $z_{(\mathrm{Tx},\mathrm{Rx})} \cdot \sum_{k \in \mathcal{Y}_{\mathrm{Tx}}(t)} 1$. The number of constraints in (8) is $z_{(\mathrm{Tx},\mathrm{Rx})} \cdot \sum_{j \in \mathcal{B}} z_{(i,j)}$. So the total number of constraints is $(z_{(\mathrm{Tx},\mathrm{Rx})})^2 + z_{(\mathrm{Tx},\mathrm{Rx})} \cdot \sum_{k \in \mathcal{Y}_{\mathrm{Tx}}(t)} 1 + z_{(\mathrm{Tx},\mathrm{Rx})} \cdot \sum_{j \in \mathcal{B}} z_{(i,j)} = z_{(\mathrm{Tx},\mathrm{Rx})} \cdot (z_{(\mathrm{Tx},\mathrm{Rx})} + \sum_{k \in \mathcal{Y}_{\mathrm{Tx}}(t)} 1 + \sum_{j \in \mathcal{B}} z_{(i,j)})$. In our DoF allocation at Tx, the total number of DoFs allocated for SM and IC cannot exceed A, i.e., $(z_{(\mathrm{Tx},\mathrm{Rx})} + \sum_{k \in \mathcal{Y}_{\mathrm{Tx}}(t)} 1 + \sum_{j \in \mathcal{B}} z_{(i,j)}) \le A$, where $z_{(\mathrm{Tx},\mathrm{Rx})}$ is the number of DoFs for SM, $\sum_{k \in \mathcal{Y}_{\mathrm{Tx}}(t)} 1$ is the number of DoFs for IC to primary receivers, and $\sum_{j \in \mathcal{B}} z_{(i,j)}$ is the number of DoFs for IC to neighboring secondary receivers. Therefore, the total number of constraints is no more than $z_{(\mathrm{Tx},\mathrm{Rx})} \cdot A$.

In the above constraints, v_k ($k \in \mathcal{Y}_{\mathrm{Tx}}(t)$) are constants, and $\mathbf{v}_j^q$ ($j \in \mathcal{B}$) belong to the existing secondary nodes (not on the path of the new secondary session), which are already configured. For precoding vector $\mathbf{u}_{\mathrm{Tx}}^a$ for data stream a ($1 \le a \le z_{(\mathrm{Tx},\mathrm{Rx})}$), it is an $A \times 1$ vector. So the total number of variables for $z_{(\mathrm{Tx},\mathrm{Rx})}$ vectors at transmit node Tx is $z_{(\mathrm{Tx},\mathrm{Rx})} \cdot A$, which is no less than the number of constraints. On the other hand, since the channels are of full rank and independent of each other, it can be shown that the constraints in (5), (6), (7), and (8) are linearly independent with each other [20]. So for any *given* $\mathbf{v}_{\mathrm{Rx}}^b$ for $1 \le b \le z_{(\mathrm{Tx},\mathrm{Rx})}$, we are guaranteed to construct feasible precoding vectors $\mathbf{u}_{\mathrm{Tx}}^a$ ($1 \le a \le z_{(\mathrm{Tx},\mathrm{Rx})}$) at Tx.

After we construct feasible precoding vectors at Tx. We can construct the decoding vectors $\mathbf{v}_{\mathrm{Rx}}^b$ for $1 \le b \le z_{(\mathrm{Tx},\mathrm{Rx})}$ in time slot t based on $\mathbf{u}_{\mathrm{Tx}}^a$ following the same argument. Therefore, for the proposed DoF allocation for SM and IC in a time slot for the new secondary session, we can show that there exist precoding vectors at Tx and decoding vectors at Rx. After Tx and Rx are configured, we move on to the next link and use the same approach to construct precoding vectors at the transmit node and the decoding vetors at the receive node for the next link and so forth. In essence, since the number of DoFs that can be allocated for SM and IC is no more the number of antennas (i.e., A) at each node in the admission process, the number of constraints is no more than the number of variables. Therefore, we can always construct feasible precoding/decoding vectors at each secondary node along the path. This completes the proof. ■

A primary session initiates After a new primary session successfully joins the network, the impacted sessions should first cease their transmission and then go through a new admission process again. This operation is the same as the initiation of a new secondary session. The feasibility proof at the PHY layer is the same as that for Lemma 1.

Termination of a primary or a secondary session. In either case, the secondary nodes involved in IC only need to release DoFs (i.e., freeing up the variables in precoding/decoding vectors), this operation is always feasible at the PHY layer.

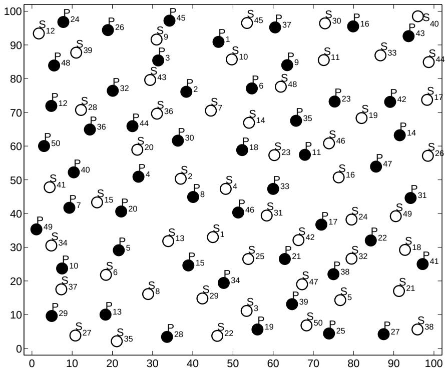


Fig. 5. The locations of the primary and secondary nodes.

VI. PERFORMANCE EVALUATION

In this section, we evaluate the performance of our online admission control algorithm to handle traffic dynamics. We organize our evaluation into two parts. In the first part, we study the performance of our online algorithm in terms of lost secondary sessions. As a benchmark, we compare the performance of our algorithm to that of an offline algorithm. In the second part, we examine whether underlay coexistence holds at all time in the network.

A. *Parameter Settings*

We consider a 50-node primary network and a 50-node secondary network randomly deployed in an 100×100 area. The location of the primary and secondary nodes are shown in Fig. 5. Each primary node is equipped with a single antenna while each secondary node is equipped with four antennas. Both the primary and secondary networks share the same spectrum bandwidth. For generality, we normalize all units for distance and bandwidth with appropriate dimensions. We assume the transmission range and interference range for both the primary and secondary nodes are 30 and 50, respectively. For scheduling, a time frame is divided into four time slots (i.e., $T = 4$).

We assume primary and secondary session arrivals follow a Poisson process. The arrival rate of the primary and secondary sessions will be specified in the respective performance studies. The holding time for each primary or secondary session follows an exponential distribution with a mean of 1 minute. For each primary session, it can only request 1 data stream. But for each secondary session, it can request R data streams. We set $R = 2$ in our study.

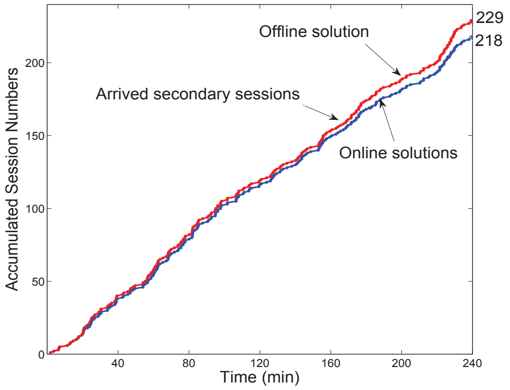


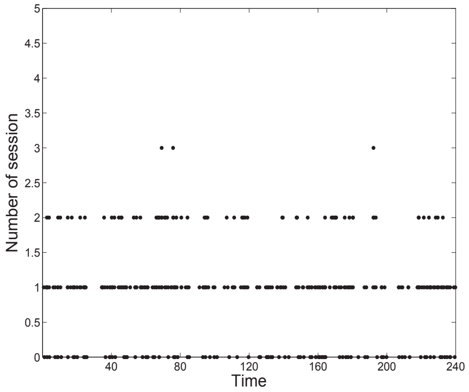
Fig. 6. Cumulative secondary arrivals, admitted secondary arrivals by offline algorithm, and admitted secondary arrivals by our online algorithm. Both primary and secondary session arrival rates are 1 per minute.

B. Lost Secondary Sessions

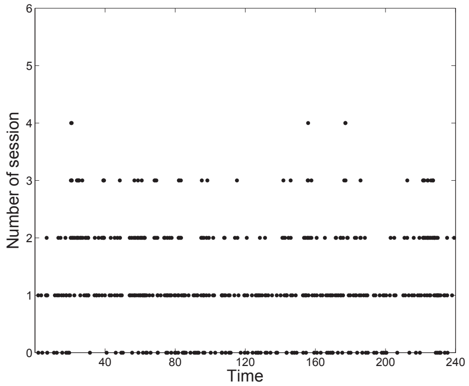
A key performance measurement of our proposed online admission control algorithm is its ability to accommodate as many new secondary sessions into the network as possible while meeting underlay coexistence requirements. A secondary session may be lost under two circumstances: (i) it may be rejected by our algorithm when it initially arrives the network; (ii) it may be suspended due to the arrival of a new primary session and subsequently cannot be re-admitted into the network. In both cases, we consider that the secondary session is lost.

To measure the performance of our distributed algorithm, we compare it to that of an offline algorithm. For fairness, an offline algorithm will employ the same shortest path routing as our online algorithm. The difference is that an offline algorithm will perform a global optimization (among all secondary sessions) to find a feasible DoF allocation. Under a new feasible DoF allocation, a secondary node with its current precoding/decoding vectors will need to reconfigure these vectors, which is hardly practical in real time. In contrast, for an online algorithm, it will not alter the DoF allocation on those secondary nodes that are already active. It will only allocate DoFs (and configure precoding/decoding vectors) on the nodes that are traversed by the new secondary session.

The offline algorithm is a global (centralized) optimization problem.[2] It is in the form of a mixed integer linear program (MILP), which is NP-hard in general [19]. For an MILP, the running time of a commercial solver varies and depends on the underlying computer hardware and the structure of the specific problem. We will use a commercial solver (CPLEX) to solve this MILP. The CPLEX solver is run on a Dell Precision T7600 workstation, with 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. We set the termination time to 1 hour for the MILP problem. There are several possibilities: (i) before or by the termination time, CPLEX finds a new feasible DoF allocation for all secondary sessions; (ii) before or by the termination time, CPLEX finds that there does not exist a feasible DoF allocation to accommodate the new session; (iii) by the termination time, CPLEX still cannot find a feasible DoF allocation (due to the complexity of the global optimization problem). Under case (i), the new session is admitted into the network under the offline algorithm, while under cases (ii) and (iii), we consider the offline algorithm unable to accommodate the new secondary session (i.e., lost).



(a) The number of active primary sessions in the network.



(b) The number of secondary sessions that are admitted into the network by our online algorithm.

Fig. 7. The number of active primary sessions in the network and the number of secondary sessions that are admitted into the network by our online algorithm, all over a 4-hour period.

Fig. 6 shows the cumulative total arrivals of secondary sessions, admitted secondary sessions by the offline algorithm, and admitted secondary sessions by our online algorithm. Both the primary and secondary sessions' arrival rates are 1 per minute. Note that the curves for cumulative total arrivals of secondary sessions and admitted secondary sessions by the offline algorithm coincide completely, indicating that all new secondary sessions are admitted without any loss. This clearly represents operation in the low traffic load region. In this region, we find that the online algorithm also performs very well. Over a period of 4 hours, there is a total of 229 new secondary session arrivals, all of them can be admitted by the offline algorithm, while our online algorithm can admit 218 (95.19%).

To show the session dynamics in Fig. 6, Fig. 7 (a) and (b) show the number of active primary sessions in the network and the number of secondary sessions that are admitted into

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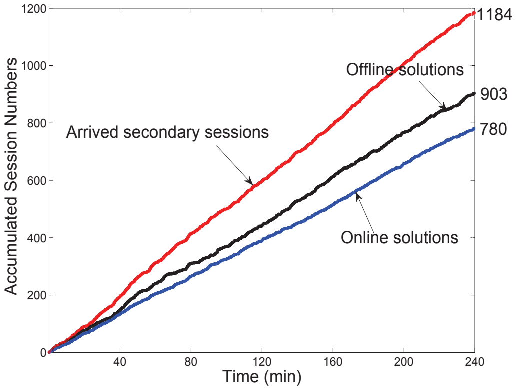
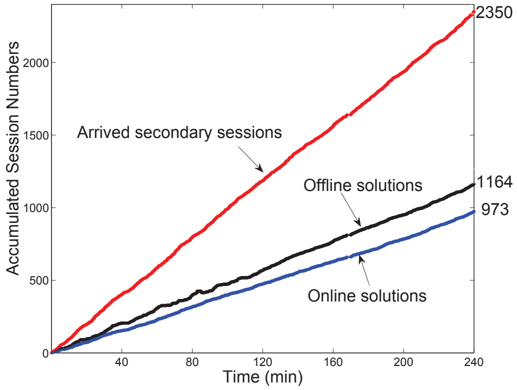
[2] The centralized formulation is in shown in [29]



(a) Secondary arrival rate=5



(b) Secondary arrival rate=10

Fig. 8. Cumulative secondary arrivals, admitted secondary arrivals by offline algorithm, and admitted secondary arrivals by our online algorithm. The primary session arrival rate is 1 per minute. The secondary session arrival rates are 5 and 10 per minute, respectively.

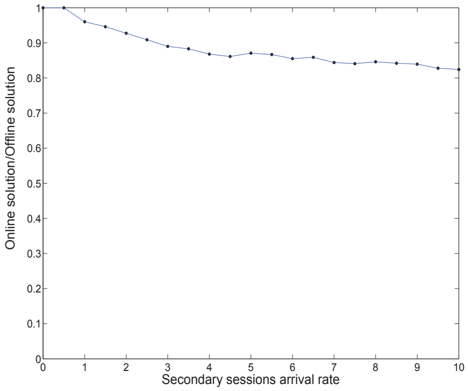


Fig. 9. Ratios between admitted secondary sessions by our online algorithm and that by the offline algorithm with different secondary sessions arrival rate.

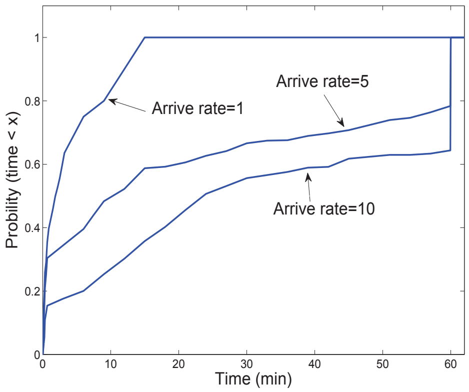
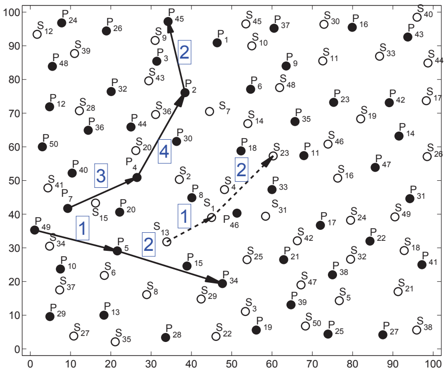


Fig. 10. The CDFs of computation time by the offline algorithm when the secondary sessions arrival rates are 1, 5, and 10 respectively. The cutoff termination time for the offline algorithm is set to 1 hour.

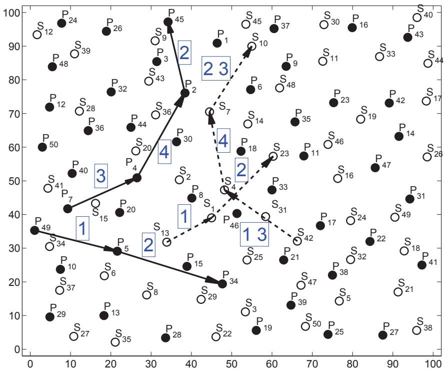
the network by our online algorithm, all over the same 4-hour period, respectively. We find that the number of primary sessions vary from 0 to 3 while the number of secondary sessions vary from 0 to 4.

We now increase traffic load on the network by increasing the arrival rate of new secondary sessions. The arrival rate for the primary sessions and session hold time are the same as before. Figures 8(a) and (b) show the cumulative secondary arrivals, admitted secondary arrivals by offline algorithm, and admitted secondary arrivals by our online algorithm over a 4-hour period when the secondary session arrival rates are 5 and 10, respectively. Clearly, we find that there is a gap between the curves of cumulative secondary arrivals and admitted secondary arrivals by the offline algorithm, indicating that the new secondary arrivals are lost even under the offline algorithm. This gap widens as the arrival rate of new secondary sessions increases from 5 to 10 per minute. We now compare the performance of our online algorithm with that of the offline algorithm. When the secondary session arrival rate is 5 per minute (moderately heavy load), there are 780 new sessions admitted by our algorithm while 903 admitted by the offline algorithm. The ratio between the two is 86.37%. When the secondary session arrival rate is 10 per minute (heavy load), there are 973 new sessions admitted by our algorithm while 1164 admitted by the offline algorithm. The ratio between the two is 83.59%. Fig. 9 shows the ratios between admitted secondary sessions by our online algorithm and that by the offline algorithm under a wide range of traffic load. We find the minimum ratio is 82%, which indicates that our online algorithm is competitive.

We now compare the computation time by our online algorithm to that by the offline algorithm. The computation time by our online algorithm includes local computation time at secondary nodes (negligible) and communication time among the secondary nodes. The latter is on the same order of round trip time between any two secondary nodes (source and destination) in the network, which is again very small. On the other hand, the computation time by the offline algorithm is the time used by CPLEX solver, with a cutoff termination time of 1 hour. Fig. 10 shows the CDFs of computation time by the offline algorithm when the secondary sessions arrival rates are 1, 5, and 10 respectively, which correspond to our studies in Figs. 6, 8(a) and (b). Note that even under very light traffic load (with secondary session arrival rate being 1 per minute), more than 20% of new sessions still require at least 5 minutes for the CPLEX solver to find a feasible solution. This is not acceptable for the arrival rate, which is 1 per minute. When the secondary session arrival rate increases, the situation deteriorates. For example, when the secondary session arrival rate is 5 per minute (moderately heavy load),

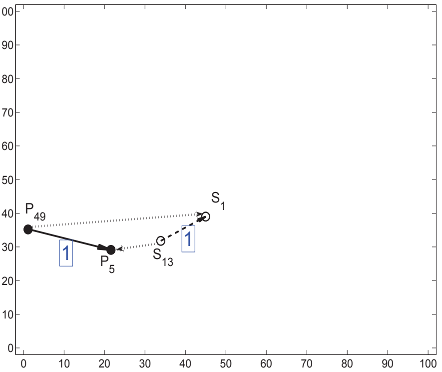


(a) Before the new secondary session arrives.

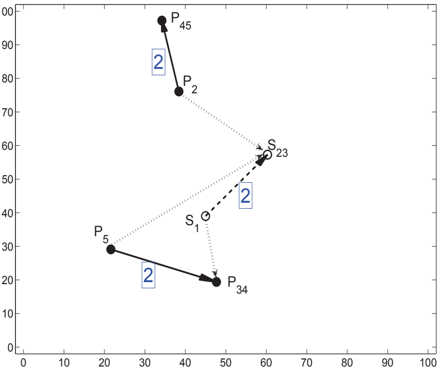


(b) After the new secondary session arrives.

Fig. 11. Scheduling and routing before and after the new secondary session $S_{42} \to S_{10}$ arrives.



(a) In time slot 1.



(b) In time slot 2.

Fig. 12. Interference relationship in the first two time slots before new secondary session $S_{42} \to S_{10}$ arrives.

TABLE I

DoF ALLOCATION FOR SM AND IC FOR THE SECONDARY SESSIONS IN EACH TIME SLOT BEFORE THE NEW SESSION ARRIVES.

Time Slot 1				
Node i	TX/RX	DoF for SM	DoF for IC to/from primary nodes	DoF for IC within secondary network
S_{13}	TX	2	1 to P_5	NO
S_1	RX	2	1 from P_{49}	NO
Time Slot 2				
S_1	TX	2	1 to P_{34}	NO
S_{23}	RX	2	1 from P_2, 1 from P_5	NO

more than 50% of new sessions require at least 5 minutes for the CPLEX solver to find a feasible solution while more than 20% of sessions exceed the cutoff termination time (1 hour). The situation for the case when the secondary session arrival rate is 10 per minute (heavy load) is even worse. The results in Fig. 10 shows that even under light load, an offline algorithm is not practical.

C. Validation of Underlay Coexistence

In this section, we examine whether the underlay coexistence of secondary sessions are always maintained by our online admission control algorithm. That is, we want to check that inter-network interference (interference to/from the primary network) and intra-network interference (interference within the secondary network) are all cancelled properly.

For validation, we randomly pick some time instances and examine how interference is canceled. Let's consider time at 17.3 minute in Fig. 6 and Figs. 7 (a), (b), and (c), when there is a new secondary session arrival ($S_{42} \to S_{10}$). Fig. 11(a) and (b) show the routing and scheduling of primary and secondary sessions before and after the new secondary session arrival. We will validate whether underlay coexistence holds in each case.

Before the new secondary session arrives (see Fig. 11(a)), there are two primary sessions ($P_7 \to P_{45}$ and $P_{49} \to P_{34}$) and one secondary session (i.e., $S_{13} \to S_{23}$) in the network. The scheduling (in time slot) for each link is marked in a box next to the link. For example, in time slot 1, primary link $P_{49} \to P_5$ and secondary link $S_{13} \to S_1$ are active. To illustrate how each interference is canceled, Table I shows the first two time slots (there is no inter-network interference in time slots 3 and 4 and its discussion is omitted). As shown in Fig. 12(a) and Table I, in the first time slot, secondary node S_{13} interferes P_5 with 1 DoF. So node S_{13} allocates 1 DoF to cancel this interference. Also, primary node P_{49} interferes S_1 with 1 DoF. So node S_1 allocates 1 DoF to cancel this interference. Both primary link $P_{49} \to P_5$ and secondary link $S_{13} \to S_1$ are active in time slot 1. Since all inter-network interference is canceled by the secondary nodes, underlay coexistence for the secondary nodes holds in time slot 1. In the second time slot, secondary node S_1 interferes P_{34} with 1 DoF. So node S_1 allocates 1 DoF to cancel this interference. Also primary nodes P_2 and P_5 interfere with secondary node S_{23}, each with 1 DoF. So S_{23} allocated 2 DoF to cancel each of these interference. Both primary links $P_5 \to P_{34}$ and $P_2 \to P_{45}$, and secondary link $S_1 \to S_{23}$

TABLE II
DoF ALLOCATION FOR SM AND IC FOR THE SECONDARY SESSIONS IN EACH TIME SLOT AFTER THE NEW SESSION ARRIVES.

Time Slot 1				
Node i	TX/RX	DoF for SM	DoF for IC to/from primary nodes	DoF for IC within secondary network
S_{13}	TX	2	1 to P_5	NO
S_1	RX	2	1 from P_{49}	NO
S_{42}	TX	1	1 to P_5	2 to S_1
S_4	RX	1	0	2 from S_{13}
Time Slot 2				
S_1	TX	2	1 to P_{34}	NO
S_{23}	RX	2	1 from P_2, 1 from P_5	NO
S_7	TX	1	1 to P_{45}	2 to S_{23}
S_{10}	RX	1	1 from P_2	No
Time Slot 3				
S_{42}	TX	1	1 to P_4	NO
S_4	RX	1	1 from P_7	NO
S_7	TX	1	1 to P_4	1 to S_4
Time Slot 4				
S_4	TX	1	1 to P_2	NO
S_7	RX	2	1 from P_4	NO

are active in time slot 2. Since all inter-network interference is canceled by the secondary nodes, underlay coexistence for the secondary nodes holds in time slot 2.

After our online admission control algorithm admits the new secondary session into the network, the scheduling and routing for the primary and secondary sessions are shown in Fig. 11(b). Table II shows the details of DoF allocation for SM and IC at each secondary node, where the shaded rows correspond to those secondary nodes that are active before the arrival of this new secondary session. Comparing to Table I, the DoF allocation for the shaded rows are not changed by our online algorithm. The interference relationships in each time slot are given in [29]. By cross-referencing the detailed information in Table II, it is easy to verify, as we did for Fig. 12 and Table I, that all inter-network and intra-network interference is canceled by the secondary nodes. Therefore, the underlay coexistence holds in all time slots.

Following the same validation methodology, we have verified that underlay coexistence indeed holds at all time instances (that we choose randomly for validation) for all possible arrival/departure events. Therefore, we conclude that our online algorithm can guarantee underlay coexistence.

VII. CONCLUSIONS

The underlay paradigm allows extremely efficient utilization of spectrum by allowing simultaneous activation of the secondary nodes with the primary nodes. Such simultaneous activity is made possible through aggressive IC by the secondary nodes without any noticeable burden on the primary nodes. An effective online algorithm for traffic management and IC is crucial for the secondary nodes to achieve underlay coexistence. In this paper, we proposed an online admission control algorithm to handle traffic dynamics for multi-hop primary and secondary networks. For IC, we employed MIMO at each secondary node and relied on local DoF allocation at each secondary node for IC. Through distributed computation and DoF resource allocation, we showed that all inter-network and intra-network interference can be effectively canceled by the secondary nodes so that data can be transported free of interference in both the multi-hop primary and secondary networks. More important, we proved that such inter-network and intra-network IC through our DoF allocation is indeed feasible at the PHY layer at all time under traffic dynamics. By conducting performance evaluation under various traffic loads, we found that our online algorithm offers competitive performance when compared to an offline centralized algorithm.

ACKNOWLEDGMENTS

This work was supported in part by NSF under Grants 1642873, 1617634, 1443889, 1343222, 1102013, 1443434 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 authors thank Virginia Tech Advanced Research Computing for giving them access to the BlueRidge computer cluster.

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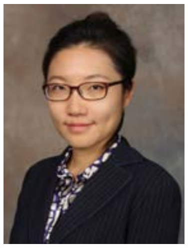
Xu Yuan (S’13–M’16) is a Postdoctoral Fellow of Electrical and Computer Engineering at University of Toronto, Toronto, ON. He received his Ph.D. degree in the Bradley Department of Electrical and Computer Engineering at Virginia Tech, Blacksburg, VA in 2016. His research interest focuses on algorithm design and optimization for spectrum sharing, coexistence, and cognitive radio networks.



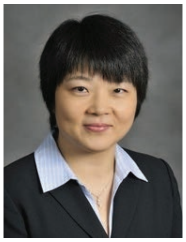
Xiaoqi Qin (S’13) received her B.S., M.S., and Ph.D. degree in Computer Engineering from Virginia Tech in 2011, 2013 and 2016, respectively. She is currently a instructor in Beijing University of Posts and Telecommunications. Her research interests are algorithm design and cross-layer optimization for wireless networks.

Feng Tian (M’13) received his Ph.D. degree in Signal and Information Processing from Nanjing University of Posts and Telecommunications, Nanjing, China in 2008. He is currently an Associate Professor at the same university. He was a visiting scholar at Virginia Tech, USA from 2013-2015. His research focuses on performance optimization and algorithm design for wireless networks.

Brian Jalaian (S’09–M’15) received his Ph.D. degree from the Bradley Department of Electrical and Computer Engineering in 2016 at Virginia Tech, Blacksburg, VA USA. He is currently a Postdoctoral Research Fellow at US Army Research Lab. His interests lie in the application of optimization and operation research in complex wireless communication system and networking problems.

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 several 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 120 papers on wireless network algorithm design and optimization. He has named an IEEE Communications Surveys and Tutorials Exemplary Editor in 2014. He has 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.

Y. Thomas Hou (F'14) is Bradley Distinguished Professor of Electrical and Computer Engineering at Virginia Tech, Blacksburg, VA, USA, which he joined in 2002. During 1997 to 2002, he was a member of Research Staff at Fujitsu Laboratories of America, Sunnyvale, CA, USA. He received his Ph.D. degree from NYU Tandon School of Engineering (formerly Polytechnic Univ.) in 1998. His current research focuses on developing innovative solutions to complex science and engineering problems arising from wireless and mobile networks. He has published over 100 journal papers and 130 conference papers in networking related areas. His papers were recognized by five best paper awards from the IEEE and two paper awards from the ACM. He holds five U.S. patents. He authored/co-authored 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 was/is on the editorial boards of a number of IEEE and ACM transactions and journals. He is the Steering Committee Chair of IEEE INFOCOM conference and a member of the IEEE Communications Society Board of Governors. He is also a Distinguished Lecturer of the IEEE Communications Society.



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).

Wade Trappe (F'14) is a Professor in the Electrical and Computer Engineering Department at Rutgers University, and Associate Director of the Wireless Information Network Laboratory (WINLAB), where he directs WINLAB's research in wireless security. He has led several federally funded projects in the area of cybersecurity and communication systems, projects involving security and privacy for sensor networks, physical layer security for wireless systems, a security framework for cognitive radios, the development of wireless testbed resources (the ORBIT testbed, www.orbit-lab.org), and new RFID technologies. His experience in network security and wireless spans over 15 years, and he has co-authored a popular textbook in security, *Introduction to Cryptography with Coding Theory*, as well as several monographs on wireless security, including *Securing Wireless Communications at the Physical Layer* and *Securing Emerging Wireless Systems: Lower-layer Approaches*. Professor Trappe served as an editor for *IEEE Transactions on Information Forensics and Security (TIFS)*, *IEEE Signal Processing Magazine (SPM)*, and *IEEE Transactions on Mobile Computing (TMC)*. He served as the lead guest editor for September 2011 special issue of the *Transactions on Information Forensics and Security* on "Using the Physical Layer for Securing the Next Generation of Communication Systems" and served as the IEEE Signal Processing Society representative to the governing board of IEEE TMC.