

# A Cross-layer Study on Multiple-antenna Techniques in Wireless Backhaul Networks\*

Yun Hou<sup>#</sup>, Alexandr M. Kuzminskiy<sup>†</sup>, Federico Boccardi<sup>†</sup>, Kai Yu<sup>†</sup>, Kin Leung<sup>#</sup>

<sup>#</sup>*Electrical and Electronic Engineering, Imperial College, United Kingdom, SW7 2BT*

<sup>†</sup>*Alcatel Bell Labs, Wireless and Broadband Access Research, Alcatel-Lucent, Swindon, United Kingdom, SN5 7DJ*

<sup>#</sup>{yun.hou, kin.leung}@imperial.ac.uk, <sup>†</sup>{ak9, fb, kaiyu}@alcatel-lucent.com

**Abstract** -- Wireless multi-hop, backhaul networks transfer data traffic from access networks to the wired Internet. Scheduling algorithms for wireless backhaul networks activate multiple simultaneous transmissions, which in turn introduce concurrent interference into the network. Although multiple-antenna techniques have been extensively studied in the literature, not much research for multiple antennas has been received in the backhaul context. In this paper, we investigate the cross-layer performance between various multiple-antenna techniques and backhaul schedulers using physical layer abstraction. Simulation results reveal that with multiple antennas the backhaul network can accommodate a higher density of concurrent links, relative to the network with single antenna. Furthermore, simulation results unfold that the dominant eigenmode transmission and the least square interference cancellation schemes are optimized for noise-limited and interference-limited scenarios, respectively.

## I. INTRODUCTION

Backhaul networks transfer data between access points to gateway nodes, which in turn are connected to the wired Internet. Traditionally, backhaul networks are based on wired technologies such as ADSL, T1 and optical fiber. For low cost and ease of deployment, wireless networks are being considered to provide the backhaul capability. Due to proliferation of access points as well as reduction of cell size to meet growing traffic demands in cellular networks, there is a strong need to develop new wireless backhaul technologies. Notably, IEEE 802.16 [1] specifications are devised to meet such need and indeed one of the expected applications of the 802.16 standards is to backhaul traffic to and from 802.11 [2] access points. In addition, research projects such as [3] are also actively exploring new wireless backhaul technologies. In this paper we concentrate on the MAC layer (scheduling algorithms) and the PHY layer (transceivers) in the backhaul networks with time-division-duplex (TDD) operations.

In the backhaul networks with TDD operations, since nodes cannot transmit and receive simultaneously, each backhaul router can be involved in to at most one transmission at a time. As a result, a feasible schedule for the backhaul networks with TDD operations is a set of separated links, as illustrated by the solid arrows in Figure 1. Please note that nodes in the figure are the wireless routers of the wireless backhaul network, although they are assumed to be located according to the typical hexagonal layout for illustration purposes. In graph theory [4], a set of separated links is also referred to as a matching of the graph. Furthermore, for a fixed graph, there could be multiple matchings. Then as presented in [5], the objective of a scheduling algorithm for the backhaul networks is to find the matching which is with the largest aggregated utility of the links in that matching.

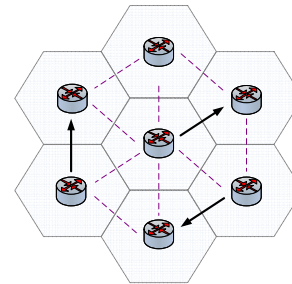


Figure 1 An feasible schedule for the backhaul network in hexagonal topology.

In this paper we adopt the scheduling algorithm that was originally proposed in [5] and later extended in [6], to investigate its interaction with various physical layer techniques. The scheduling algorithm activates multiple concurrent transmissions in a distributed and opportunistic manner, relying on the control exchange between neighboring routers. Especially, [6] analyses the average number of concurrent transmissions activated by the so-called 1-round and 2-round scheduling algorithms where the control information can be exchanged with neighbors up to one-hop and two-hop away, respectively. The 2-round scheduling, which is more complicated in terms of control exchange, can activate 30% more concurrent links relative to the simple 1-round scheduler.

Intuitively, the additional concurrent links should translate into greater network throughput to compensate the high complexity. However, whether the 2-round scheduling algorithm can provide a higher network throughput over the 1-round algorithm is still an open question. It is because that for any physical layer techniques, the network throughput is a concave function of the density of concurrent links. In other words, an increase in concurrent links in a given network may or may not lead to an increase in the throughput, since greater interference is injected by the addition links. Furthermore, to the best of our knowledge, conventional studies on physical layer techniques mainly target at the per-link throughput performance. Not much research attention has been received to investigate the network performance of the physical layer techniques in backhaul networks. For example, the network performance of multiple-input-multiple-output (MIMO) techniques has been seldom studied in the backhaul scenario where multiple transmissions are co-existing.

To answer the above questions, we conduct a cross-layer study between various physical layer techniques and the backhaul scheduling algorithms in this paper. We first integrate the simplest single-antenna transceivers into the backhaul scheduling algorithm. Motivated by the finding that

single antennas cannot achieve higher network throughput for the 2-round scheduler relative to the 1-round scheduling, we introduce various MIMO techniques, namely the Maximal-Ratio-Combining (MRC), the Least Square Interference Cancellation (LSIC) and the Dominant Eigenmode Transmission (DET). We investigate the network performance of these multiple-antenna techniques by comparing the cross-layer performance of the three techniques in the MAC layer via physical layer abstractions. Simulation results confirm that with multiple-antenna techniques, the 2-round scheduler achieves greater network throughput relative to the 1-round scheduler. Moreover, with the same setting, DET and LSIC show their strengths in noise-dominant and interference-dominant scenarios, respectively.

The remainder of this paper is organized as follows. In section 2 we provide further motivation for the use of multiple-antenna techniques by investigating the performance degradation of the 2-round scheduling due to single-antennas. Section 3 elaborates the methodology of the physical layer abstraction, followed by a brief introduction to the physical layer techniques in section 4. Section 5 presents the simulation results and section 6 concludes the paper.

## II. SCHEDULING PERFORMANCE WITH SINGLE-ANTENNA

As proved in [6], on average, the 2-round scheduling can activate 30% more concurrent links, compared to the 1-round scheduling. In order to clarify the marginal gain of the 2-round over the 1-round algorithm, we briefly introduce the main procedures of these scheduling algorithms as follows.

Let us assume that the system is time-slotted and the network has a hexagonal topology such that each backhaul router lies in the central of a hexagonal cell as shown in Figure 1. Consequently, each router has 6 immediate neighboring routers and 12 links associated with it. The objective for the distributed scheduling is for each router to choose one high-utility link from the links associated with it to activate in the next time slot. However, because all the routers simultaneously select links towards high utilities, the resultant scheduling decisions may be conflicting to each other. For example, imagine node  $i$  makes a decision to transmit to its neighbor node  $j$ . However, node  $j$  may want to transmit to another node  $k$  because it is more profitable. As a result, node  $j$  is involved in a conflict in terms of duplexing status. To resolve the conflicts, both the 1-round and the 2-round scheduling algorithms use three phases to finalize a conflict-free scheduling decision for a router every. They are

1. To exchange the link utility with the neighboring routers.
2. To make an initial decision, e.g. to find a link which is with a good utility and a small prior probability to collide with neighbors' decision.
3. To exchange the initial decisions with neighbors and finalize the scheduling by dropping the conflicting initial decisions.

Since the 2-round scheduling algorithm allows utility and initial decision exchange to a larger extent than the 1-round scheduling algorithm, the probability to have conflicting decision for the 2-round scheduling is smaller. Therefore, more routers make a *right* initial decision with 2-round scheduling algorithm, and hence more links can be retained from the phase 2 to be the final decision.

With a higher complexity, the 2-round scheduling activates a larger number of concurrent links. Meanwhile, it injects

greater interference into the network as well. Therefore, whether the 2-round scheduling can provide higher throughput for the entire network is an open question. To answer this question, we run simulation to compare the network throughput performance of the 1- and 2-round scheduling algorithms, by using Shannon capacity [7] to abstract the throughput performance for single antennas.

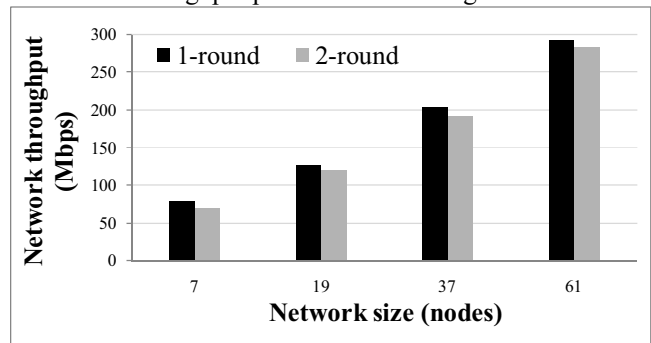


Figure 2 The averaged aggregated network throughput for 1-round and 2-round scheduling using the single antenna as the physical layer.

Figure 2 compares the time-averaged network throughput provided by the 1- and 2-round scheduling algorithms with single antennas over 10,000 time slots. For every time slot, the network throughput is equal to the sum of the throughputs of all active links in that time slot. A negative result is observed that the network throughput provided by the 2-round scheduling is *lower* than the throughput provided by the 1-round scheduling, even though the two-round scheduling activates more concurrent transmissions. The result reveals that the link density generated by the 2-round scheduler exceeds the optimal link density for the single-antenna backhaul network. Enhancement in throughput performance of the 2-round scheduling algorithm could be expected if interference elimination techniques are used to improve the per-link throughput-interference performance, and hence to raise the optimal link density for the backhaul scenario. This finding motivates the study on multiple-antenna techniques (physical layer) integrated with the schedulers (MAC layer) in the wireless backhaul scenario, which has not been investigated sufficiently in the existing literature.

## III. METHODOLOGY OF PHYSICAL LAYER ABSTRACTION

There are two simulation methods to produce cross-layer (physical and MAC layer) results in terms of network performance. One is to run a huge two-layer simulation, which contains a full scheduling protocol and a full bit-wise physical layer. The other one is to first obtain the per-link error performance of the interesting physical layer techniques, and then utilize the per-link error function to construct the MAC layer simulation. For example, in the MAC layer simulation, once the entire network schedule for a snapshot is determined, the strengths of all interference components are known to the simulation. Then one can “look up” the per-link error function for the specific interference and noise combination to obtain the error rate for that transmission at link level.

We adopt the separated approach because this approach is with a much lower complexity, compared to the two-layer simulation. Moreover, the separated approach also provides

the great flexibility to build different MAC-layer simulations using the results from only one physical-layer simulations.

Physical-layer (PHY) abstraction is used to create the per-link error performance for multiple-antenna techniques. The objective is to run a physical-layer bit-wise simulation to find out the average packet error rate (PER) over various noise and interference combinations. Specifically, the PHY abstraction simulation results would finally construct a function as shown in (1) to be called in the MAC-layer simulation.

$$PER = f_{PHY}(SNR, SIR_1, SIR_2, \dots, SIR_N) \quad (1)$$

The output of the function is the average PER for various physical layer techniques, i.e., MRC, LSIC and DET. The input arguments to the function include the SNR (in dB) of the desired signal and a vector of SIR (in dB) which indicates the SIR for individual interference components from distinguished interfering routers. However, the PHY abstraction which accommodates a large quantity of continuous input of SNR and SIR's requires extremely high complexity. Practically, we proposed to run the simulation over a subset of discrete values of one SNR and five SIR's as the first step. Afterwards, a linear interpolation is performed to form a continuous PHY abstraction function.

#### IV. MULTIPLE ANTENNA TECHNIQUES

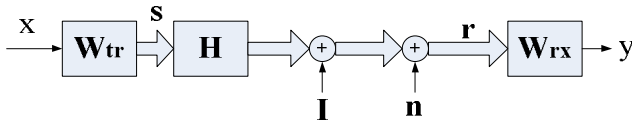


Figure 3 Block diagram of the wireless channel

The block diagram of the wireless channel in common for the three multiple-antenna technique is shown in Figure 3.  $x$  is the scalar complex modulated channel symbol fed into the transmitting antenna, with weighting coefficients  $\mathbf{W}_{tr}$ .  $\mathbf{W}_{tr}$  is a column vector of dimension 1 by  $M$ . Similarly,  $\mathbf{W}_{rx}$  is the 1 by  $M$  weighting coefficient vector for the receiving antennas.  $\mathbf{s}$  is the transmitted vector signal after transmitting antenna splitting.  $\mathbf{H}$  stands for the time-varying  $M$  by  $M$  channel matrix between the transmitter and receiver.  $\mathbf{I}$  and  $\mathbf{n}$  denote the interference from other transmitting routers and the background noise, respectively.  $\mathbf{r}$  is the vector signal received by  $M$  receiving antennas with impairment of interference and noise. Then according to Figure 3,  $\mathbf{r}$  is equal to

$$\mathbf{r} = \mathbf{H}\mathbf{s} + \sum_{i \in \text{Active routers}} \mathbf{I}_i + \mathbf{n}.$$

$y$  is the scalar received signal after the receiving-antenna combining and  $y = \mathbf{W}_{rx}'\mathbf{r}$ . Since the difference among the three multiple antennas is in terms of antenna weighting vectors, we elaborate the derivation for  $\mathbf{W}_{tr}$ 's and  $\mathbf{W}_{rx}$ 's for MRC, LSIC and DET as follows.

##### A. Maximal Ratio Combining (MRC)

MRC is a diversity technique locally at the receiver. Therefore, the transmitter antenna is free weighting. One possible weighting scheme is that only one transmitting antenna is used to send  $x$  with coefficient 1.0, with all the other  $M-1$  antennas being weighted by 0. Then the channel  $\mathbf{H}$  becomes a column vector of dimension 1 by  $M$ . In our simulation, the combining coefficient is equal to:

$$\mathbf{W}_{rx} = \frac{\mathbf{H}_e}{\mathbf{H}_e'\mathbf{H}_e}. \quad (2)$$

$\mathbf{H}_e$  denotes the channel estimate of the current time slot. The channel estimation is performed at the receiver, based on the pilot signals. In our cross-layer investigation, the MRC method serves as a benchmark, given that the MRC is a multiple antenna technique without interference elimination capability.

##### B. Least Square Interference Cancellation (LSIC)

LSIC is an interference cancellation technique that is based on estimation of the receiver weighting vector over the pilot data interval [9]: Similar to the MRC scheme, LSIC optimize the receiving weighting vector only. The Least-Square criterion for the channel model in is embodied by an optimization problem towards the objective function:

$$\mathbf{W}_{rx} = \arg \min_{\mathbf{W}_{rx}} \|\mathbf{P} - \hat{\mathbf{P}}\mathbf{W}_{rx}\|^2$$

where  $\mathbf{P}$  is the known pilot vector and  $\hat{\mathbf{P}}$  stands for the received copy of the pilots. Then, the optimal weighting coefficients can be calculated according to:

$$\mathbf{W}_{rx} = \hat{\mathbf{R}}^{-1}\hat{\mathbf{r}} \quad (3)$$

where  $\hat{\mathbf{R}}$  denotes the covariance matrix of the received signal and  $\hat{\mathbf{r}}$  denotes the cross-correlation vector between the transmitted and received pilots. OFDM versions of LSIC are studied in [8]. A group-based interpolation technique is used in the simulations in Section V, which exploits a single weighting vector for a group of adjacent sub-carriers.

##### C. Dominant Eigenmode Transmission (DET)

DET is one of the beamforming MIMO technique used to enhance the received signal strength. The pre-condition for the use of DET is that the MIMO channel is known to both the transmitter and the receiver. For a given  $\mathbf{H}$ , the  $\mathbf{W}_{tr}$  and the  $\mathbf{W}_{rx}$  are computed as follows. First, conduct the singular value decomposition (SVD) to  $\mathbf{H}$ :

$$SVD(\mathbf{H}) = \mathbf{U}\mathbf{\Sigma}\mathbf{V}'.$$

Then the transmitting and receiving weights are equal to the first column of  $\mathbf{U}$  and the first row of  $\mathbf{V}$ , respectively:

$$\begin{aligned} \mathbf{W}_{rx} &= U_1 \\ \mathbf{W}_{tr} &= V_1' \end{aligned} \quad (4)$$

Then the resultant received signal  $y$  in Figure 3 is:

$$\begin{aligned} y &= \mathbf{W}_{rx}'\mathbf{r} \\ &= (U_1'\mathbf{U})\mathbf{\Sigma}(V_1'V_1)x + \mathbf{W}_{rx}'\left(\sum_{i \in \text{Active routers}} \mathbf{I}_i + \mathbf{n}\right) \end{aligned}$$

Since  $U_1'\mathbf{U} = \mathbf{V}'V_1 = [1, 0, \dots, 0]$  then

$$y = \lambda_1 x + \mathbf{W}_{rx}'\left(\sum_{i \in \text{Active routers}} \mathbf{I}_i + \mathbf{n}\right), \quad (5)$$

where  $\lambda_1$  is the largest eigenvalue of the channel matrix  $\mathbf{H}$ . As shown in (5), the desired signal is amplified by  $\lambda_1$  times. Since the interference and noise are not optimized for  $\mathbf{W}_{rx}$ , they are not amplified. Then with ideal channel information, the beamforming gain of DET scheme is equal to the expected value of  $\lambda_1$  which is in the range of  $M$  to  $M^2$  [10].

## V. NUMERICAL RESULTS

### A. Physical layer abstraction results

TABLE 1 SIR COMBINATIONS USED IN PHY ABSTRACTION

	01-14		15-28		29-42		43-56													
1	-10	-10	-10	-10	-10	-10	0	10	20	-10	0	10	20	20	0	0	10	10	20	
2	-10	-10	-10	-10	0	-10	-10	0	20	20	-10	0	20	20	20	0	0	10	20	20
3	-10	-10	-10	-10	10	-10	-10	10	10	10	-10	10	10	10	10	0	0	20	20	20
4	-10	-10	-10	-10	20	-10	-10	10	10	20	-10	10	10	10	20	0	10	10	10	10
5	-10	-10	-10	0	0	-10	-10	10	20	20	-10	10	10	10	20	0	10	10	10	20
6	-10	-10	-10	0	10	-10	-10	20	20	20	-10	10	20	20	20	0	10	10	20	20
7	-10	-10	-10	0	20	-10	0	0	0	0	-10	20	20	20	20	0	10	20	20	20
8	-10	-10	-10	10	10	-10	0	0	0	10	0	0	0	0	0	0	20	20	20	20
9	-10	-10	-10	10	20	-10	0	0	0	20	0	0	0	0	10	10	10	10	10	10
10	-10	-10	-10	20	20	-10	0	0	10	10	0	0	0	20	10	10	10	10	10	20
11	-10	-10	0	0	0	-10	0	0	10	20	0	0	0	10	10	10	10	10	20	20
12	-10	-10	0	0	10	-10	0	0	20	20	0	0	0	10	10	10	10	20	20	20
13	-10	-10	0	0	20	-10	0	10	10	10	0	0	0	20	20	10	20	20	20	20
14	-10	-10	0	10	10	-10	0	10	10	20	0	0	10	10	10	20	20	20	20	20

In the simulation of PHY abstraction, there is one transmitter, one receiver and five interferers. All the transmitters and receivers are equipped with 5 antennas. The frequency-selective channel between any transmitter-receiver or interferer-receiver pair varies once every frame/packet. The transmission is 256-point-OFDM QPSK modulated using 1/2 convolution coding, with bandwidth of 20 MHz. All the transmitters are synchronized so that they know the boundary of time slots. One packet contains four slots. The packet is received successfully only if all the slots are received correctly. However, jitters in terms of arrival time of interfering packets are injected to simulate random interferer locations. The discrete values of SNR adopted in the simulation are 0, 5, 10, 15 and 20dB. The discrete SIR combinations used in the first step are listed in TABLE 1. Basically, it is the entire set of possible combinations of -10, 0, 10 and 20 dB. Once every 1000 packets, the simulation updates the SNR/SIR vector to obtain the averaged PER for another combination.

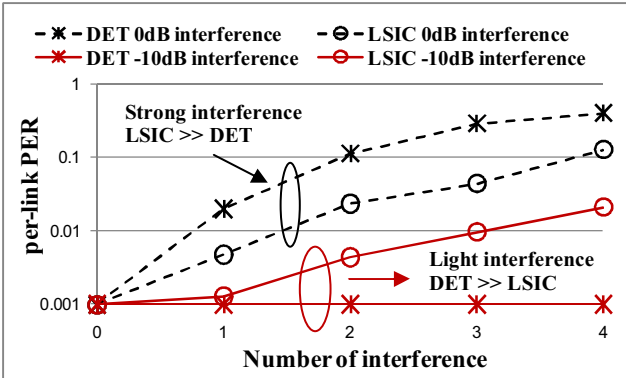


Figure 4 Comparison between DET and LSIC with various interference quantity and strength.

Figure 4 compares the DET and LSIC in terms of PER with respect to some specific interference combinations with SNR of 10dB. The horizontal axis of the figure shows the number of interferers, varying from 0 to 4. The solid and dashed lines denote the strength of individual interference components of -10 and 0dB, respectively. For example, at the x-axis equal to 2, the solid lines correspond to the interference combination of [-10,-10] dB, relative to the desired signal strength; whereas the dashed lines correspond to the interference combination of [0 0] dB. Figure 4 unfolds that when there are strong interference components, the LSIC uniformly outperforms the DET in the whole range of

quantity of interferers (the dashed lines). In the case that there is no strong interference, the solid lines show that the DET can provide better PER (0.001) performance than the LSIC, even though the quantity of interferers is large.

Figure 5 compares the DET and LSIC in terms of PER with varying SNR and fixed SIR of 0 dB. It is revealed by Figure 5 that the LSIC and the DET have their strong points in opposite SNR scenarios. The dashed lines suggest that with strong noise, the DET scheme is able to generate a smaller PER than the LSIC. Meanwhile, the solid lines demonstrate that the LSIC can further enhance the PER performance by cancelling interference when the SNR is already high enough (20dB).

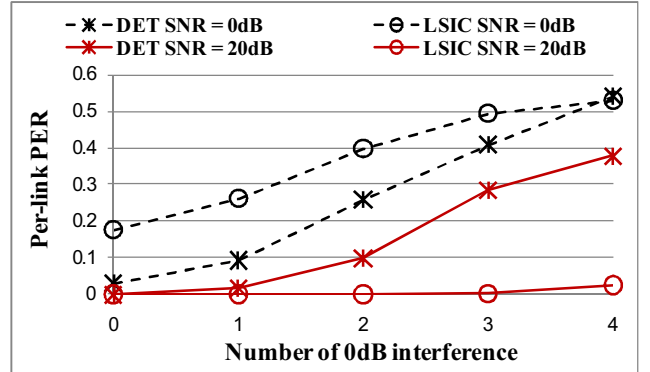


Figure 5 Comparison between DET and LSIC with various SNR and quantity of interference.

The most interesting observation from Figure 4 and Figure 5 is that LSIC and DET show their strengths in opposite SNR/SIR scenarios. The reason is that LSIC and DET are originally designed for different objectives. On one hand, LSIC was particularly designed for interference limited scenarios and the main job of LSIC is to “cancel” individual interference elements at the receiver. On the other hand, the DET is devised to improve the received signal strength at the receiver by matching the transmitting and receiving vectors. To conclude the PHY abstraction results, DET is more powerful in noise-limited scenarios and LSIC is more effective in interference-limited scenarios.

### B. Network level simulation results

In this subsection, we imbed the PHY abstraction into the MAC layer simulation on the network level. The network contains 37 network nodes in a hexagonal layout. At the end of every time slot, each router activates one of the links associated with it following the scheduling algorithms in [6], using the SINR utility. After the network schedule is determined by all routers in a distributed manner, the SNR/SIR combination for every active link is known. Hence the average PER is known according to the resultant error function from PHY abstraction. In the MAC-layer simulation, the PHY abstraction error function gives the theoretical PER value for specific SNR/SIR combinations. Then, to ensure that the actual PER generated in MAC-layer conforms to the theoretical PER, in every time slot the MAC-layer simulation generates a random number with uniform distribution in the range of [0,1]. A packet is considered to be correctly received, only if the random number is greater than the theoretical PER for the corresponding SNR/SIR combination.

Figure 6 shows the time-averaged network throughput provided by various multiple-antenna techniques over 10,000 packets. The major message conveyed by Figure 6 is that with the LSIC and the DET, the 2-round scheduler show up to 30% improvement in terms of network throughput over the 1-round scheduler. Besides, with the MRC scheme, the 2-round scheduling can enhance the network throughput by up to 10% relative to the 1-round scheduler. This result confirms that multiple-antenna techniques can raise the optimal link density for the backhaul network, compared with the single-antenna case discussed in Section 2. It is observed that the marginal gain provided by the MRC is limited, relative to the DET and the LSIC. This is because that the MRC is not an interference mitigation technique. In other words, the MRC cannot fully combat the negative impact of the additional concurrent transmissions, i.e., the greater interference.

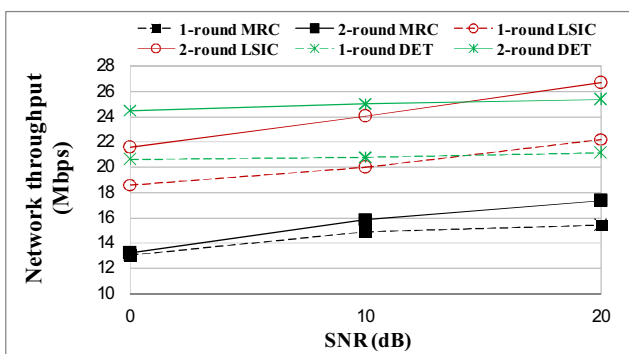


Figure 6 Comparison in terms of network throughput among different PHY techniques with varying SNR.

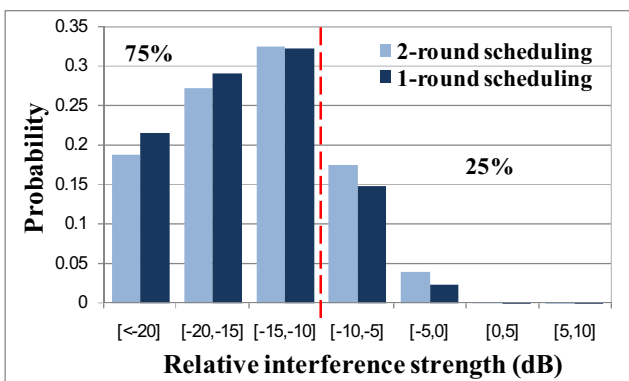


Figure 7 Interference strength in the wireless backhaul network.

Another significant observation from Figure 6 is regarding the intersection between the LSIC and the DET curves. Based on the PHY abstraction conclusion, the DET is designed to enhance the received SNR and is helpful in noise-limited scenarios; while LSIC is an interference cancellation scheme which is originally devised for interference-limited systems. To form a better understanding of the interference characteristics in backhaul scenario, we record the strength of individual interference components for the central-located router, and plot the probability mass for the recorded interference strength as demonstrated in Figure 7. It is noticeable that among all the interferers for the central router, most (75%) of them are transmitting fairly weak interference, e.g. the interference strengths are smaller than -10dB relative to the desired signal. Based on this probability mass, a rough calculation suggests that the averaged SIR for an arbitrary is around 15 dB, which is dominant when the SNR equals to 20

dB and non-dominant when the SNR is 0 and 10 dB. Thus, it is confirmed that the backhaul network transits from noise-limited to interference-limited at the intersection.

To summarize, the multiple-antenna techniques can raise the optimal link density for backhaul networks, compared to the single-antenna technique. For the 2-round scheduler, interference elimination capability at the physical layer is essential to achieving satisfactory network throughput so as to compensate the price of high complexity. Moreover, in high SNR region, the LSIC can provide excellent network throughput without high complexity. While, in poor SNR scenarios, the more sophisticated DET is needed to guarantee satisfactory network throughput.

## VI. CONCLUSIONS

In this paper, we have investigated three multiple antenna techniques, namely the MRC, the LSIC and the DET in the context of backhaul networks. A cross-layer study composed of the physical layer abstraction and the scheduler simulation reveals that with the DET and the LSIC, the 2-round scheduler can mitigate the greater interference due to the greater link density, and further enhance the network throughput by 30% over the 1-round scheduler. Furthermore, simulation results unfold that the DET and the LSIC schemes are optimized for noise-limited and interference-limited scenarios, respectively.

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