Concurrent Channel Access and Estimation for Scalable Multiuser MIMO Networking

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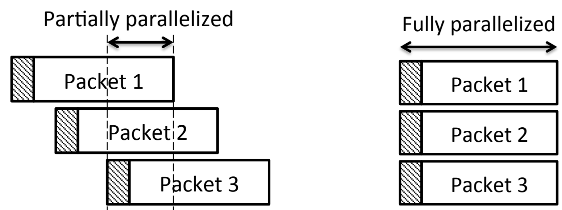
***Abstract*—This paper presents MIMO/CON, a PHY/MAC cross-layer design for multiuser MIMO wireless networks that delivers throughput scalable to many users. MIMO/CON supports concurrent channel access from uncoordinated and loosely synchronized users. This new capability allows a multi-antenna MIMO access point (AP) to fully realize its MIMO capacity gain. MIMO/CON draws insight from compressive sensing to carry out concurrent channel estimation. In the MAC layer, MIMO/CON boosts channel utilization by exploiting normal MAC layer retransmissions to recover otherwise undecodable packets in a collision. MIMO/CON has been implemented and validated on a 4×4 MIMO testbed with software-defined radios. In software simulations, MIMO/CON achieves a 210% improvement in MAC throughput over existing staggered access protocols in a 5-antenna AP scenario.**



(a) Staggered access (b) Concurrent access

Fig. 1: Two access strategies for multiuser MIMO networks. Shaded areas denote packet preambles: (a) conventional staggered approach and (b) concurrent approach of this paper.

I. Introduction

MIMO technologies create an opportunity for boosting wireless data throughput [4]. A base station with K receive antennas can be viewed to own a K-dimensional vector space for K incoming data streams, each from a separate transmit antenna. The K antennas can transmit data streams concurrently as long as their basis vectors are linearly independent. When transmitters are with geographically separated users, the rich spatial diversity can support concurrent transmissions from a large number of users [13]. This has motivated the design of large MIMO systems with many antennas. For example, 802.11ac has stipulated up to 8 antennas on an access point (AP), and an unlimited number of antennas scenario is even depicted for cellular networks [8].

However, coordinating distributed users can be a challenging task. MIMO decoding relies on accurate channel state information (CSI) at the receiver. In order to accommodate short channel coherence time, CSI is normally estimated on a per-packet basis using packet preambles. This means that concurrent transmissions of multiple packets has to be arranged into batches. Not until the last packet in a batch finishes its transmission can a new batch begin a new round of channel estimation and packet transmissions.

We consider an indoor multiuser MIMO (MU-MIMO) scenario where an AP possesses K antennas and each user possesses one. We focus on the uplink case where multiple users send data to the AP. We are interested in efficient and scalable mechanisms for coordinating transmissions of multiple MU-MIMO users (i.e., the“senders”). At one end of the design space, users are tightly synchronized and scheduled by a central coordinator. Such approaches can give efficient schedules for concurrent transmissions, but this is accomplished at the expense of high control cost. At the other end, users contend for transmission opportunities without any central coordination [11], [7]. This approach, however, has to limit the users to contend for just one of the MIMO degrees-of-freedom at a time in order to avoid preamble collisions. Forming a batch of K concurrent packets requires K sequential steps of contention resolution, meaning that concurrent packets are staggered rather than fully parallelized (as depicted in Figure 1(a)). Staggered packets lead to low channel utilization and poor scalability to large MIMO systems of many antennas.

Aiming at incorporating the best from both ends, we propose MIMO/CON (“MIMO with CONcurrent access”) that fully parallelizes concurrent transmissions (as depicted in Figure 1(b)) yet involving minimum central control. MIMO/CON uses a multi-winner contention scheme, which can grant channel access to multiple users in only one contention delay.

In designing MIMO/CON, we have to address several challenging issues. First, how can one concurrently estimate CSI from multiple uncoordinated packet preambles? The estimation has to be carried out under unknown participating senders, and has to tolerate potentially large synchronization offsets among senders. We address this issue with one insight: uncoordinated preambles do not introduce additional CSI to be estimated; rather, it merely injects the CSI into a higher-dimensional space, and the information we are interested in gathering is *sparse* in the new space. MIMO/CON leverages the recent theory of compressive sensing [3] that shows sparse information can be derived almost as if the zero unknowns did not exist. In other words, MIMO/CON can operate almost as if the concurrent senders were coordinated and perfectly synchronized.

Second, how can one alleviate collisions that occur when the number of senders exceeds the number K of antennas the AP possesses? To address this issue, we have devised a novel mechanism called *delay packet decoding*. By exploiting information from newly received retransmissions, this scheme finds new opportunities in decoding unknowns in previous collisions. As a result, only a subset of packets in a collision needs to be retransmitted. This means that the number of concurrent senders no longer needs to be bounded by K and the contention mechanism only needs to concern the average use of the medium.

We have prototyped MIMO/CON using software-defined radios [1], and also built a high-level software simulator. We have evaluated MIMO/CON with both the hardware testbed and the simulator. Our evaluation reveals the following:

- MIMO/CON delivers throughput scalable to large MIMO systems. In particular, our simulation results suggest that MIMO/CON delivers 140% and 210% throughput gains over staggered access with 5-antenna AP under PHY rates 13Mbps and 52Mbps, respectively. (See Section V-B.)
- Our testbed experiments show the CSI concurrently estimated in MIMO/CON delivers similar MIMO decoding performance to that from interference-free preambles for packet SNR as low as 5dB. (See Section V-A.)
- Compressive sensing benefits MIMO channel estimation, and MIMO antenna diversity can also benefit compressive sensing decoding. Our iterative decoding algorithm converges in 1 iteration when the AP has 4 antennas. (See Section III-B.)

II. Channel Estimation and Exploitable Sparsity

CSI describes how the channel distorts a transmitted symbol in both amplitude and phase. In a multi-path environment, multiple copies of the same symbol are received with different delays. CSI thus can be modeled as a vector of complex values $\mathbf{h}$, where each value denotes the channel distortion along paths of a particular propagation delay. CSI is normally estimated using a known preamble $\mathbf{d}$ of length M preceding a packet. Denote $\mathbf{y}$ as the signal received by the receiver and $\mathbf{n}$ as noise. CSI can be estimated by solving for $\mathbf{h}$ in Eq (1):

$$\mathbf{y} = \mathbf{d} \otimes \mathbf{h} + \mathbf{n} \tag{1}$$

where the convolution models the intersymbol interference caused by multipath. We can rewrite Eq (1) into a matrix form with a circulant matrix $\mathbf{D}$:

$$\mathbf{y} = \mathbf{D}\mathbf{h} + \mathbf{n}, \quad \text{where } \mathbf{D} = \begin{bmatrix} d_1 & d_2 & \cdots & d_M \\ d_2 & d_3 & \cdots & d_1 \\ \vdots & \vdots & \ddots & \vdots \\ d_M & d_1 & \cdots & d_{M-1} \end{bmatrix} \tag{2}$$

Eq (2) stipulates that M has to be larger than the length of $\mathbf{h}$ (i.e., the number of unknowns) for estimation. The length of $\mathbf{h}$ is determined by the longest delay path in the environment. In indoor environments, the delay spread is typically small (30-60 ns or even less [2], [5]). This means that $\mathbf{h}$ in general is short. With a 20MHz bandwidth (25ns sampling interval), the length of $\mathbf{h}$ is no more than 3.

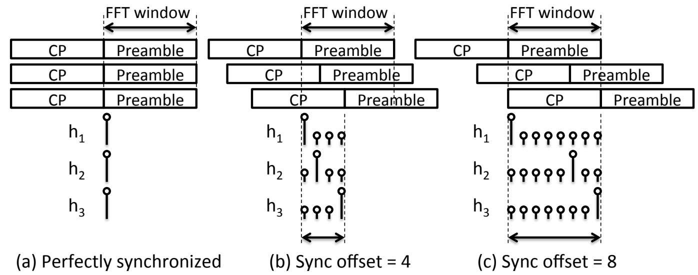


Fig. 2: Use of cyclic prefix (CP) to tolerate synchronization offsets among senders. Synchronization offsets cause an increase in the number of unknowns in CSI.

Under concurrent access of this paper, packet preambles from multiple senders are received concurrently. Consider an example where three preambles from known senders are received concurrently with perfect synchronization (as depicted in Figure 2(a)). Concurrent channel estimation can be carried out by expanding Eq (2):

$$\mathbf{y} = \begin{bmatrix} \mathbf{D}_1 & \mathbf{D}_2 & \mathbf{D}_3 \end{bmatrix} \begin{bmatrix} \mathbf{h}_1^\top & \mathbf{h}_2^\top & \mathbf{h}_3^\top \end{bmatrix}^\top + \mathbf{n} \tag{3}$$

We use the subscripts to denote the senders. In this case, we need M to be larger than the total length of $\mathbf{h}_1$, $\mathbf{h}_2$, and $\mathbf{h}_3$.

MIMO/CON seeks to realize concurrent access with minimum central control, meaning that perfect symbol-level synchronization is not available, and the receiver does not know the participating senders. For geographically distributed users, it is generally difficult and also expensive to provide tight synchronization among them; loose synchronization is desirable. Loose synchronization among senders can cause symbol misalignment as shown in Figure 2(b). The misalignment can be tolerated by exploiting the cyclic prefix (CP) structure in OFDM symbols. CP is a repetition of the end of an OFDM symbol. Therefore, even if misalignment exists, the receiver can still find a proper FFT window covering the same information of a symbol, as long as the CP is longer than the maximum synchronization offset.

An FFT window unaligned with the preamble, however, can increase the length of the CSI vector $\mathbf{h}$. The misalignment introduces an artificial delay to the preamble, and therefore adds zero entries into $\mathbf{h}$. For example, in Figure 2(b), assuming originally the length of $\mathbf{h}$ is 1 sample (or 1 "tap"), with a synchronization offset of 4 samples, the length of $\mathbf{h}$ is increased to 4 to accommodate the offset. Similarly, in Figure 2(c), a larger offset of 8 samples increases the length of $\mathbf{h}$ to 8.

When concurrent senders are uncoordinated, all potential N senders in the network have to be included into Eq (3) for channel estimation because the receiver will not know the participating senders:

$$\mathbf{y} = \begin{bmatrix} \mathbf{D}_1 & \mathbf{D}_2 & \cdots & \mathbf{D}_N \end{bmatrix} \begin{bmatrix} \mathbf{h}_1^\top & \mathbf{h}_2^\top & \cdots & \mathbf{h}_N^\top \end{bmatrix}^\top + \mathbf{n} \tag{4}$$

Denote the maximum synchronization offset as T_s. The number of unknowns in Eq (4) is then NT_s. Given the preamble length M has to be greater than NT_s for solving Eq (4), the preamble can be unpractically long. For example, with a loose synchronization method that has 2μs accuracy (e.g., the reference broadcast method [10]), the maximum synchronization offset T_s is 80-sample under 20MHz bandwidth. Assume the network has $N = 100$ senders. This means M has to be at least 8000, which translates to a long preamble of 200μs.

Suppose that 4 senders participate in the transmission and each CSI vector has no more than 3 taps. If the participating senders and timing misalignment for the preambles were known, we only need to solve for 12 unknowns. A 300ns long preamble would suffice to estimate the CSI. This motivates us to exploit compressive sensing for concurrent channel estimation.

III. Concurrent Multiuser CSI Estimation

Compressive sensing shows that for an $N \times 1$ sparse vector $\mathbf{x}$ that has only K nonzeros, one can form an $M \times 1$ sketch vector $\mathbf{y} = \mathbf{A}\mathbf{x}$, and recover $\mathbf{x}$ from $\mathbf{y}$ with M as small as $O(K \log \frac{N}{K})$ [3]. The key insight is to use certain *random projections* to form the sketch vector, i.e., use random matrix drawn from certain random distributions for $\mathbf{A}$. In this way, the recovery will be successful with high probability, and the number of equations required is approximately a small constant multiple of the sparsity K rather than the total number of unknowns N. MIMO/CON leverages compressive sensing for concurrent channel estimation to overcome the explosion of unknowns due to timing misalignment and uncoordinated senders.

A. Random projections from random preamble sequence

A natural way to form random projections of multiple CSI vectors is to use random preamble sequences. For simplicity, we form the preamble sequences of {1,-1} from Bernoulli distribution. To work with OFDM, we assume the number of OFDM subcarriers is equal to the preamble length M, and the preamble sequence is transmitted over the subcarriers.

Denote the preamble sequence owned by sender i as a vector $\mathbf{a}_i$ and $\hat{\mathbf{y}}$ as the signal received at the AP on the subcarriers. $\hat{\mathbf{y}}$ can be written as a linear combination of the preambles transmitted from the senders:

$$\hat{\mathbf{y}} = \mathbf{A}\mathbf{h} + \hat{\mathbf{n}} = \begin{bmatrix} \Phi_1 \mathbf{F} & \Phi_2 \mathbf{F} & \cdots & \Phi_N \mathbf{F} \end{bmatrix} \begin{bmatrix} x_1 \mathbf{h}_1 \\ x_2 \mathbf{h}_2 \\ \vdots \\ x_N \mathbf{h}_N \end{bmatrix} + \hat{\mathbf{n}} \quad (5)$$

where $\Phi_i = diag(\mathbf{a}_i)$. Note that the Fourier matrix $\mathbf{F}$ is inserted because we are interested in the time-domain channel response. Binary variables x_i are included to indicate whether sender i participates in the transmission.

We now can interpret Eq (5) using compressive sensing. Assume the channel has delay spread T_d and no more than K senders participate in the concurrent transmission. The $\mathbf{h}$ is a $T_d K$-sparse vector of length MN that contains CSI from active senders. $\mathbf{A}$ is a random matrix that forms random projections $\hat{\mathbf{y}}$ from the sparse vector $\mathbf{h}$. In this case, the preamble length M, which is also the OFDM FFT size, only needs to be a small multiple of $T_d K$ for $\hat{\mathbf{y}}$ to preserve sufficient information to recover $\mathbf{h}$. Note that the preamble sequences can be assigned to users during initial association by the AP, and so the AP has access to $\mathbf{A}$ for solving Eq (5).

Before we describe how to solve Eq (5), there are a few points worth noting. First, the formulation can be thought of as a generalized form of CDMA that attempts to multiplex preambles without creating mutual interference. Traditional CDMA requires that the codes possessed by different senders be orthogonal to each other. However, this assumes the worst case that all senders will transmit concurrently. Since we know the number of concurrent senders is limited by some number K, we can have a less constraining requirement that only every subset of K codes is orthogonal.

Second, although the delay spread in an indoor environment is small and should contain only 2 or 3 significant taps, in practice the measured channel impulse response can have more nonzero taps due to the leakage effect [14]. This is due to the fact that propagation delays are not necessary multiples of the sampling intervals, and the energy of these delays leaks into other taps during the discretization process. Fortunately, the leakage is concentrated around the most significant tap, and can be almost entirely captured by including a few neighboring taps as unknowns.

B. CSI recovery with MIMO antenna diversity

CSI has to be estimated within a packet time in order to facilitate MIMO decoding. This can be a demanding computation requirement for the hardware. We show that MU-MIMO not only can leverage the insight of compressive sensing, the MIMO antenna diversity can also benefit sparse recovery in reducing its computation load. In particular, we exploit the antenna diversity for a popular class of sparse recovery algorithms based on orthogonal matching pursuit (OMP) [12].

OMP is a greedy algorithm that iteratively identifies the nonzero entries in a sparse signal by finding the most correlated column vectors in $\mathbf{A}$ with the signal residual. The residual for the next iteration can then be computed by projecting $\hat{\mathbf{y}}$ to the subspace span by the identified columns. The algorithm continues until the residual is sufficiently small.

Multiple antennas on the AP offer independent observations of the same concurrent preambles. Similar in spirit to classic diversity combining [13], we combine the correlations computed from the observations to reduce the “noise”. The noise here comes from the underconstrained linear system that an incorrect column vector may be mistakenly correlated with $\hat{\mathbf{y}}$. Combining multiple independent observations can make this much more unlikely to occur. We argue that this improvement comes from the diversity in *phase* in the observations. A more detailed justification can be found in [6].

We incorporate this idea into the CoSaMP decoding algorithm [9], a variant of OMP. In our testbed experiments described in Section V-A, we observe the modified algorithm can identify the correct senders and timing misalignments even in only one iteration.

IV. Maximizing Channel Utilization

Beyond concurrent channel estimation, MIMO/CON's MAC layer needs to control the number of concurrent senders. Suppose the AP has K receive antennas. Ideally we want to ensure a batch of concurrent transmissions always has K packets. However, contention inevitably leads to fluctuations between underutilizing (less than K senders) and collisions due to overbooking the channel (more than K senders). This problem cannot be generally solved without exchanging information between senders.

MIMO/CON mitigates the problem by allowing channel overbooking over small periods of time via *delay packet decoding*. The scheme exploits newly received retransmissions in the MAC layer, and finds new opportunities in decoding unknowns in previous collisions. To illustrate the idea, consider a simple scenario that the AP has two antennas. At time t_1 three senders transmit packets p_1, p_2, and p_3 concurrently. The AP receives:

$$\mathbf{y} = \mathbf{h_1}p_1 + \mathbf{h_2}p_2 + \mathbf{h_3}p_3 \quad (6)$$

Since the AP has degrees-of-freedom two, at this point the AP cannot decode $\mathbf{y}$. Suppose p_3 is retransmitted and received correctly at a later time t_2. We then can regenerate $\mathbf{h_3}p_3$ to eliminate it from $\mathbf{y}$:

$$\mathbf{y} - \mathbf{h_3}p_3 = \mathbf{h_1}p_1 + \mathbf{h_2}p_2 \quad (7)$$

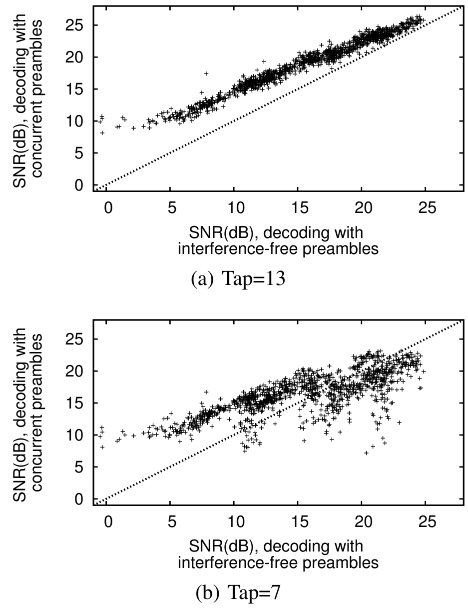
Now we can proceed to decode p_1 and p_2 because Eq (7) only has two unknowns left. This means that p_1 and p_2 no longer need to be retransmitted. Note that this scheme has to know that p_3 is involved in the collision $\mathbf{y}$, and estimate $\mathbf{h_3}$ from the preambles of $\mathbf{y}$ in order to regenerate the waveform. This can be accomplished by MIMO/CON's concurrent channel estimation with a longer preamble.

V. Performance Evaluation

We have implemented MIMO/CON on software-defined radios. We use the USRP-N200 boards with WBX daughterboards, and drive them with the UHD firmware [1]. The radios operate with center frequency 916MHz and a 6.25MHz bandwidth. In the testbed experiments, we focus on evaluating the performance of concurrent channel estimation. In the implementation, the DC subcarrier is not used for the preamble in order to avoid unwanted DC offset from the wireless transceiver. This is necessary because the DC offset shifts the CSI vector by a constant and eliminates its sparsity.

A. MIMO decoding performance using concurrent preambles

We use 4×4 MIMO to evaluate concurrent channel estimation in a lab environment. We assume the network has 100 senders but only 4 of them transmit at any given time. The distance between the transmitters and the receivers is around 2 to 3 meters. Different packet SNRs are obtained by varying the transmission power as well as the distances between transceivers. We compare concurrent channel estimation



(a) Tap=13

(b) Tap=7

Fig. 3: MIMO decoding performance in 4x4 MIMO. Each dot represents a MIMO packet decoded by two different CSI estimated from concurrent preambles and sequential preambles. Dots above the 45-degree line mean that using CSI from concurrent preambles yields higher decoded packet SNR.

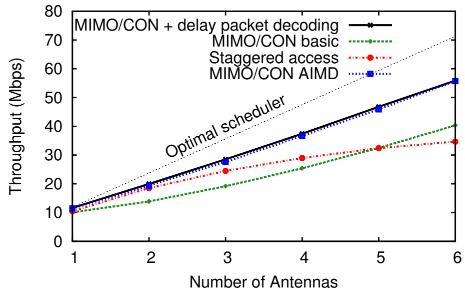
against a baseline scheme where interference-free preambles are scheduled to be transmitted sequentially. The standard least squares method [14] is used for channel estimation in the baseline scheme.

In the experiment, we have the senders consecutively transmit sequential interference-free preambles, concurrent preambles, and MIMO packets. We use the CSI estimated from both preambles for MIMO decoding and compare the SNR of the decoded packets. For MIMO decoding, we use the zero-forcing method with successive interference cancellation [13]. We set the number of OFDM subcarriers to 128 for both cases. Each experiment is repeated 300 times with different random preamble sequences.

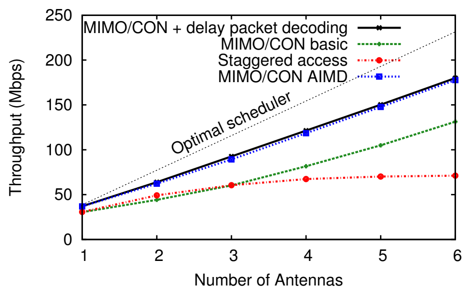
Figure 3 shows the scatter plots of the decoded packet SNR using sequential preambles versus that using concurrent preambles. We can see that for concurrent channel estimation, when a sufficient number of taps (13 taps in our experiments) is solved, the decoded packet SNR can even be better than that using sequential preambles by noticing that the dots are above the 45-degree line. This is because sparse-recovery based channel estimation can filter out noise by setting the channel response of large-delay taps to zero. On the other hand, if too few taps are solved, the less accurate CSI can result in loss in packet SNR.

B. Throughput improvement with MIMO/CON

We use a high-level software simulator to evaluate throughput performance of MIMO/CON. Our current hardware system cannot run fast enough to support carrier sensing and real-time concurrent preamble decoding for a large number of



(a) PHY data rate 13Mbps



(b) PHY data rate 52Mbps

Fig. 4: MIMO/CON throughput with 20 users in simulations.

active users. We implemented an event-driven simulator, which assumes standard 802.11n parameters: 28 μs DIFS, 10 μs SIFS, and 9 μs slot time. We assume a standard 1500-byte data packet size and a 14-byte ACK packet size.

We compare MIMO/CON with SAM [11], a staggered access design for MU-MIMO systems. In addition, to evaluate the effectiveness of delay packet decoding, we run experiments for MIMO/CON with and without the feature turned on. For simplicity, we assume first that the users know the optimal transmission probability for contention. Later we will add AIMD (additive-increase-multiplicative-decrease) control to MIMO/CON for transmission probability adaptation. Throughput under an optimal scheduler is reported for reference.

The simulations assume 20 senders under two different PHY data rates, 13Mbps and 52Mbps, to represent the low and high SNR regimes, respectively. Figure 4 shows that when there are fewer MIMO antennas, staggered access outperforms MIMO/CON without delay packet decoding. However, the throughput of staggered access quickly saturates when there are more antennas. The saturation is due to the serialized channel contention that limits the maximum number of overlapping packets. For example, assume an average contention delay of 10 slots. Given that a packet under 52Mbps spans 27 slots, when the fourth sender joins concurrent transmission, the first packet is already finished. In contrast, the throughput of MIMO/CON scales well with more antennas. With 5 antennas, MIMO/CON can improve the throughput of staggered access by 140% under 13Mbps; a larger improvement of 210% is observed with a higher 52Mbps data rate.

Delay packet decoding can significantly increase channel utilization. It can reduce the throughput gap between MIMO/CON and the optimal scheduler by 50%. The remaining gap is mainly due to channel underutilization that a concurrent transmission involves fewer than K packets. Lastly, MIMO/CON with AIMD delivers similar throughput performance. This shows MIMO/CON with AIMD can search for and use the optimal transmission probability.

VI. Conclusions

In this paper, we have proposed an ambitious scheme for achieving full utilization of uplink capacity offered by an AP equipped with many receive antennas. A key to our scheme is a novel channel estimation method in the PHY layer which can estimate CSI and identify active senders from concurrently received packet preambles. This is achieved under the assumption that senders are only loosely synchronized and not subject to mutual or central coordination. In the MAC layer, MIMO/CON maximizes channel utilization by exploiting normal MAC layer retransmission mechanism to recover otherwise undecodable packets in a collision. We believe the concurrent channel access and estimation schemes of this paper, or similar approaches, are important for future high-throughput multiuser MIMO networks.

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