Virtual MISO: Experimental Evaluation of MAC to Network-Scale Factors

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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 been shown to vastly improve wireless link reliability and bit error rates by exploiting spatial diversity. Nevertheless, vMISO's performance in operational networking environments has not been studied. Namely, link gains obtained at the physical layer can be hindered by MAC and network-scale effects thus potentially diminishing the overall system performance gains. Moreover, while a vMISO cooperator can significantly improve the intended vMISO link, it may also influence neighboring flows, sometimes hindering other flows due to an increased spatial footprint of vMISO, and other times helping other flows due to altering inter-flow connectivity and improving coordination. In this paper, we build the first multi-flow vMISO testbed and explore the limits and capabilities of vMISO from a networking and MAC perspective. We identify and evaluate key factors affecting the performance of vMISO techniques in small- and large-scale topologies. Our evaluation reveals that *(i)* 802.11 MAC mechanisms represent a major bottleneck to the gains that can be attained by vMISO, *(ii)* negative effects such as interference due to activity of a cooperator node are overcome by the throughput gains achieved by vMISO, and *(iii)* gains achieved in small, isolated topologies decrease significantly when implemented at network scale for mesh networks (from 110% to 14% respectively). Furthermore, our study provides a deeper understanding of the regimes in which vMISO systems perform poorly, and can help in the design of effective protocol solutions for such cases.**

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 [6], [10], [11], [12], [13]. 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, the originating sender, and the helper.

In this work we present an experimental evaluation of a STBC vMISO system and build the first multi-flow virtual MISO testbed. Namely, we present a comprehensive experimental evaluation of vMISO medium access control (MAC) protocols under different network topologies. To this end, 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, we implement a NACK-based protocol (termed Nack-based vMISO or NvMISO) which we choose as a representative example of a broader family of On-Demand schemes, e.g., [5]. NACK-based protocols trigger vMISO transmission only via explicit feedback from the receiver when the original transmission failed and a vMISO retransmission is required. The NACK serves as the "trigger" for the cooperative transmission at a time that the helper node has (ideally) already overheard the required transmission symbol sequence. Moreover, we define a suite of benchmarking protocols that characterize *idealized* vMISO protocols 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 the NACK is not needed as a vMISO trigger. Second, we use 3-node single-flow scenarios to explore vMISO when coupled with MAC-layer mechanisms such as bit rate adaptation and evaluate the performance in single flow topologies (i.e., sender, vMISO cooperator, and receiver) as a function of signal attenuation, helper node position, and transmission power. Third, we extend our evaluation to 5-node two-flow scenarios where we explore effects that the additional transmitter (the vMISO helper) has on network contention, inter-flow coordination, and topology. Finally, we consider large-scale topologies comprised of multi-hop flows, ad hoc networks, and mesh networks, and assess the performance of NvMISO in these configurations.

Our key experimental findings are three fold: First, in our evaluation of MAC mechanisms we show that the protocol handshakes required to instantiate vMISO diminish gains attained by the vMISO physical layer. Moreover, the discrete and limited number of possible transmission rates supported by the 802.11 MAC can limit these gains. Furthermore, 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 SISO, i.e., rates higher than a SISO channel would allow.

Second, we consider effects of the fundamental alteration of topology due to vMISO cooperation. 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.

Third, we consider large-scale networks and find that transmissions from vMISO cooperators lead to significant increases in deferrals. Fortunately, the improved link robustness from virtual MISO significantly increases successful packet transmissions thereby overwhelming the penalty caused by longer deferral times. That is, for networks consisting of many flows, the additional interference (i.e., spatial footprint) due to the helpers transmissions is not significant enough to reduce aggregate throughput. In contrast, in the case of large scale mesh topologies with multi-hop flows, we observe that gains from virtual MISO are significantly lower than those observed in small-scale, isolated scenarios. For example, when deployed in a planned, well structured network such as a mesh network backhaul, vMISO gains are negligible simply because links are already reliable enough that they do not need any further assistance from a helper node. Therefore, 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 and experimental methodology. In Section III we explore the interactions that arise from the coupling of traditional MAC mechanisms and virtual MISO. Section IV covers small-scale 6 node (two-flow) 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. Section VI discusses prior work in more detail, and finally in Section VII we present our concluding remarks.

II. Virtual MISO Network

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

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 [8]. 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 vMISO protocols that rely on the use of space-time block codes (i.e., Alamouti codes [1]) to orthogonalize these two signal copies. Moreover, the vMISO protocol we implement is based on a decode-and-forward (DF) scheme (see [8] for example), and can be classified as a feedback-based (where the protocol uses explicit feedback to trigger a simultaneous sender-helper transmission to the receiver), reactive (On-Demand) protocol.

B. vMISO MAC

To study MAC and network-scale behavior of vMISO, we implement a scheme that is representative of a broad group of protocols that employ Negative ACKnowledgements (or NACKs) as a feedback mechanism to trigger a simultaneous retransmission. We denote this protocol as Nack-based virtual MISO or NvMISO. NvMISO closely resembles Distributed On-Demand Cooperation (DOC) [5] which also belongs to the same group of protocols. NvMISO protocols are reactive and use NACKs to trigger cooperation whenever the receiver determines that the failed reception is due to a channel fade and not due to a collision.[1] During the failed original transmission, the helper node overhears the senders original transmission and after the NACK trigger, both the original sender and the helper simultaneously transmit. We choose NvMISO as a protocol family as it employs cooperation only when needed (when the original transmission failed) and triggers cooperation with low overhead (a NACK). Otherwise, NvMISO retains 802.11-like protocol primitives.

We define a suite of benchmarking protocols for evaluation of vMISO, two of which 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 trigger is not required and the cooperator has the sender's data in advance. *(b) Two-Phase vMISO*: the sender transmits in the first phase such that the helper can overhear the data and a redundant cooperative transmission between both the sender and the vMISO cooperator always occurs in a second phase so that the NACK trigger is not required. This is naive approach since it will always require two phases even if the first transmission was successful, therefore unnecessarily wasting air time and helper's resources, and increasing interference. *(c) Perfect NACK NvMISO*: the cooperator receives a NACK with 100% probability therefore always triggering a vMISO retransmission, also the cooperator always has the data it needs to transmit error free by the second phase. 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"

[1] In our implementation (NvMISO), NACKs are sent regardless of whether a collision or a channel fade occurred

for the assisted flow due to the same reason, hence vMISO will always be triggered.

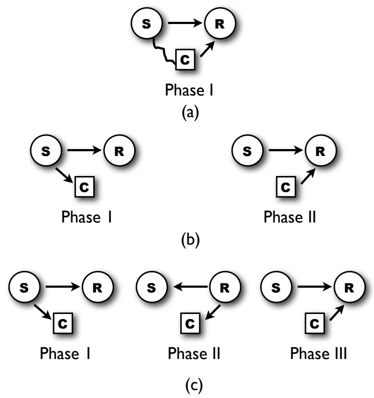

Fig. 1. vMISO benchmarking protocols. Sender transmits to a receiver with the help of a vMISO cooperator node.

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

TABLE I
SIMULATION PARAMETERS

Carrier Frequency	2.427 GHz
Transmit Power	10dBm
OFDM Symbol	64 Subcarriers
Header Rate	BPSK (6 Mbps)
Payload Rate	16-QAM (24Mbps)
Packet Size	1412 Bytes
Traffic Pattern	Fully Backlogged Flows, CBR

TABLE II
WARP PARAMETERS - MAC AND PHY

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,[2] a framework that enables communication among wireless nodes in a network setting. WARPnet provides a software interface connecting the WARP boards and a host PC running server and client scripts, via an ethernet switch. Figure 2 presents our experimental setup.

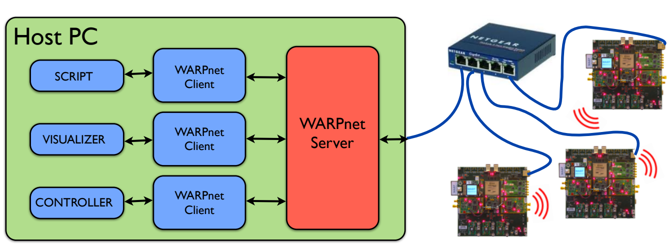

Fig. 2. WARPnet: Host PC runs both client and server scripts to communicate with the WARP boards to retrieve statistics and conduct experiments.

Furthermore, we implement vMISO and all related MAC variations as an extension to ns-2 in order to consider topologies beyond 5 nodes. Refer to Tables I and II for a list of parameters used in both simulations and the physical testbed.

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

III. MAC MECHANISMS AS LIMITING FACTORS IN PERFORMANCE OF VIRTUAL MISO

At the physical layer, vMISO improves link reliability by reducing error rates and outage probabilities [8], [12]. 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 link robustness techniques employed by 802.11 such as rate adaptation, represent a bottleneck for the potential gains that can be achieved through virtual MISO. We use simulations in order to compare with the benchmark protocols and to replay the exact same channel conditions under multiple protocols. We use Nakagami random block fading [4] 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.

A. Multi-Rate 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 impact of employing a rate adaptation mechanism on the achievable gains of vMISO.

For a three node network consisting of a sender, a receiver, and a vMISO cooperator, we vary transmit power to vary channel conditions which in turn requires use of a different transmission rate to maximize throughput (an excessively high rate choice leads to packet loss whereas an unnessecarily low rate choice underutilizes). We analyze throughput performance of NvMISO as a function of transmit power for different transmission rates.

Figure 3 demonstrates that gains from cooperation are highly dependent on the coding and transmission rate used.

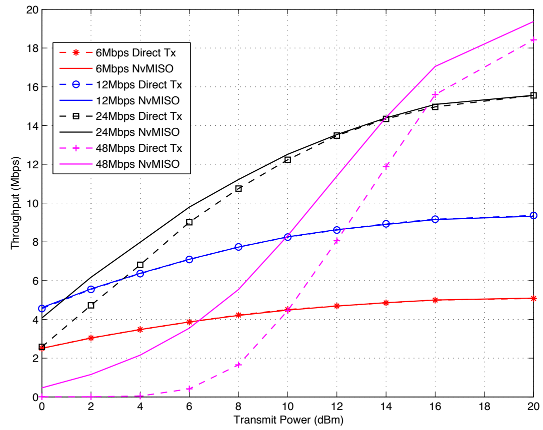

Fig. 3. Throughput of NvMISO for different transmission rates.

As the rate increases, the difference in throughput between NvMISO and direct transmission increases as well. Thus, in this scenario, vMISO does not provide any gains for lower rates such as the ones achieved by BPSK and QPSK. The reason is that since packets are more likely to successfully arrive due to the more robust lower rate, no assistance from the helper is needed.

Consequently, observe in Figure 4 that vMISO transmissions occur mostly at the higher modulation orders or rates; while, cooperative transmissions occur rarely, if at all for the lower rates. This means that a rate-adaptive cooperation protocol should refrain from operating at such lower rates in order to avoid wasting any resources trying to find the best cooperator, or even triggering a vMISO transmission. Namely, vMISO must opportunistically *increase* the transmission rate in order to be able to trigger cooperation and increase throughput.

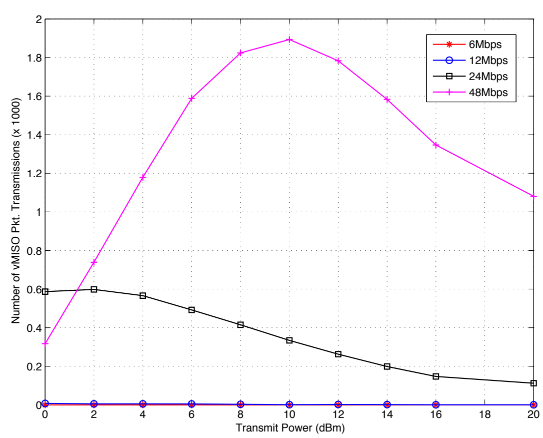

Fig. 4. Number of *cooperative* NvMISO packet transmissions for different rates.

More interestingly, observe that if the rate adaptation algorithm must make a decision as to whether to decrease the transmission rate (rate adaptation) or just employ NvMISO based on the current conditions, there is a point where switching to a lower rate becomes a significantly better option than using NvMISO. For example, at 14 dBm, utilizing NvMISO would not be advantageous because we could use direct transmission instead, therefore avoiding the overhead incurred by use of the cooperator. Similarly, below approximately 2 dBm, switching to a lower rate is also preferred.

B. MAC Overhead at High Rate

Next, since we observed that the highest vMISSO 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 a three node network consisting of a sender, a receiver, and a vMISO cooperator which is chosen among a pool of uniformly distributed nodes within a circle where the sender and receiver nodes are located on opposite sides of the circle's circumference. 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). Moreover, 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 5 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.

Moreover, 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 realizable at the MAC layer.

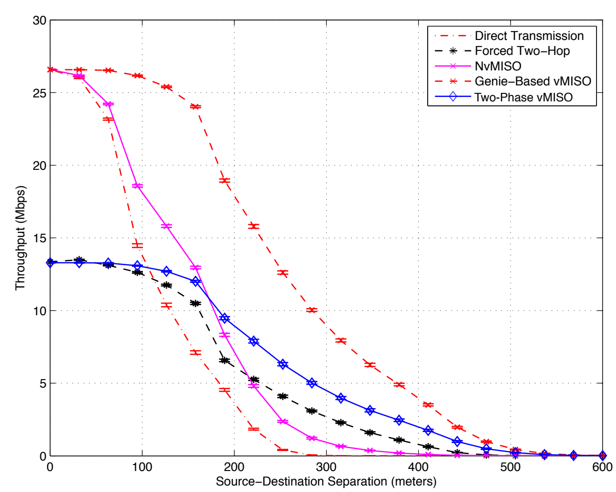

Fig. 5. Comparison of vMISO schemes with direct transmission and multi-hopping.

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 5 and Figure 6 demonstrate that for short distances (i.e., below 30 meters) in a moderate fading environment, any help provided by the vMISO cooperator is not required and should preferably be avoided to reduce overhead. Regardless of the number of vMISO transmissions, the gains for the ideal genie-based scheme and NvMISO are negligible. However, past this distance, a smart decision whether the helper should be used or not has to be made.

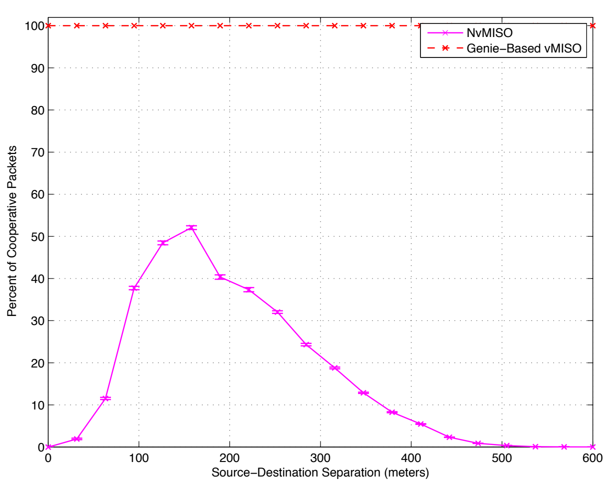

Fig. 6. Percentage of vMISO transmissions out of the total number of MAC transmissions.

Observe in Figure 5 that for moderate distances (at approximately 170 meters), Two-Phase vMISO achieves higher throughput than a "smart" feedback protocol. In the case of NvMISO, the initial transmissions from the sender begins to fail and at this point is when the highest percentage of vMISO transmissions are triggered (as shown in Figure 6). However instead of successfully transmitting a packet in two phases like the naive scheme, NvMISO requires three phases therefore wasting more air time. Furthermore, we observe that at longer distances, a forced two-hop transmission outperforms NvMISO. This tipping point occurs when the distance between the source and destination is approximately 210 meters. This happens because more time is wasted in waiting for feedback and doing a retransmission, and even though we are performing better than no cooperation, multi-hopping does not require as many retransmissions, thus achieving better performance. After this point, out of all the feasible schemes, Two-Phase vMISO is still the option that yields highest throughput due to the higher transmission power as a results of the cooperation between sender and cooperator.

Findings: MAC protocol overhead and the discrete and limited number of transmission rates in 802.11 represent a major hinderance to realizing vMISO gains available at the physical layer. Regardless of the magnitude of the performance improvement at the PHY, the highest rate available for data packets combined with low rates used for control packets sets a ceiling on the performance of vMISO. Nevertheless, there are particular regimes where vMISO can yield more than 200% throughput gains compared to direct transmissions.

IV. Effects of Virtual MISO on Topo-logy and Medium Contention

Transmissions of vMISO cooperators in multi-flow topologies introduces additional interference that could lead to performance losses. However, depending on the topology, such interference could also be *beneficial* since it can potentially 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 topology on the performance of vMISO, and vice versa.

A. Topology Generation and Validation

We consider four basic topologies in order to isolate effects of vMISO inter-flow interaction: a single cooperating flow with 3 nodes, a fully connected network comprised of 5 nodes and two flows, a 4 node network with 2 hidden terminals, a receiver, and a cooperator, and a 5 node two-flow information asymmetry (see Figure 7).

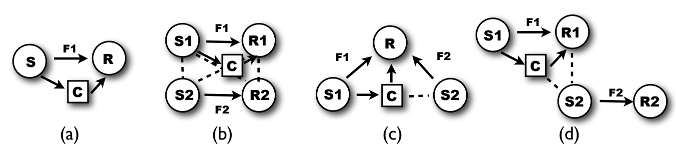

Fig. 7. Small-scale topologies. Circles: senders and receivers. Squares: vMISO cooperators. Arrows indicate traffic flows, and dotted lines indicate connectivity. Topologies: (a) Single Flow, (b) Fully Connected, (c) Hidden Terminal, and (d) Information Asymmetry.

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. We conducted all experiments at night and ensure that no other transmitters were active for the entire duration of each experiment by using a spectrum analyzer.

Figure 8(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 8(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.

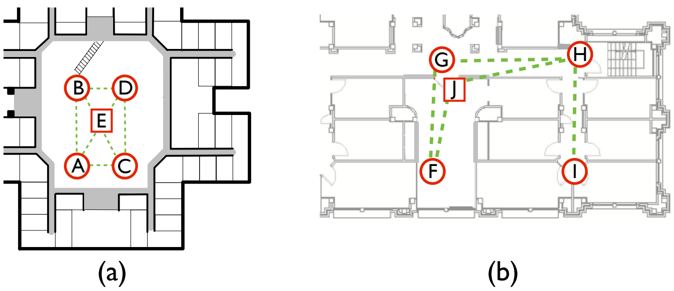

Fig. 8. Layout of our indoor testbed. (a) Used for single flow and fully connected topologies, (b) Used for hidden and information asymmetry scenarios

B. Single Flow Baseline

As a baseline, we first evaluate the performance of NvMISO with 3 nodes and a single flow (Figure 7(a)). For this case, NvMISO is expected to perform equally or better than direct transmission because the cooperator only transmits when needed and cannot interfere with any other nodes. The results are depicted in Figure 9(a) and indicates NvMISO 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 NvMISO simulator which we use extensively in our evaluation.

C. Fully Connected Topology

With a second (competing) flow, the NvMISO flow's increased transmission footprint due to the presence of the cooperator leads to additional interference. Here, we evaluate NvMISO for a two flow network where all nodes can carrier sense each other (see Figure 7(b)), and the cooperator assists only one flow at all times (i.e., flow 1).

Observe in Figure 9(b) that as expected, the throughput achieved by flow 1 is much higher when NvMISO 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

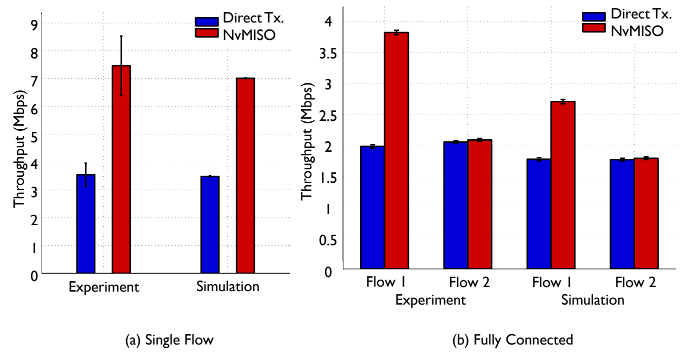

Fig. 9. vMISO in Fully Connected Topologies

is already deferring to the cooperative one. This means that the NvMISO cooperator transmits only when the competing flow is deferring. Furthermore, since the NvMISO 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.

D. 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 10, 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 10(a)), thus becoming an important influencing factor on the performance of such flow.

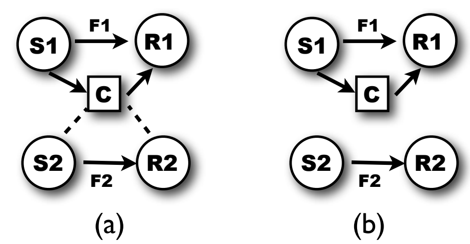

Fig. 10. Topologies where the helper assists only one flow. In (a), F2 can only sense the helper and vice versa; in (b), both flows are decoupled.

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 11 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 11(a) and 11(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 9(b), Figure 11(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.

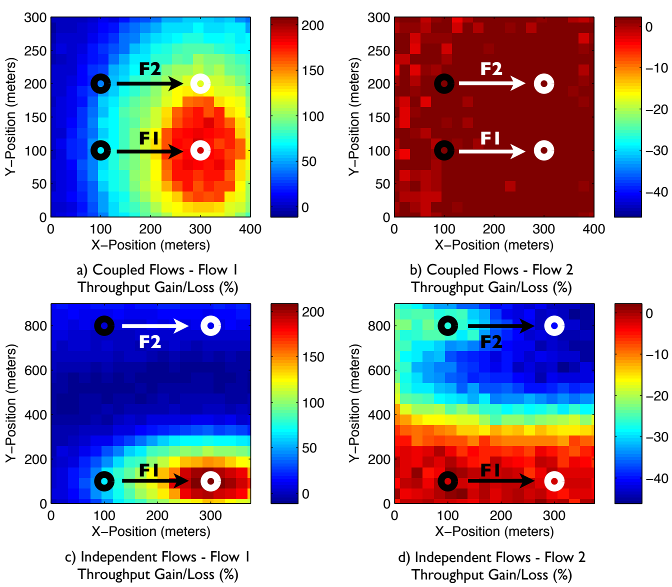

Fig. 11. Influence of helper's transmission footprint in coupled and uncoupled flows as a function of its position.

Next, we consider the case where farther away flows can employ spatial re-use without vMISO. Figure 11(c) shows that for flow 1, the vMISO flow, gains can again reach up to 200%. However, Figure 11(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.

E. 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 7(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 12(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.

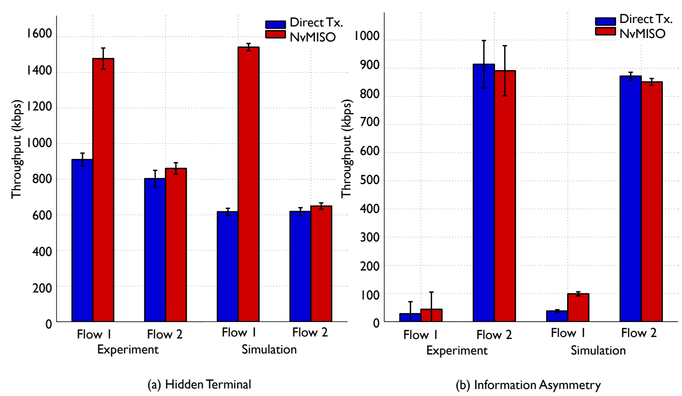

Fig. 12. Cooperation in Hidden Terminal (a), and Information Asymmetry (b) Topologies

F. 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 7(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 12(b) that as expected, the difference in throughput between the advantaged and the disadvantaged flows is significant. However, even though gains from vMISO for flow 1 are high (approximately 55%), its performance is still unsatisfactory compared to that of flow 2. 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, vMISO can still help alleviate the starvation problem by adding coordination, but MAC behavior dominates flow performance.

Findings: The presence of the vMISO cooperator has the potential to influence the interactions between two flows in proximity, therefore altering the intrinsic behavior of the original topology. Namely, it can cause a competing sender to defer during vMISO transmissions therefore coordinating transmissions thus leading to decreased number of collisions if both senders are hidden from each other, or increasing fairness if the vMISO flow is in disadvantage. Furthermore, unless the two flows are completely decoupled, the presence of the cooperator does not cause any negative effects on the neighboring flow regardless of its position.

V. The Virtual MISO Cooperator in Network-Scale Performance

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 simulate 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, receiver and vMISO cooperator at each flow are chosen such that NvMISO would yield a gain if the flow was completely isolated (according to the results from Figure 5). Such topologies provide network configurations spanning from isolated flows to fully connected scenarios.

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 our *perfect NACK NvMISO* benchmarking protocol, which we defined in Section II. This is done to explore the "worst-case scenario" in terms of interference where vMISO transmissions are always triggered if a NACK is sent.

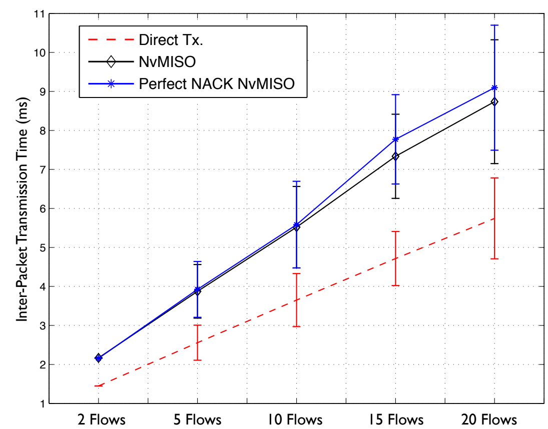

Fig. 13. Mean packet inter-transmission time for different network sizes.

Figure 13 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.

Next, we examine the effect that increased contention has on the overall network performance. To this end, we investigate the per-flow gains achieved by vMISO protocols as the number of flows in the network varies. Figure 14 shows that in average, for 2 flows, NvMISO is capable of achieving up to 2.2 Mbps throughput gains, which corresponds to roughly 47% gains

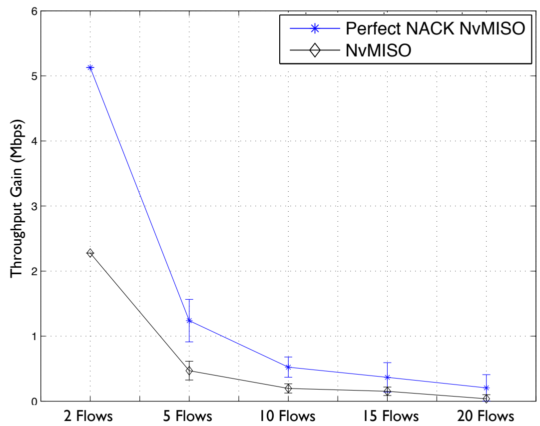

Fig. 14. Per-flow throughput gains/losses for different network sizes.

compared to direct transmission. On the other hand, the ideal cooperator is able to reach gains of more than 5 Mbps or 104% throughput gains. However, observe that 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.

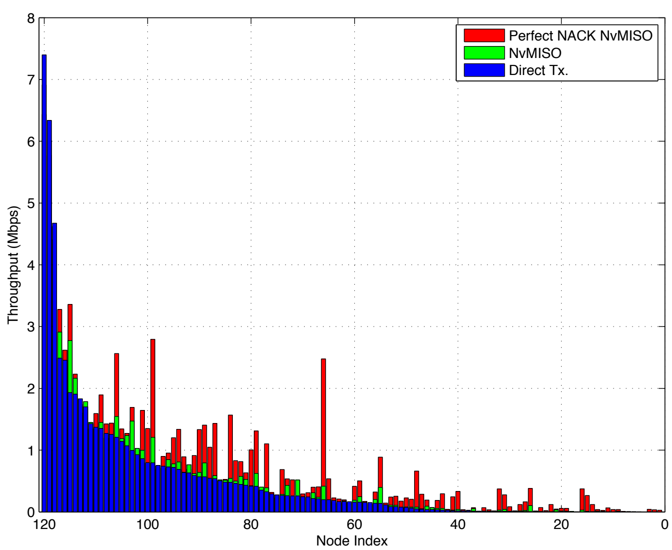

Fig. 15. Network consisting of 120 flows.

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 15 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. 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. 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 an operational urban mesh network deployment by matching all available AP and backhaul measurement data to simulation parameters.[3] We generate up to 25 clients with uniformly random locations that are within 250 meters from at least one AP. Moreover, we randomly select dedicated helpers to assist both the APs and the clients with their transmissions whenever vMISO is enabled. 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. 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.

Figure 16 depicts the percent of vMISO transmissions triggered due to adverse channel conditions for both clients

[3]Details on the network (such as name, location, etc.) omitted due to double-blind reviewing process

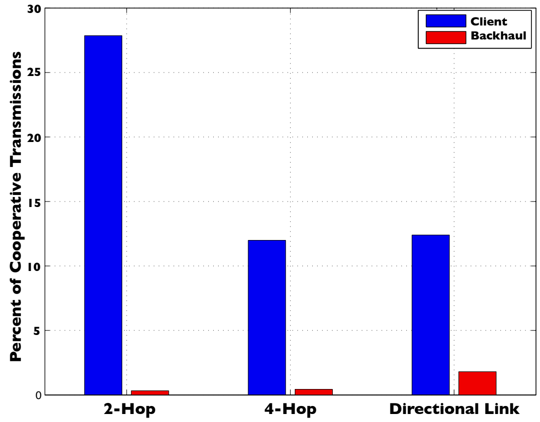

Fig. 16. Percent of cooperative transmission for different flows in mesh network.

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 III
OVERALL PERFORMANCE RESULTS OF THE MESH NETWORK

and backhaul nodes. We present results for a subset of the different types of flows encountered in the mesh network such as 2-hop and 4-hop routes where all nodes use omnidirectional antennas, as well as a 2-Hop route via 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 III 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: In large scale networks, vMISO transmissions significantly increase interference and thus contention. Moreover, average vMISO gains are greatly reduced as the number of flows in the network increases. Nonetheless, the average performance increase achieved by vMISO dominates the adverse effects due to increased interference. Furthermore, the cooperator can help alleviate throughput degradation due to the presence of highly advantaged flows.

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 [12], [13] 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 [8]. Likewise, studies such as [10] 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 [1,7-10,12,13,19,20] 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 assessing the performance of vMISO in multi-flow networking scenarios. 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 [3], [2], [7] and synchronous systems [9]. Although asynchronous cooperation circumvents the challenge of strict timing coordination, vMISOs synchronous cooperation at symbol time scales has been shown to yield larger benefits [9]. 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 perform a study of network factors affecting the gains that can be achieved through cooperation under different small-scale networking scenarios consisting of at most two flows.

We identify the current MAC protocols and non-ideal position of the vMISO cooperator as major limiting factors to the gains that can be attained by virtual MISO. We also show that negative effects such as interference due to activity of cooperator node are outweighed by the throughput gains achieved by virtual MISO. 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.

References

[1] S.M. Alamouti. A simple transmit diversity technique for wireless communications. *IEEE Journal on Selected Areas in Communications*, 16(8):1451 –1458, Oct 1998.

[2] A. Bletsas and A. Lippman. Implementing cooperative diversity antenna arrays with commodity hardware. *IEEE Communications Magazine*, 44(12):33 –40, Dec. 2006.

[3] G.J. Bradford and J.N. Laneman. An experimental framework for the evaluation of cooperative diversity. In *Proc. Annual Conference on Information Sciences and Systems*, 2009.

[4] Q. Chen, F. Schmidt-Eisenlohr, D. Jiang, M. Torrent-Moreno, L. Delgrossi, and H. Hartenstein. Overhaul of IEEE 802.11 modeling and simulation in ns-2. In *Proc. of MSWiM*, 2007.

[5] C. Hunter, P. Murphy, and A. Sabharwal. Real-time testbed implementation of a distributed cooperative MAC and PHY. In *Proc. Annual Conference on Information Sciences and Systems*, 2010.

[6] G. Jakllari, S. V. Krishnamurthy, M. Faloutsos, P. V. Krishnamurthy, and O. Ercetin. A framework for distributed spatio-temporal communications in mobile ad hoc networks. In *Proc. of IEEE Infocom*, 2006.

[7] T. Korakis, S. Narayanan, A. Bagri, and S. Panwar. Implementing a cooperative MAC protocol for wireless LANs. In *IEEE International Conference on Communications*, 2006.

[8] J.N. Laneman, D.N.C. Tse, and G.W. Wornell. Cooperative diversity in wireless networks: Efficient protocols and outage behavior. *IEEE Transactions on Information Theory*, 50(12):3062 – 3080, Dec. 2004.

[9] P. Murphy, A. Sabharwal, and B. Aazhang. On building a cooperative communication system: testbed implementation and first results. *EURASIP J. Wirel. Commun. Netw.*, 2009:7:1–7:9, February 2009.

[10] C.T.K. Ng and A.J. Goldsmith. Capacity and cooperation in wireless networks. In *Proc. of Information Theory and Applications*, 2006.

[11] A. Nosratinia, T.E. Hunter, and A. Hedayat. Cooperative communication in wireless networks. *Communications Magazine, IEEE*, 42(10):74 – 80, Oct. 2004.

[12] A. Sendonaris, E. Erkip, and B. Aazhang. User cooperation diversity. Part I. system description. *IEEE Transactions on Communications*, 51(11):1927 – 1938, Nov. 2003.

[13] A. Sendonaris, E. Erkip, and B. Aazhang. User cooperation diversity. Part II. implementation aspects and performance analysis. *IEEE Transactions on Communications*, 51(11):1939 – 1948, Nov. 2003.