Virtual MISO Triggers in WiFi-like Networks

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Technical Report

***Abstract*—Virtual Multiple-Input Single-Output (vMISO) systems distribute multi-antenna diversity capabilities between a sending and a cooperating node. vMISO has the potential to vastly improve wireless link reliability and bit error rates by exploiting spatial diversity. In this paper, we present the first experimental evaluation of vMISO triggers (when to invoke vMISO rather than traditional transmission) in WiFi networking environments. We consider the joint effect of gains obtained at the physical layer with MAC and network-scale factors and show that 802.11 MAC mechanisms represent a major bottleneck to realizing gains that can be attained by a vMISO PHY. In contrast, we show how vMISO alters node inter-connectivity and coordination and therefore can vastly transform the network throughput distribution in beneficial ways that are not described merely by vMISO link gains. Moreover, we show how to avoid triggering vMISO when the increased spatial footprint of the new cooperator would excessively hinder other flows' performance. In this paper, we build the first multi-flow vMISO testbed and explore the cooperative trigger criteria that is essential to attain substantial gains in a fully integrated vMISO system. We find that the largest gains are achieved by a largely isolated flow (gains of 110%) whereas cooperator interference effects are pronounced in dense mesh topologies, reducing typical gains to 14%.**

I. Introduction

Virtual MISO (vMISO) systems in combination with space-time block coding (STBC) have the potential to mitigate link performance degradation due to signal fading and multipath effects by exploiting spatial diversity [9], [17]–[20]. In its simplest form, a vMISO link consists of a distributed system comprised of a sender node and a helper or cooperator node simultaneously transmitting to a common receiver. STBC is a technique for orthogonalizing multiple streams across several transmit antennas. Thus, vMISO can employ STBCs to increase robustness by using simultaneous transmission of two data streams from two independent nodes, i.e., the originating sender, and the helper.

By means of an experimental evaluation of vMISO protocols, we design vMISO trigger policies for Wifi-like networks. We define trigger policies as the set of specifications that dictate when vMISO should be *enabled* in a given flow in order to guarantee substantial throughput performance gains while minimizing the negative impact due to additional interference caused by the helper node. Our goal is to identify the criteria that these policies must account for, in order to provide such guarantees. Towards this end, we build the first multi-flow virtual MISO testbed, and present a comprehensive experimental evaluation of vMISO medium access control (MAC) protocols which we use to determine these criteria. Namely, we employ a methodical approach by which we gradually increase the complexity of the network scenario and study isolated and joint factors affecting performance of virtual MISO schemes.

In particular, this paper has the following main contributions: First, in order to develop trigger policies we implement and evaluate different protocols that employ distinct mechanisms to invoke vMISO transmissions, in small and large scale networks: *i) Reactive* vMISO schemes (also known as On-Demand) invoke vMISO transmissions only via explicit feedback from the receiver when the original transmission failed and a retransmission is required, e.g., [8]. *ii) Proactive* protocols on the other hand, invoke vMISO transmissions in an opportunistic manner via a two-phase process where initially the information is delivered to the helper and then a simultaneous sender-helper transmission is started without requiring any feedback. In addition, we define a suite of benchmarking protocols that characterize *idealized* vMISO schemes for simulation-based comparison. For example, this method enables us to compare an operational vMISO protocol with a genie-based protocol in which the original failed transmission is not needed to share data with the helper and a vMISO transmission occurs within a single phase.

Second, we determine that in single-flow scenarios, a combination of reactive and proactive vMISO triggers yields the largest gains for a wide range of SNR regimes. For instance, proactive vMISO is more suitable at low SNR because it does not waste resources on a SISO transmission attempt, whereas reactive vMISO is more advantageous for medium to high SNR because vMISO transmissions are only enabled if an initial SISO attempt failed. Furthermore, we explore vMISO when coupled with MAC-layer mechanisms such as bit rate adaptation, and evaluate the protocols' performance as a function of signal attenuation, helper node position, and transmission power. Our evaluation reveals that MAC mechanisms such as the discrete and limited number of possible transmission rates supported by the 802.11 can limit the gains attained by vMISO at the physical layer. Moreover, for a given channel condition, vMISO gains vary significantly with transmission rate, with the largest gains available at rates that would yield a poor channel with Single-Input Single-Output (SISO), i.e., rates higher than a SISO channel would allow. Thus, a joint decision of which transmission rate to choose and whether or not to trigger vMISO is ideal to maximize gains.

Third, in two-flow scenarios we demonstrate that the additional transmitter (the vMISO helper) alters the network graph, medium contention, and inter-flow coordination. We show that in some cases, a bigger footprint due to the additional helper node substantially inhibits spatial reuse. However, in other scenarios, the helping nodes added "links" (i.e., interactions between the helper and other nodes), improve MAC coordination, thereby improving fairness and throughput. For example, in hidden terminal scenarios the vMISO cooperator can add coordination by forcing other senders to defer thereby avoiding hidden terminal collisions. Consequently, proactively triggering vMISO transmissions in such cases leads to increased overall throughput performance.

Finally, we establish that vMISO cooperators lead to significant increase in deferrals in large-scale topologies comprised of multi-hop flows, ad hoc networks, and mesh networks thus decreasing the gains attained by vMISO compared to small-scale scenarios. While in small scale scenarios each individual flow can greedily choose whether to enable vMISO, in large-scale networks a coordinated decision that only allows certain flows to trigger vMISO, strongly benefits the entire network (i.e., those that yield maximum gains while minimizing their interference footprint). We show that even a simple policy allowing only the flows achieving the highest gains to trigger vMISO, can significantly increase the gains in large-scale networks. Nonetheless, without distributed coordination, vMISO has the largest gains in small-scale topologies where it can significantly improve a single link's performance. For example, a poor quality link in a home WLAN might be dramatically improved by using a nearby device as a helper.

The rest of this paper is structured as follows. Section II describes our vMISO system implementation. In Section III we explore the interactions that arise from the coupling of traditional MAC mechanisms and virtual MISO. Section IV covers small scale topologies where we explore vMISO in isolated scenarios. Further, in section V we consider large scale topologies consisting of both structured and structure-less networks. Sections VI and VII discuss the prior work and concluding remarks, respectively.

II. vMISO Protocols and Implementation

We present the first multi-flow vMISO indoor testbed, comprised of several nodes forming different topologies. In this section we introduce such testbed, as well as the protocols we implemented.

A. vMISO and STBC Implementation

Virtual MISO, also known as cooperative diversity, takes advantage of spatial diversity and the relatively independent channel realizations seen by different antennas. This is done in a distributed manner by exploiting the presence of multiple single-antenna nodes, which by operating together can emulate an antenna array [12]. That is, both the sender and the helping node (i.e., the vMISO cooperator) act as if they were a single multi-antenna device by transmitting cooperative packets to a common receiver.

Our implementation consists of single-antenna distributed nodes where the sender and cooperating node form a vMISO link by simultaneously transmitting two copies of the same signal to a common receiver. We consider OFDM systems and vMISO protocols that rely on the use of space-time block codes (i.e., Alamouti codes [2]) to orthogonalize these two signal copies. In contrast to receiver diversity schemes such as maximal ratio combining, Alamouti STBC distributes information across two senders thus making it a transmit diversity scheme. Our implementation performs the encoding/decoding in the time domain and follows the implementation presented in [15]. Moreover, the vMISO protocol we implement is based on a decode-and-forward (DF) scheme (see [12] for example).

B. vMISO MAC

Virtual MISO requires at least two nodes to have a copy of the information to be transmitted, and since these nodes are separated, at least two phases are needed in order to first deliver the data to the cooperator and finally start a vMISO transmission. The vMISO MAC determines how and when a vMISO transmission should be happen. Thus, in order to identify the criteria required to design trigger policies that provide with most substantial gains, we implement two types of vMISO MAC protocols.

Reactive vMISO schemes invoke vMISO transmissions only via explicit feedback from the receiver. Specifically, we implement a protocol that relies on Negative Acknowledgements or NACKs and we refer to it as Nack-based vMISO or NvMISO. The NACK serves as the "spark" for the cooperative transmission at a time that the helper node has (ideally) already overheard the required transmission symbol sequence. That is, if the original transmission failed, a vMISO retransmission is provoked by the NACK. The reception of the NACK also synchronizes both the source and the helper. In our system, the time between the transmission from the source and the one from the helper is at most 200ns. Thus, for a few hundred meters of separation between the two transmitting nodes, the length of the OFDM cyclic prefix allows us to treat the two copies as multipath at the receiver. Since the NACK is transmitted at base rate, we expect it to be highly reliable. According to 802.11 standard, it can be received as lows as -85dBm (for 10MHz channels), which increases the likelihood of successfully starting a vMISO transmission if needed.

Proactive protocols trigger vMISO transmissions in a two-phase process where initially the information is delivered to the helper and then a simultaneous sender-helper transmission is triggered without requiring any feedback. The proactive protocol we implement is called *Two-Phase vMISO* (see Figure 1(b)) . With good channel conditions this is considered a naive approach since it will always require two phases even if the first transmission would have been successful, therefore unnecessarily wasting air time and helper's resources, and increasing interference.

Additionally, we define two benchmarking protocols for evaluation of vMISO; These are unrealizable and unimplementable in real systems but are valuable for simulation-based comparison. These benchmarking protocols are illustrated in Figure 1: *(a) Genie vMISO*: the vMISO cooperator acts as a genie that *a priori* possesses the information the sender is about to transmit. Therefore, a vMISO transmission occurs in one phase without requiring any feedback, i.e., the NACK is not required, and the cooperator has the sender's data in advance. *(c) Perfect NACK NvMISO*: the cooperator receives a NACK with 100% probability therefore always starting a vMISO retransmission if needed, also the cooperator always has the data it needs to transmit. This is done in order to study the extreme case where a vMISO retransmission always occurs when requested, regardless of the position of the cooperator. Using this protocol provides us with a potential "worst-case scenario" for neighboring flows (since the cooperator will always hear and transmit even when far from the vMISO flow), while providing a "best-case scenario" for the assisted flow due to the same reason, hence a vMISO transmission will always be started.

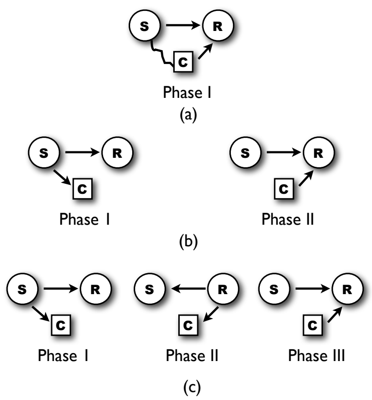

Fig. 1. Operation of vMISO protocols. Sender transmits to a receiver with the help of a vMISO cooperator node.

C. Network Platform

For all over-the-air experiments we utilize the Wireless Open-Access Research Platform (WARP). The board is a fully programmable wireless platform consisting of a Xilinx Virtex-II Pro FPGA, and four daughter card slots for up to four 2.4/5 GHz radio boards able to support wideband applications (e.g., OFDM). The current state of the platform's OFDM physical layer supports BPSK, QPSK, and 16-QAM modulations in 10 MHz. To control the boards, conduct experiments, and gather data in real-time, we use WARPnet,[1] a framework that enables communication among wireless nodes in a network setting. WARPnet provides a software interface connecting WARP and a host PC running server and client scripts, via an ethernet switch. Figure 2 presents our experimental setup.

Furthermore, we implement vMISO and all related MAC variations as an extension to ns-2 in order to consider topologies beyond 5 nodes. We use Nakagami random fading [6] which in addition to average pathloss effects due to node location, also characterizes received power as a random variable that changes its value at each transmission. In order to validate our simulator extensions and channel model used, we compare our testbed results to the simulation results in Section III.

[1]http://warp.rice.edu/trac/wiki/WARPnet

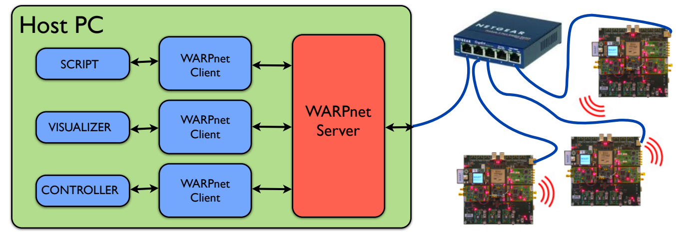

Fig. 2. WARPnet: Host PC runs both client and server scripts to communicate with the WARP boards to retrieve statistics and conduct experiments.

Carrier Frequency	2.427 GHz
Transmit Power	10dBm
Header Rate	BPSK (1/2 rate code)
† Payload Rate	64-QAM (3/4 rate code)
‡ Payload Rate	16-QAM (24Mbps)
Packet Size	1412 Bytes
Traffic Pattern	Fully Backlogged Flows, CBR
† Fading Model	Nakagami (moderate fading)
‡ OFDM Symbol	64 Subcarriers

TABLE I
SIMULATOR AND TESTBED PARAMETERS - † INDICATES PARAMETERS UNIQUE TO THE SIMULATOR WHEREAS ‡ INDICATES PARAMETERS UNIQUE TO THE TESTBED

Unless otherwise stated, we use the parameters in Table I in both the simulations and the physical testbed.

III. TRADITIONAL MAC MECHANISMS HINDER VMISO PERFORMANCE GAINS

At the physical layer, vMISO improves link reliability by reducing error rates and outage probabilities [12], [19]. However, the magnitude of these gains on the overall system can be influenced by MAC and network-scale factors. In this section we show that the policies used to trigger vMISO transmissions should be aware of MAC mechanisms such as modulation and coding rate, as well as the SNR regimes at which the system is operating in order to ensure throughput gains.

A. Transmission Rate in vMISO

Like vMISO, coding and modulation rate adaptation techniques are used to combat unreliable channel conditions caused by fading and multipath. Namely, a transmitter adjusts its coding and modulation rate according to channel fluctuations induced by either transmitter or receiver mobility, as well as scatterers. Therefore, in a real system, vMISO would operate in conjunction with a rate adaptation technique and here, we explore the coupling of a multi-rate system with vMISO transmissions.

For a three node network consisting of a sender, a receiver, and a vMISO cooperator, we vary the attenuation on the transmitted signals which in turn requires use of a different transmission rate to maximize throughput (an excessively high rate choice leads to packet loss whereas an unnecessarily low rate choice underutilizes). Observe in Figure 3(a) that even though vMISO gains are attained at a wide range of

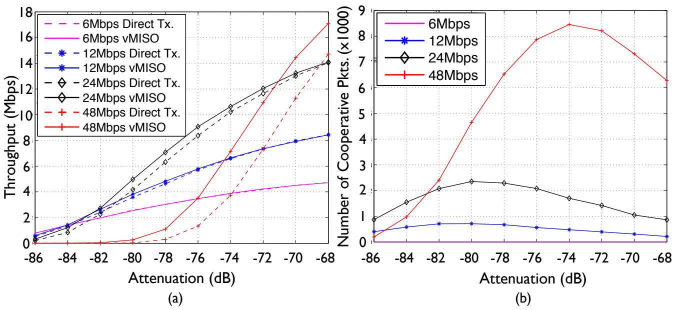

Fig. 3. (a) Throughput of NvMISO for different transmission rates. (b) Number of *cooperative* NvMISO packet transmissions for different rates.

SNR regimes, the magnitude of the gains achieved by each different rate is highly dependent on where the system operates within that range. That is, vMISO transmissions at a lower rate can only yield gains at lower SNR, whereas for higher rates, gains are observed at higher SNR. The reason for this is that higher rates will require a vMISO retransmission in order to successfully deliver a packet even at a much higher SNR compared to lower rates. Moreover, observe the absolute highest gains are achieved by higher modulation rates. Consequently, notice in Figure 3(b) that vMISO transmissions occur mostly at the higher modulation orders or rates; while, vMISO transmissions occur rarely, if at all for the lower rates. Observe that for all cases, as attenuation decreases, the number of vMISO transmissions decreases because a direct transmission suffices and no retransmissions are triggered.

These results imply that a vMISO MAC can only maximize its throughput performance at all times by jointly considering transmission rate and the vMISO trigger criteria. This should be done to avoid wasting any resources trying to find the best cooperator, or even triggering a vMISO transmission unnecessarily. Namely, vMISO must opportunistically *increase* the transmission rate in order to be able to trigger cooperation and increase throughput. Although the shown results are for reactive vMISO, notice that a proactive vMISO scheme would be a better option in the case of low SNR, however it would have a negative impact for higher SNR (as we will observe in the next section).

B. MAC Overhead at High Rate

Next, since we observed that the highest vMISO gains occur when the transmission rate is highest (i.e., 64-QAM at 48 Mbps for this case), we focus on this rate and investigate how the MAC protocol overhead can affect these maximum gains.

We consider the same three node network where the vMISO cooperator is chosen among a pool of uniformly distributed nodes located near the sender-receiver pair. To choose the cooperator we run an exhaustive search for the best performer (i.e., the node with which the highest avg. throughput over the entire run was obtained). For comparison we consider the case where the vMISO cooperator is a store and forward node such that in the first phase, the sender transmits to the cooperator, and in the second phase, only the cooperator transmits data to the receiver. We refer to this case as "Forced Two Hop."

Figure 4(a) depicts the average results and 95% confidence intervals of throughput performance for different protocols as a function of the link distance between a sender and receiver. Observe that at all times, both the genie-based vMISO and NvMISO schemes outperform direct transmission, except when the probability of error due to channel conditions is close to zero (which occurs at distance zero in this scenario) where all these protocols perform the same. More importantly, notice that the genie-based vMISO sets an upper bound in throughput performance for any type of vMISO scheme due its idealized one-phase operation.

Theoretical physical-layer SNR gains and corresponding error rate reductions consider a continuum of available rates. However, because a real system can only support a discrete and limited number of rates, such gains cannot always be realizable at the MAC layer.

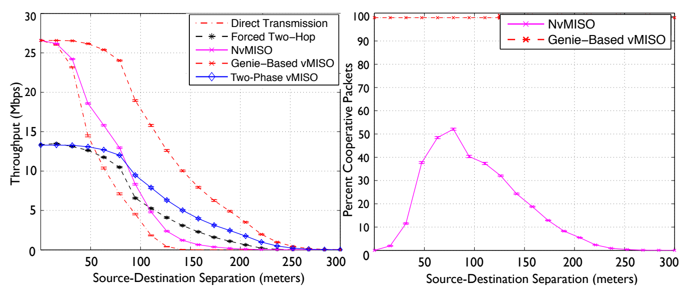

Fig. 4. (a) Comparison of vMISO schemes with direct transmission and multi-hopping, and (b) Percentage of vMISO transmissions out of the total number of MAC transmissions.

For each packet, the transmission time consists of the time it takes to send the actual data packet plus channel access, data preamble and acknowledgement overheads. For example, transmitting at 48 Mbps physical layer rate even when channel conditions are "best" (no pathloss effects) only yields up to 26.6 Mbps MAC-layer throughput due to this overhead. Therefore, assuming the overhead is kept constant, the only way to increase the performance of this particular system would be by increasing the data rates. Doing this would allow vMISO to provide throughput gains not only when the distance between the sender and receiver is very small, but also considerably higher gains at longer distances. The implications of this limit imposed by the MAC are reflected on wasted resources at the helper as well as unnecessary increased interference. Both Figure 4(a) and (b) demonstrate that for short distances in a moderate fading environment, any help provided by the vMISO cooperator is not required and should preferably be avoided to reduce overhead and potential interference. Regardless of the number of vMISO transmissions, the gains for the ideal genie-based scheme and NvMISO are negligible. However, for moderate to large distances, a smart decision whether the helper should be used or not has to be made.

Observe in Figure 4(a) that except for small distances (below 20 meters), vMISO schemes are always the best option. Nevertheless, to outperform all other techniques at any regime, the vMISO MAC must switch between being reactive (NvMISO) or proactive (two-phase vMISO). For moderate distances (between 20 and 80 meters), a NvMISO can still benefit from successful one-phase transmissions if the channel is good, and use three-phase transmissions only if required. However, when initial transmissions from the sender begin to fail (when highest percentage of vMISO transmissions are triggered as shown in Figure 4(b)), the proactive two-phase vMISO becomes the better option because it requires fewer phases to achieve the same diversity and reliability. In contrast to two-hop transmissions, vMISO schemes rely on both an increase in diversity, as well as increased power due to a simultaneous transmission from two nodes. Alternately, vMISO nodes could transmit with $1/N$ of the power required in a SISO transmission [9], thus keeping only the gains achieved from diversity. In Figure 4(b) after reaching the highest point, the number of vMISO transmissions decreases due to increased distance between destination and helper, therefore reducing the likelihood of successfully NACK reception.

Findings: vMISO gains and trigger conditions must incorporate the protocol (reactive or proactive), transmission rate and SNR. Namely, vMISO gains are best achieved when the transmission rate is high for a given SNR such that only with vMISO, transmissions at that higher rate are successful. Additionally, while in theory vMISO gains are available even at very high SNR (only bounded by capacity), in practice the maximum transmission rate is limited, and therefore once this rate is achieved no further gains are possible. Thus, regardless of the magnitude of the gains at the PHY, the MAC represents a performance-limiting factor. Nevertheless, regardless of the sender-receiver link distance, the adequate choice between a proactive or reactive vMISO guarantees better performance compared to other transmission schemes such as multi-hopping.

IV. vMISO Transforms the Network Graph and Contention Behavior

Transmissions of vMISO cooperators in multi-flow topologies introduce additional interference that can cause other flows to defer potentially leading to net performance losses. However, depending on the topology, such interference could instead be *beneficial* since it can add coordination by implicitly informing other senders via carrier sense that a transmission is occurring (e.g., the case of hidden terminals that can mutually sense the active cooperator). In this section we explore four different scenarios via experiments and simulations to study the effects of the vMISO triggers on the network topology.

A. Topology Generation and Validation

In order to isolate effects of vMISO inter-flow interaction, we consider the four basic topologies shown in Figure 5. These topologies have been widely studied due to their significant impact on real network deployments [7], and for this reason we explore their behavior in the presence of cooperator nodes.

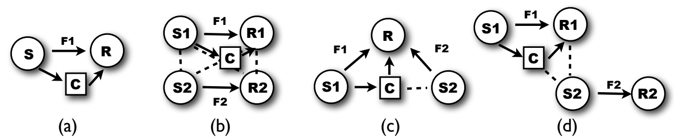

Fig. 5. Small-scale topologies. Circles: senders and receivers. Squares: vMISO cooperators. Arrows indicate traffic flows, and dotted lines indicate connectivity. Topologies: (a) Single Flow, (b) Fully Connected, (c) Hidden Terminal, and (d) Information Asymmetry.

To create the required topologies, we performed our experiments in a static environment where no moving scatterers were present. Before each 60-second experiment, we used two transceivers to test bidirectional connectivity between them. We established that two nodes could not sense each other when neither would defer to one another. In each case, positions between senders and receivers were chosen such that the link would guarantee $>90\%$ packet reception at BPSK. Thus, in this section we focus on the SNR regimes where vMISO yields the most substantial gains i.e., medium to high SNR, and show results only for reactive protocols which are expected to perform best in these situations. Nonetheless, we also provide insights on the performance of proactive schemes for these scenarios. We conducted all experiments at night and ensured that no other transmitters were active for the entire duration of each experiment by using a spectrum analyzer.

Figure 6(a) depicts the over-the-air deployment used for both the single flow (nodes A, B and E are sender, receiver and cooperator, respectively) and the 5 node, 2-flow fully connected network (nodes C and D form the competing flow). Likewise, Figure 6(b) depicts the deployment used for the hidden terminal (nodes F and H are the senders, G is the receiver, and J is the cooperator) and for the information asymmetry scenarios (node H represents the sender and node I the receiver of the competing flow). For validation, in this section both experiments and simulations are performed at 16-QAM. Unless otherwise stated, throughout this section we present average throughput results with 95% confidence intervals.

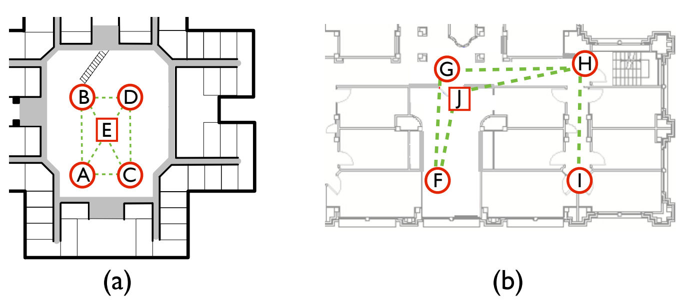

Fig. 6. Layout of our indoor testbed. (a) Used for single flow and fully connected topologies, (b) Used for hidden and information asymmetry scenarios

As a baseline, we first evaluate the performance of vMISO with 3 nodes and a single flow (Figure 5(a)). vMISO is expected to perform equally or better than direct transmission because the cooperator only transmits when needed and cannot interfere with any other flows. The results are depicted in Figure 7(a) and show vMISO gains as high as 110% with the largest gains occurring when the cooperator is approximately halfway between the sender and the receiver (see also Section 3). More apropos, these results validate the vMISO simulator which we use extensively in our evaluation.

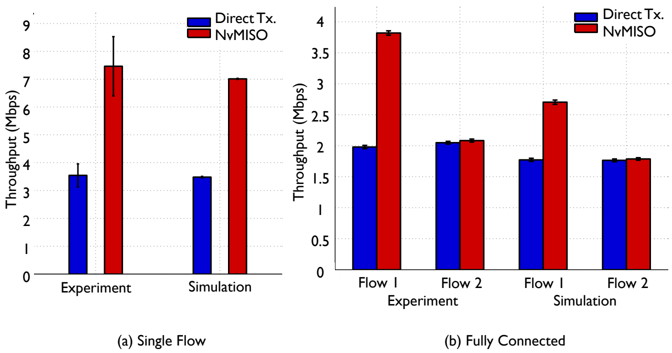

Fig. 7. vMISO in Fully Connected Topologies

B. Fully Connected Topology

With a second (competing) flow, the vMISO flow's increased transmission footprint due to the presence of the cooperator leads to additional interference. Here, we evaluate vMISO for a two flow network where all nodes can carrier sense each other (see Figure 5(b)), and the cooperator assists only one flow at all times (i.e., flow 1).

Observe in Figure 7(b) that as expected, the throughput achieved by flow 1 is much higher when vMISO transmissions are enabled. However, more importantly, there is no negative effect on the performance of the competing flow. Since both sources mutually carrier sense, the competing flow is already deferring to the cooperative one. This means that the vMISO cooperator transmits only when the competing flow is deferring. Furthermore, since the vMISO flow becomes more efficient with fewer dropped packets, the increased amount of air time leads to a slight increase in the performance of the other flow.

C. Hidden Terminals

Hidden terminals cannot coordinate via carrier sensing, thus leading to a high number of collisions compared to fully connected networks. Here, we explore wether vMISO's cooperator could potentially reduce collisions if its location would allow the different sources to sense it. For example, in Figure 5(c) if the source of flow 2 is able to sense the cooperator in a vMISO transmission, then it would defer to it, therefore decreasing the number of collisions.

Figure 8(a) presents the throughput achieved by both flows with and without vMISO transmissions (RTS/CTS is disabled - a common practice in current deployments). Observe that just by enabling vMISO links in flow 1, its throughput increases by approximately 64% in average. More importantly, vMISO not only increases link reliability but can further coordinate sender nodes that are not able to sense each other. If the cooperator can be sensed by the different senders, a vMISO transmission will cause other nodes to defer. The transmission of a NACK from the common receiver (due to either a collision or channel fade), triggers a vMISO retransmission which in this case is more likely to be overheard by the competing sender. Such coordination and collision reduction also allows the competing flow to experience a slight performance increase. Thus, vMISO cooperators can provide the network with more information regarding the overall state of different transmitters. For instance, our simulations showed a decrease in the average number of collisions of approximately 15%. Such improvement corresponds to the increase in throughput at flow 2. For this particular case, notice that triggering a NACK even due to a collision, at worst will lead to one node backing off and one sending an immediate retransmission. This does not represent a major issue in such as small topology, however, it could have a significant effect on congestion experienced in bigger networks.

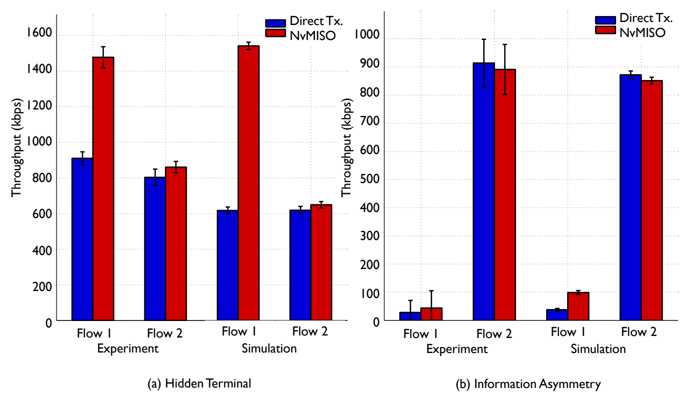

Fig. 8. Cooperation in Hidden Terminal (a), and Information Asymmetry (b) Topologies

D. Information Asymmetry

In a scenario with two active flows, in which only one of them interferes with the other, the disadvantaged flow could eventually reach starvation. We denote such scenario as *information asymmetry* (see Figure 5(d)).

The starvation problem can be diminished by the presence of a cooperator which is within range of both senders. If this is the case, a vMISO transmission would cause the sender of the dominating flow to defer, hence decreasing the number of collisions at the receiver of the disadvantaged flow. Every single failed packet in flow 1 triggers a vMISO transmission that can potentially cause the competing sender to defer.

Observe in Figure 8(b) that as expected, the difference in throughput between the advantaged and the disadvantaged flows is significant. Even though gains from vMISO for flow 1 are high (approximately 55%), its performance is still unsatisfactory compared to that of flow 2. That is, using Jain fairness index we observe only a very small increase from 0.51 to 0.56. In our case, since vMISO transmissions are triggered only through feedback from the receiver, if collisions are not resolved for the entire length of both packets, no vMISO retransmission will occur. Likewise, if the cooperator is not sensed by the competing sender, it will not defer. Such behaviors limits the extent to which the presence of the cooperator can positively affect the disadvantaged flow. Nevertheless, if the collision is resolved and a NACK is triggered, it will make the disadvantaged flow more aggressive. Thus, vMISO can still help alleviate the starvation problem by adding coordination, but MAC behavior dominates flow performance.

E. Discussion on Helper Footprint and Spatial Reuse

To better understand the interference effect caused by the position of the cooperator with respect to different flows in a network, we investigate each flow's performance for the two scenarios depicted in Figure 9, compared to the fully connected case. In the fully connected scenario, the position of the cooperator influences the magnitude of the gains that can be obtained through NvMISO without significantly affecting the performance of the other flow. However, if both flows are decoupled, the position of the cooperator could potentially cause the competing flow to defer (as seen in Figure 9(a)), thus becoming an important influencing factor on the performance of such flow.

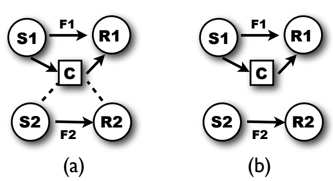

Fig. 9. Topologies where the helper assists only one flow. In (a), F2 can only sense the helper and vice versa; in (b), both flows are decoupled.

To explore these potential effects that originate from the position of the cooperator with respect to other flows, we create two 5-node two-flow topologies where the first consists of *coupled flows* (fully connected), and the second one consists of *uncoupled flows* (independent flows), and evaluate the *Perfect NACK NvMISO* scheme. For every scenario we vary the position of the cooperator inside a square grid while we keep both senders and receivers fixed in their respective positions. We allow one cooperator to assist only one of the flows (flow 1) in order to analyze its influence on the competing flow (flow 2).

Figure 10 depicts the results with the x-y axis representing the grid position of the cooperator. As a reference, locations of the senders are represented by black circles and receivers by white. The dependent variable throughput gain or loss is represented by a colormap as illustrated on beside the figure.

For nearby flows in which spatial re-use was not possible independent of having a cooperator, the top two Figures 10(a) and 10(b) indicate that if a vMISO protocol is able to cooperate every time it is needed, gains can be in the order of 200%. Equally important, as was the case with the results reported in Figure 7(b), Figure 10(b) shows that cooperating with one flow has minimal effect on the performance of the competing one. Hence, in a fully connected network, the cooperator (regardless of its position) is not consuming any extra channel resources than those that flow 1 would consume if its path to the destination was relatively good and no cooperator was present. The best-case helper location significantly improves the performance of the vMISO flow whereas the worst-case location does not have any considerable effect on the competing flow.

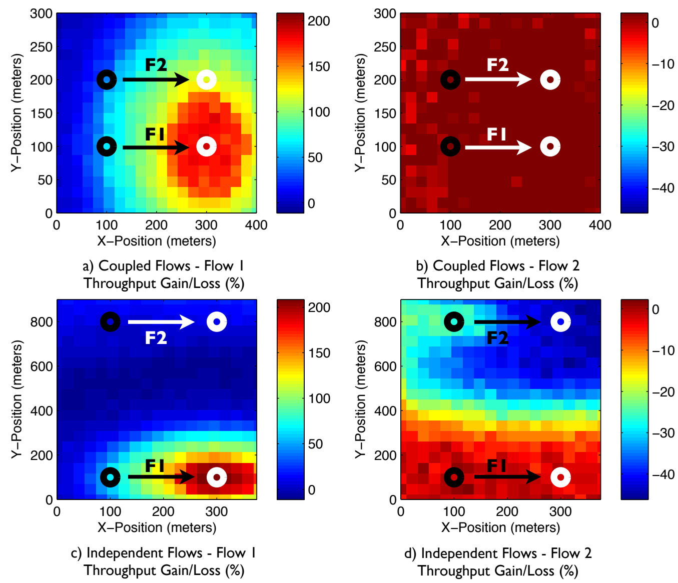

Fig. 10. Influence of helper's transmission footprint in coupled and uncoupled flows as a function of its position.

Next, we consider the case where farther away flows can employ spatial re-use without vMISO. Figure 10(c) shows that for flow 1, the vMISO flow, gains can again reach up to 200%. However, Figure 10(d) indicates that if the cooperator is farther away from the assisted flow, it increasingly adversely impacts the competing flow. These results show that such degradation reaches approximately 40% throughput losses. Moreover for some vMISO cooperator positions, while the gains that can be achieved by the vMISO flow are practically null, attempts to cooperate can lead to significant adverse effects on the performance of the surrounding flow.

In a proactive scheme, the negative effects on the competing flow (for both topologies in Figure 9) are more significant since it would be required to defer for two consecutive phases for every single original transmission instead of only when a retransmission is needed.

Findings: For two contending flows, the addition of a vMISO cooperator alters the node interconnectivity and thus MAC-layer coordination. Namely, the cooperator can cause a nearby sender that should defer but cannot sense the other transmitter to sense the cooperator and correctly defer. This yields new MAC-layer coordination that can lead to decreased collisions when senders are hidden or increased fairness when the vMISO flow would have otherwise been topologically disadvantaged. Therefore, both hidden terminals and asymmetrically disadvantaged flows should proactively invoke vMISO if a suitably located cooperator is available in order to increase the flow's aggressiveness. Thus, compared to reactive schemes, a proactive protocol can have a more significant impact on competing flows due to a more constant vMISO triggering.

V. Network-Scale Evaluation

In networks consisting of multiple flows, vMISO links lead to complex flow interactions that amplify and combine several of the issues we observed in isolation in smaller topologies. For instance, transmissions by numerous cooperators lead to a more significant increase in interference compared to small-scale networks. This in turn leads to increased contention, which could potentially translate into performance losses. Nevertheless, the added coordination due to vMISO transmissions could also be augmented and have a stronger beneficial impact on the network performance. Additionally, if vMISO is implemented in a structured operational network as in the case of a mesh network, the non-ideal position of the cooperator could also have a meaningful influence on the gains that can be achieved with vMISO in such scenarios. Therefore, we dedicate this section to explore the aggregate effects that arise from the activity of the cooperator on the overall performance of the system in a large-scale network.

A. vMISO Cooperator Interference in Large-Scale Networks

To study the increase in interference due to vMISO in large-scale networks, we emulate static ad hoc single-hop topologies comprised of different number of flows (i.e., from 2 to 20 flows). For each case, we report averages over 30 different topologies where flows have been randomly positioned based on a uniform distribution. Distances between sender and receiver at each flow are chosen such that NvMISO would yield a gain if the flow was completely isolated (according to the results from Figure 4(a)). Moreover, whenever vMISO is enabled we select the cooperator that is closest to the midpoint between source and destination (i.e., the one we expect to provide with the highest gains). Such topologies provide network configurations spanning from isolated flows to fully connected scenarios. Due to the prohibitive cost and complexity of building a fully-scaled cooperative network, we employ our validated simulator model to evaluate vMISO techniques. We present results for reactive protocols since these cause the least amount of interference compared to proactive schemes, thus providing with higher gains and demonstrating vMISO's potential.

We compute the time in between a successful packet transmissions and the next transmission for each individual flow. Since sources are fully backlogged, the rate at which packets leave each source node will depend on MAC and PHY behavior. Contention and interference affect this rate via carrier sense. Therefore we use the inter-packet transmission time to analyze the amount of contention present in the network: the longer the time, the higher the contention. Moreover, we compare against *perfect NACK NvMISO* defined in Section II to explore the "worst-case scenario" in terms of interference where vMISO transmissions are always triggered if a NACK is sent.

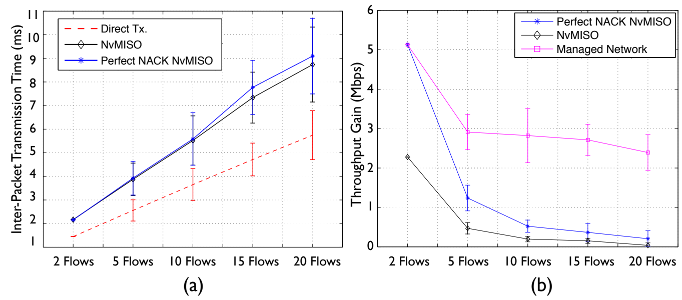

Fig. 11. (a) Mean packet inter-transmission time for different network sizes. (b) Per-flow throughput gains/losses for different network sizes

Figure 11(a) depicts the mean packet inter-transmission time per-flow. Error bars show the range of results for the different flows in the network. Observe that for all cases, the mean inter-transmission time is much lower when vMISO is disabled. Moreover, the gaps between the direct transmission scheme and both NvMISO and *perfect NACK NvMISO* widen with an increased number of flows (same behavior observed in percent difference between the vMISO protocols and the direct transmission scheme). Since each flow uses one cooperator, this indicates that the larger the number of cooperators used in the network, the bigger the spatial footprint of each flow. This increase causes most flows to experience higher contention, meaning that fewer packet transmissions occur.

In Figure 11(b) we present per-flow throughput gains for networks with different number of flows. Observe that in average, for 2 flows, NvMISO achieves up to 2.2 Mbps gains, which corresponds to roughly 47% gains compared to direct transmission. On the other hand, *perfect NACK NvMISO* reaches gains of more than 5 Mbps or 104% throughput gains. However, as the number of flows increases to 20, the additional interference due to the cooperators leads to a significant decrease in gains of approximately 98% and 96% for NvMISO and *perfect NACK NvMISO*, respectively. To overcome such degradation, we modify the latter protocol by reducing the extra interference generated throughout the entire network. That is, after observing all vMISO flows for some period of time (10 seconds in our case) we only allow those that achieve more than 10% gains to enable vMISO transmissions. This approach would require a centralized network manager (or distributed coordination) as well as a thorough study of the optimal threshold to use to decide which flows can enable vMISO. Nevertheless, we demonstrate in Figure 11(b) that this simple management policy significantly improves overall performance.

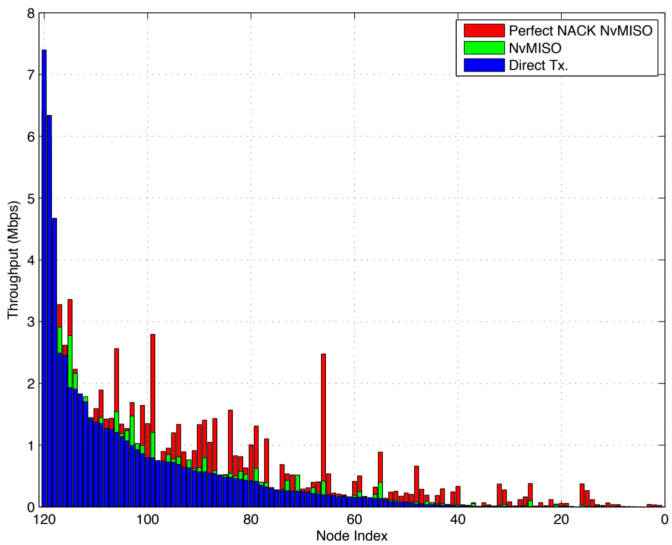

Fig. 12. Network consisting of 120 flows.

Finally, we investigate how vMISO affects the individual performance of each flow in a large-scale ad hoc network. To do this, we simulate a network of 120 potential vMISO flows and evaluate the same three schemes. Figure 12 depicts the per-flow average throughput and shows that both vMISO protocols yield throughput gains compared to direct transmission for all flows except for the first three highest throughput flows (where both vMISO schemes reach only up to 4Mbps). In particular, these three flows have an overwhelming advantage over all other flows. With vMISO, the throughput of these advantaged flows drops significantly (i.e., between 10 and 20% drop), while the throughput of the rest increases. Jain's fairness index grows from 0.186 using direct transmissions to 0.253 with NvMISO and 0.387 with *perfect NACK NvMISO*. Thus, vMISO improves fairness by providing additional throughput to underserved flows at the expense of the highest-rate "privileged" flows.

B. vMISO in Multi-Hop Mesh Networks

Unlike ad hoc networks, deploying planned mesh networks (as opposed to "organic" community mesh networks) involves a structured planning process in order to target a certain level of performance. This means that access points (APs) and gateways are positioned in a way such that they are able to communicate with each other while maintaining relatively strong connectivity. Therefore, we evaluate the potential gains of vMISO in an environment featuring links that are engineered to operate at a "satisfactory" average channel condition, but are nonetheless subject to fading and all of the topological effects explored previously.

We emulate the TFA mesh network[2] deployed in Houston TX by matching all available AP and backhaul measurement data to simulation parameters in ns-2. We generate up to 25 clients with uniformly random locations that are within 250 meters from at least one AP. As in the previous section, for this scenario we choose the cooperator that is expected to yield highest gains. We assume these cooperators are other users in the network that are not actively transmitting or receiving any data of their own. The network is comprised of 15 APs that form the backhaul, and one fiber-connected gateway acting as a sink. A total of 25 nodes are mobile stations generating CBR traffic, which is forwarded via static routing.

Based on over-the-air measurements on the network, we create a simulation model that takes into account the gains at each antenna depending on their angle with respect to other AP nodes. All APs consist of a single omnidirectional interface operating at 2.4 GHz, with the exception of the gateway and one AP which feature multiple interfaces (i.e., 2.4 GHz for the omnidirectional link and 5 GHz for a directional link connecting both). Each client transmits at 15 dBm which is the typical transmission power of notebook computers with WiFi cards. However, all APs transmit at a power of 23 dBm as specified in [3]. We modify the carrier sense and receive thresholds of the simulator to emulate those employed by the radio cards at each one of these nodes. We utilize a moderate fading Nakagami propagation model since the actual network is located in a residential urban area, and we are only considering stationary clients.

We analyze the performance of NvMISO by exploring the number of vMISO packet transmissions at both the clients as well as the backhaul in order to visualize to what extent the cooperator assists these nodes. This is a measure of how necessary the cooperator is for a given source-destination pair. Results present averages over 10 simulations, each running for 700 seconds.

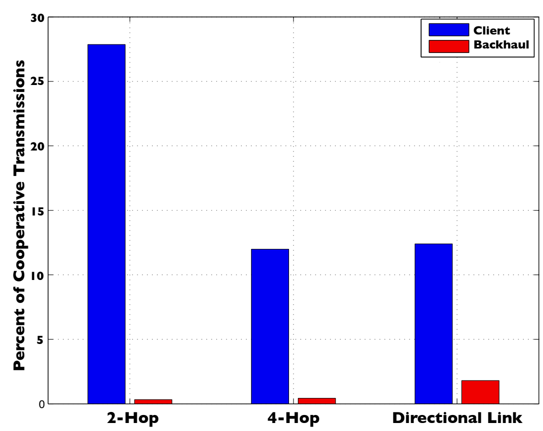

Fig. 13. Percent of cooperative transmission for different flows in mesh network.

Figure 13 depicts the percent of vMISO transmissions triggered due to adverse channel conditions for both clients

[2]http://www.tfa.rice.edu/

Avg. Per-Flow Throughput Gain	14.26%
Throughput Gain (min,max)	[-9.80%,69.44%]
75^{th} Percentile	[-2.5%,11.0%]
25^{th} Percentile	[11.0%,21.5%]

TABLE II
OVERALL PERFORMANCE RESULTS OF THE MESH NETWORK

and backhaul nodes. That is, the amount of cooperative transmissions out of the total number of transmissions. From all the different flows in the network, we present results for a subset of them (in this case the 2-hop and 4-hop flows) where all nodes use omnidirectional antennas. Additionally, we analyze a 2-hop route that utilizes a directional link. For clients, vMISO is triggered in at least 10% of the total transmissions. At the backhaul, the maximum percent of triggered vMISO packets occurs at the directional link. However this number is rather low, only reaching 2%. This happens mainly due to the following two reasons: First, APs transmit at a much higher power than clients. This means that at the backhaul, packets are more likely to arrive with a much higher SNR to either the gateway or a routing AP. Hence, instead of a packet being lost due to channel quality, most are lost due to congestion and interference, which translates into having very few vMISO retransmissions. On the other hand, clients, which are already transmitting at lower power, can also be affected by their distance to the closest AP they can associate with. Second, antenna gains between APs are also higher than those at the clients.

Table II presents per-flow average throughput gains achieved. Observe that vMISO provides an average throughput gain of 14% to the network. While one flow experienced throughput losses of nearly 10%, another flow achieved nearly a 70% gain. More importantly, notice the 75 percentile is located mostly between 0-10%. We conclude that even though some flows experienced small losses, most of them improved their performance. Clearly, vMISO is not able to achieve the same high gains in large-scale networks as it does with smaller-scale topologies. Nevertheless, it improves the overall system by helping more flows than it hurts, and providing substantial gains to some disadvantaged flows.

Findings: Although in large scale networks the potential for each flow to find an ideally positioned cooperator is greatly increased, when the number of active flows is large, network-wide vMISO gains are greatly reduced compared to small scale networks due to substantially increased interference and contention caused by the cooperators. Therefore, while flows in small scale networks can independently choose whether to trigger vMISO, large scale networks will benefit from a coordinated decision (e.g., via a network manager) that determines which flows will invoke vMISO transmissions (e.g., those with maximum gains for themselves and minimum interference for others).

VI. Related Work

Prior work can be broadly categorized into two main areas. First, most prior work on virtual antenna arrays and cooperative-diversity is information theoretic and focuses on performance at the physical layer. The concept of user cooperation is introduced in [19], [20] and was targeted to cellular networks where distributed nodes establish virtual MISO links to increase capacity and robustness against channel variations. This work employs information-theoretic concepts to analyze capacity and outage probability. An analytical study of different cooperative-diversity protocols, e.g., amplify-and-forward (AF) and decode-and-forward (DF), is presented in [12]. Likewise, studies such as [17] focus on outage probabilities corresponding to different cooperation schemes as well as their fundamental capacity limits. In contrast, we address MAC-layer and network-scale issues that arise from implementation of vMISO. Furthermore, our approach to evaluate vMISO (or cooperative-diversity) protocols is purely experimental rather than theoretical.

Second, there have been recent efforts to develop MAC protocols exploiting spatial diversity and virtual MISO transmissions. MAC protocol designs have been presented and evaluated in [1], [8]–[11], [13], [14], [21] for example. In contrast, our work does not focus on protocol design, but instead comprises a study of generalized vMISO MAC mechanisms with the purpose of identifying the triggering criteria that provides with largest gains while minimizing interference. This is crucial for understanding how and for which scenarios a vMISO protocol should be designed and used. Likewise, hardware implementations have been developed for both asynchronous [4], [5], [10] and synchronous systems [15]. Although asynchronous cooperation circumvents the challenge of strict timing coordination, vMISOs synchronous cooperation at symbol time scales has been shown to yield larger benefits [15]. Unlike asynchronous implementations, vMISO transmissions in our work occur simultaneously by means of STBCs so that symbol level synchronization is a key factor in our implementation. In contrast to all previous implementations, our work focuses on diverse network topologies and evaluates performance of vMISO protocols in multi-flow networks.

VII. Conclusion

In this work, we evaluate the performance of vMISO schemes in critical networking scenarios that span from fully connected topologies, to cases leading to information asymmetry in both isolated and network-wide designs. We evaluate reactive and proactive vMISO protocols to identify the regimes in which vMISO transmissions should be triggered based on network and channel conditions. We perform a study of network factors affecting the gains that can be achieved through vMISO under different small-scale networking scenarios consisting of at most two flows. Further, we extend our evaluation to multi-flow, multi-hopping network configurations consisting of more complex interactions among nodes. We present results from both an experimental setup as well as simulations where we implement different vMISO protocols and demonstrate that the high gains from vMISO achieved in small topologies decrease in large-scale network scenarios.

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