Diversity Routing for Multi-hop Wireless Networks with Cooperative Transmissions

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***Abstract*—In this paper, we consider the use of cooperative transmissions in multi-hop wireless networks to achieve virtual MISO (Multiple Input Single Output) links. Specifically, we investigate how the physical layer VMISO benefits translate into network level performance improvements. We show that the improvements are non-trivial (15% to 300% depending on the node density) but rely on two crucial algorithmic decisions: the number of co-operating transmitters for each link; and the cooperation strategy used by the transmitters. Finally, we present Proteus, an adaptive diversity routing protocol that includes algorithmic solutions to the above two decision problems and leverages VMISO links in multi-hop wireless network to achieve performance improvements. We evaluate Proteus using NS2 based simulations with an enhanced physical layer model that accurately captures the effect of VMISO transmissions.**

I. INTRODUCTION

Space Time communication is a technique that leverages the spatial and temporal variations of the channel to significantly enhance the performance of wireless networks. This communication paradigm can be realized using multiple antenna element arrays where the antenna elements are separated sufficiently (of the order of the wavelength of the carrier used) such that the channel fading of each antenna is independent. In lieu of using multiple elements of an array on a node, the antennas of multiple transmitters in the vicinity of a node can be used to realize space time communication. This approach is called *cooperative communication* or a virtual antenna array communication. Depending on the number of cooperating nodes used at the transmitting and receiving ends of a link, a Virtual MISO (VMISO), Virtual SIMO (VSIMO) or Virtual MIMO (VMIMO) link can be established. Virtual arrays use the wireless channel for co-ordination. Of the different virtual array approaches, VMISO requires the lowest coordination effort because it can leverage the broadcast property of the wireless channel to distribute information to the cooperating transmitters with a single transmission. This is unlike VSIMO or VMIMO, where multiple information exchanges are required at the receiver to decode information (We elaborate on the merits of VMISO over VSIMO and VMIMO later in the paper).

In a VMISO system, multiple transmitters transmit encoded versions of the same signal so that the error performance at the receiver is improved significantly compared to a traditional Single Input Single Output (SISO) system. In this work, we consider a specific instance of VMISO communication, where all transmitters of the array transmit with the same fixed power [1]. In such systems, the cooperation gain directly leads to a smaller Signal-to-Noise Ratio (SNR) requirement to achieve the same error performance. The gain in SNR in turn can be used to either increase the data rate by the use of higher order modulations or to increase communication range, thereby improving communication performance in the wireless channel. In this context, we first investigate the benefits achievable when using VMISO in a multi-hop wireless network.

While there have been several related works [2], [3] that discuss how cooperative diversity can improve performance at the physical layer, the higher layer benefits of cooperative diversity have been explored only by a few related works [4],[5]. Using a combination of theoretical analysis, simulations and specific examples with arbitrary topologies, we study how physical layer benefits of cooperative diversity translate to network level performance metrics. Our studies reveal that the network benefits of using VMISO links are non-trivial. We then identify two important decisions that influence the achievable benefits in a multi-hop wireless network that uses VMISO: the choice of the *the number of cooperating transmitters* such that the diversity gain and interference trade-off is appropriately leveraged; and the choice of the *cooperation strategy* such that the diversity gain is appropriately used for either an increase in the range or the rate of the links or both. Finally, we propose centralized and distributed versions of a *diversity routing* protocol that includes algorithms for optimally arriving at both of the above decisions.

The rest of this paper is organized as follows. §III provides the background on VMISO links while §IV motivates the need for adaptive consideration of strategy and cluster size. §V discusses the algorithm design, while §VI describes the realization of the routing protocol. §VII presents the performance evaluation. §VIII-§IX discuss related work and conclusions.

II. SCOPE AND CONTRIBUTIONS

While cooperative transmissions can be used to realize VMISO or VMIMO communications, the focus of this paper is

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This work was funded in part by NSF under grants CNS-0721296 and CNS-0519841.

[1] With power control, the same optimization framework and solution used in this paper can be applied with slight modifications in the decision making as described in [1]

on VMISO communication. First, although both VMISO and VMIMO allow improved data rates, the coordination overhead and complexity of channel state processing are significant challenges in VMIMO which do not affect VMISO. Further, we believe that understanding VMISO is an essential step towards realizing VMIMO and the principles developed in this work can be used as a building block for realizing various distributed space time communication approaches. Although there are several challenges to realizing the potential of VMISO communications, the scope of this paper is restricted to routing.

The paper makes the following specific contributions:

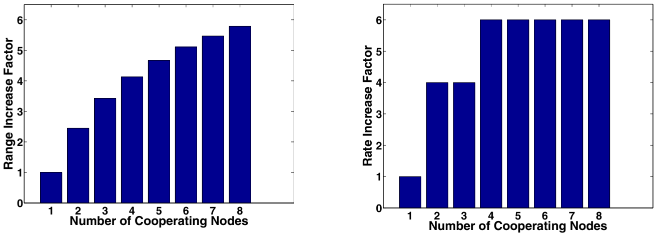
1: Joint Throughput-Hop distance optimization for VMISO routing- In this work, we identify the importance of jointly optimizing the link rate and the hop distance to achieve performance improvements using VMISO transmissions. Specifically, we show that a simple approach of optimizing the throughput of links followed by optimizing the range, can greatly reduce the aggregate throughput of flows compared to jointly optimizing the link rates and the hop distances [2]. Additionally, we highlight that the joint adaptation of rate and range becomes especially important for VMISO rather than MIMO/MISO due to the larger diversity gains obtainable with VMISO. We elaborate on the rationale for this phenomenon, later in this paper.

2: Cluster size determination- While the majority of the works involving smart antennas or distributed space-time communication [4], use a fixed cluster size throughout the network, we show that such a strategy is sub-optimal using both simulations and analysis. We propose an adaptive clustering algorithm that dynamically adjusts the cluster size for each flow in the network.

3: Strategies for routing- In this paper, we also identify several approaches for adapting the rate, range and cluster size and establish the limitations of each of them. The insights are used to identify the best approach to joint optimization of all three parameters and incorporated in a routing protocol.

III. VMISO BACKGROUND

In a SISO link, a single transmitter sends one symbol in each symbol duration to its intended receiver. However, in a VMISO link, l ($1 \leq l \leq n_c$) of the n_c transmitters transmit coded symbols to the (single) receiver in each symbol duration . The complex symbols transmitted by the l transmitters over a block of duration kT_s seconds are arranged to follow a certain structure which aids the decoding at the receiver in the presence of independent channel fading from each of the transmitters. This structure is called the Space Time Block Code (STBC) and is represented by a $k * n_c$ matrix which determines the symbols transmitted on each of the n_c transmitters for each of the k symbols periods. The bandwidth utilization of an STBC is determined by its rate $R = \frac{l}{k}$ called the code rate, where $R \leq 1$ [7].



a) Range Increase

b) Rate Increase

Fig. 1. Rate and Range improvements of a VMISO transmission

Benefits: When spatially separated transmitters transmit encoded symbols across space and time, the receiver, with the knowledge of the channel fading coefficients, can process the signals to recover the symbols with much lesser bit error rate than otherwise. This spatial diversity benefit leads to a smaller SNR requirement (and E_b/N_o requirement, where E_b is the bit energy and N_o is the power spectral density of white noise). For instance, for a target Bit Error Rate (BER) of 10^{-3}, the E_b/N_o required for uncoded BPSK modulation is 25 dB [8] whereas with a VMISO link, the required E_b/N_o is 10 dB (while it is around 15dB for MISO links which have a reduced SNR per branch). Thus, with cooperation, the SNR required for decoding the signal is much lesser than without cooperation. [3] For a specific target BER P_b, the reduced SNR requirement, can be translated into (a) a longer transmission range for the same modulation rate or (b) higher transmission rate by the use of a higher order modulation for the same range or (c) an intermediate rate, range pair. Consider BPSK modulation with diversity order n_c and a required BER of P_b. Since the average SNR of a fading channel follows a path loss model, with exponent of α, the range extension factor can be obtained as

$$R_f(n_c) = \left(\frac{n_c * {P_b}^{\frac{1}{n_c}-1}}{\binom{2n_c-1}{n_c}^{\frac{1}{n_c}}}\right)^{\frac{1}{\alpha}} \qquad (1)$$

The range extension factor is also a function of the modulation. The maximum range extension factor for the case of $\alpha = 4$ is presented in Figure 1(a). Similarly, for a given range, the diversity gain can be used to obtain an increase in the transmission rate. We consider a discrete set of modulations namely BPSK, QPSK, 16-QAM and 64-QAM which are popularly used in the 802.11 standard. The maximum rate improvement for the same range, with increasing number of transmitters is shown in Figure 1 (b) (where the code rate of the STBC (i.e 0.75) [7] is also considered. We consider the highest code rate for each n_c in this work). The values in the table represent the *maximum* range or rate that can be obtained independently.

Since the cooperating transmitters are not co-located, the signals could be received at the receiver with different delays

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[2] which is in contrast to conventional wisdom on using space time communications [6]

[3] In a VMISO link where n_c transmitters transmit at a fixed power, the SNR per diversity branch is same as that of SISO link, unlike in MISO links, where the SNR per diversity branch is divided by n_c. Consequently, the diversity gains of transmit diversity are higher with VMISO link than with an equivalent MISO link.

and average received powers. Further, the clocks of the transmitters may not be synchronized. This leads to asynchronous reception and is similar to Inter-Symbol Interference in its effect. There have been several physical layer approaches to handle this problem, such as time-reversed space time codes and space time OFDM [9],[10].

Feasibility: There have been a few recent works which discuss the practical feasibility of cooperative transmissions. Specifically, [4] shows that the relative delays between signals from the transmitters are fairly small as compared to the symbol duration in 802.11 standard and in all cases the above physical layer approaches can be used to handle lack of synchronization. Also, [4] shows that due to spatial separation and consequent path loss differences, in more than 85%-90% of the cases, the relative power difference between two nodes is less than 5dB. These results and the related work indicate the existence of approaches to make cooperative transmissions feasible. Additionally, the feasibility has also been established recently in [11] with WLAN devices. All these works illustrate that cooperative transmissions are emerging close to practice.

IV. MOTIVATION

In this section, we motivate the need for adaptive cluster sizes and the strategy (i.e.. rate or range increase) using a combination of analysis, illustration and simulation. We are interested in obtaining the order of benefits achievable with VMISO communication.We use both the *protocol* model of interference and the *physical* (Signal to Interference and Noise Ratio) model of interference for the discussions. While we use the former for the toy topology discussions, we employ the latter in the simulations based characterization.

A. Analysis

1) Model: Consider n nodes deployed independently and uniformly at random on the surface of a disk of area A. In a conventional multi-hop transmission, each source communicates to its intended destination through multiple intermediate nodes (hops). At each stage of the route, a node transmits a packet to its neighbor on the route which is within its (SISO) communication range. We consider a model for VMISO communication consisting of two transmission stages. In the first stage, a source node of a VMISO link performs a local transmission at a rate D_L to a subset of its neighbors. This is followed by the simultaneous transmission of encoded versions of the same message by the cooperating neighbors including the source to the destination of the VMISO link. We also consider a path loss exponent of α that characterizes the long-term channel propagation.

2) Results: Let T_{SISO} represent the aggregate network throughput when using SISO (conventional) transmissions. With the VMISO model described before, we are interested in computing the dependence of the network throughput (normalized to SISO) on the average cluster size n_c and the strategy characterized by a (rate, range) pair. Specifically, we are interested in the network throughput for three cases: i.e.. when using the cooperation gains for (1) rate optimization, (2) range optimization and (3) joint rate-range optimization. We provide the gist of the analysis here and refer the interested reader to [1] for details of the derivations. For simplicity, we use the same strategy and cluster size throughout the network. Thus, the results obtained in this section serve as a lower bound to the performance improvements that can be obtained by adapting the cluster size and strategy at different nodes across the network. We also note that adapting each hop could also introduce other issues such as link asymmetry and synchronized switching among hops of a flow.

For a specific cluster size n_c and rate, the communication range is also uniquely determined since the transmit power of each node is fixed. For a given error rate performance, the data rate of a link depends on the modulation used. Hence we need an index for the different rates (modulations) under consideration. Since the relation between error rate and SNR varies with different modulations we consider several modulations of the same class such as BPSK, QPSK, etc. indexed by the order m can capture the error performance relation. The scaling of achievable rate improvements with m depends on the modulation varying from m for a PSK constellation to 2^m for QAM constellations [8]. In our model, $m = 1$ represents the basic (lowest rate) modulation. Although we develop the analysis for a single family of modulations, we consider accurately the popular modulations of interest used in IEEE 802.11 standard, when quantifying the benefits later in this section.

Let $R_f(n_c, 1)$ represents the communication range achieved using an average cluster size of n_c nodes and at the basic modulation indexed by $m = 1$ (For BPSK, the expression is given by Eqn. 1). When transmitting with a higher order modulation (m), the effective range is now reduced to $R_f(n_c, m)$, with a modulation dependent rate increase.

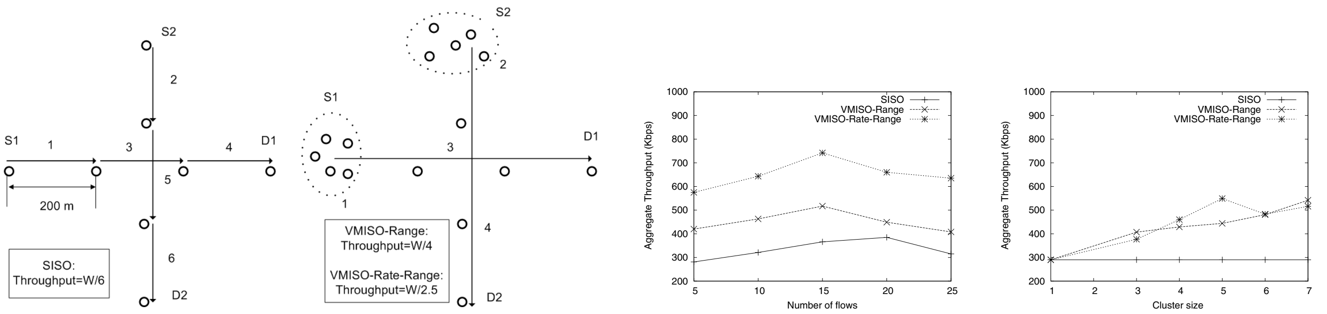
The relation between the network throughput with VMISO transmissions (T_{HYBRID}), the communication range $R_f(n_c, m)$, the cluster size n_c and modulation order m can be obtained by identifying the transmission and interference ranges as performed in [1]. This results in the following expression.

$$\frac{T_{HYBRID}(n_c, m)}{T_{SISO}} = \frac{R_f(n_c, m)}{1 + \frac{{n_c}^{\frac{2}{\alpha}}}{m}} \qquad (2)$$

The above expression can be simplified further and the detailed derivation is available in [1]. After applying the expressions for the rates achievable as a function of n_c for the same BER, we obtain the total throughput for a modulation order m and the cluster size n_c as

$$\frac{T_{HYBRID}(n_c, m)}{T_{SISO}} = O\left(\frac{m * n_c}{2^{\frac{m}{2}} * (m + {n_c}^{\frac{1}{2}})}\right) \qquad (3)$$

Equation 3 (valid for $n_c \geq 2$) describes the dependence of network throughput on the cluster size and strategy using



(a) Illustrative topology for strategy (b) Strategy in Random scenarios (c) Cluster size in Random scenarios

Fig. 2. VMISO benefits in arbitrary and random topologies

VMISO communication [4].

As special cases, it is easy to identify the benefits using Range in isolation (i.e. $m = 1$) or rate in isolation (i.e. $m = m_{max}$ & $m > \sqrt{n_c}$). i.e.

$$\frac{T_{RANGE}}{T_{SISO}} = O(\sqrt{n_c}) \quad (4)$$

$$\frac{T_{RATE}}{T_{SISO}} = 0(\frac{n_c}{2^{\frac{m_{max}}{2}}}) \quad (5)$$

Several critical observations follow from Equation 3. The main insights are:

1) Using adaptive link rate and range yields almost a 2.2X improvement compared to SISO (for $n_c < 8$).
2) The end-to-end throughput is higher when optimizing the link rate and range than with the range alone.

Hence we observe that even a simple level of adaptation (network level) of the cluster size and strategy can yield significantly more (2.2X) benefits compared to SISO and over using a fixed strategy.

B. Illustrative examples

Figure 2(a) shows a topology with two flows, where nodes are separated by uniform distance of 200m. The end-to-end throughput of each multi-hop flow obtained with SISO routing is then given as $\frac{W}{6}$ where W is the bandwidth of the channel. With 4 other cooperating neighbors, when the gains are used for improving the rate of the VMISO link for the same number of hops (Rate strategy), the performance is worse than SISO achieving only 85% of the SISO throughput due to the overhead of local transmission from the source to its neighbors. Using VMISO gains for maximizing the range causes the throughput to be $\frac{W}{4}$ since there are 4 contending transmissions, two for the local transmission (source to neighbors) and two for long-range all operating at the basic rate. When using an intermediate value of rate and range, the throughput is $\frac{W}{2.5}$ since the cooperation gains for 5 transmitting nodes to this destination, enable the VMISO links to operate at 4 times their basic rate (since the SINR requirement for this rate is about 10 dB higher than the basic rate). Thus we observe that the benefits over SISO increase from (1.5X) with maximum range to (2.4X) with adaptive rate-range. Similarly cluster size determination is also important and is illustrated in [1].

C. Random scenarios

While it might appear that VMISO benefits are specific to the arbitrary scenarios presented in the illustrations, we highlight that significant benefits are obtained even in random scenarios using simulations. For the purpose of this discussion all nodes in the network use the same value of cluster size when strategy is varied and the same strategy when cluster size is varied. The simulation parameters are as described in §VII with a default value of cluster size of 5 when not varied and the node degree is always higher than the cluster size under consideration. To begin with we consider the network throughput vs the number of flows, when the strategy is varied (plotted in Figure 2(b)). VMISO-Range is the strategy where every node utilizes all its available cooperation gain for range extension. VMISO-Rate-Range is the strategy when all nodes use a higher modulation (with 4 times higher data rate in this case). Among SISO and VMISO, VMISO schemes achieve a higher throughput compared to SISO for all values of number of flows. It can also be seen that the rate-range strategy where a higher rate than the base rate is used, provides significant benefits compared to SISO and using diversity gains for complete range extension. Thus, one can see that using diversity gains for rate and range in combination can yield significant benefits (2X) compared to SISO and (around 1.6X) compared to using the maximum range. Similarly Figure 2(c) shows that the optimal cluster size is not the same for all strategies and is not always the maximum cluster size.

D. Summary

In summary, both the simulations and the analysis confirm the following main observations:

Observation 1: *Joint rate - range optimization offers the best possible performance when compared to optimizing one factor in isolation.*

Observation 2: *The optimal cluster size is not a fixed value (e.g. maximum) and varies with the strategy of operation.*

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[4] Additionally, the effect of the code rate of the space time code can be obtained by replacing m in the equation with $m * T(n_c)$. This leads to a modest decrease in VMISO benefits over SISO, but preserves rate-range benefits over range.

V. ALGORITHM DESIGN

In this section, we identify the key characteristics of VMISO links that determine network level benefits and explore how an algorithm can be developed to utilize the characteristics to adapt network layer choices.

A. Design Considerations

From a network standpoint, the key characteristics of VMISO links are as follows.

1) Many or Few - Number of cooperating transmitters: The cluster size directly determines the diversity gain and the total power transmitted by the VMISO link (cooperation gains). When translated to link level performance, the cluster size determines the data rate improvement or range improvement achievable for a specific reliability requirement. On the other hand, a larger cluster size causes increased interference powers at other nodes. The increase in carrier sense range with cluster size was found in the previous sections as ${n_c}^{\frac{2}{\alpha}}$. Thus, the choice of cluster size must balance the benefits and the interference. Specifically, for isolated flows, the self interference among links of a flow impacts the spatial reuse. Using the arguments from § IV, the number of contending links of a flow along a path P_j, is related to the interference range and transmissions range as

$$S_I(P_j, n_c, m) = \frac{2 * R_i * n_c^{\frac{2}{\alpha}}}{R(n_c, m)} \tag{6}$$

where R_i is the SISO interference range and $R(n_c, m)$ is the communication range using modulation m and n_c cooperating nodes.

Since VMISO links allow long-range hops, the above expression must be modified to include the case when all hops of the flow are within the interference range. In that case, the self interference can be quantified as

$$S_I(P_j, n_c, m) = \min\left(\frac{h * S}{R(n_c, m)}, \frac{2 * R_i * n_c^{\frac{2}{\alpha}}}{R(n_c, m)}\right) \tag{7}$$

where the flow consists of h hops with average hop-length S.

2) Farther or Faster - Strategy for cooperation: The cooperation gains can be used for increasing the rate only or increasing the range alone or for obtaining an intermediate rate, range pair. For a given cluster size, the set of rate, range pairs achievable is fixed. A straight-forward approach to using rate and range is to switch between the two strategies. However, as already seen in §IV, such a switching is unlikely to yield benefits because of the performance degradation incurred by the cost of local transmissions. Thus, a hybrid of rate and range must be chosen for each case since only that allows fine grained usage of diversity gains to the maximum extent possible. Using a fixed strategy cannot utilize all the available diversity gain as seen in §IV. For a given cluster size, the data rate of the local transmission affects the effective rate of the VMISO link. Hence, a higher VMISO link rate can give benefits only when combined with range improvement. This must be factored in the strategy decision. The effective rate of a VMISO link (normalized to SISO) is thus

$$D = \frac{T(n_c) * 2^{m-1}}{T(n_c) * 2^{m-1} + 1} \tag{8}$$

where $T(n_c)$ is the code rate for the STBC, (recall from [7] that it depends on n_c) and the factor of 1 in the denominator denotes the local broadcast at the basic rate, before each VMISO transmission. Additionally, the cluster size of a VMISO link must be less than the node degree in the vicinity of the source node and the Signal-To-Interference Noise Ratio (SINR) must be satisfied at the receiving end-point for the VMISO link to be feasible.

B. Solution Description

Since the nature of the links is changed fundamentally when VMISO transmissions are used, the routing must be performed in a manner which takes this into consideration. Hence the problem of utilizing VMISO links in a network can be formulated as a routing problem. However, even deciding the cluster size for different flows for fixed strategy is NP-HARD [1]. The problem is complicated by the inter-dependence between the cluster-size, strategy and path characteristics on throughput (§IV). Since we are interested in a distributed realization for the routing solution, we make decisions on a per-flow basis. We believe it is a justifiable choice given the reduction in complexity compared to link level decisions. The key challenge here is *how to compute good VMISO routes with just SISO path information while taking into account the conflicting trends.* To do this, we model the dependencies carefully and also collect additional statistics from the intermediate nodes to capture the interactions in a single path metric. The proposed solution consists of two main components, namely the path metric and the path computation algorithm.

1) Path Metric: Any path metric for routing in wireless networks must include three components, namely, self-interference, inter-flow interference and link data rate. All these three components change with VMISO links compared to SISO. The impact of self interference was captured already in Eqn. 7 and the link data rate in 8. Thus we need to identify the impact of VMISO on the inter-flow interference.

When multiple flows are considered, the interference between links of different flows affects performance. Due to multiple concurrent transmissions, VMISO links can have increased interference effects if the cluster size and strategy are not controlled appropriately [1]. In this sequel, we show how the bottleneck interference on each path P_i can be obtained and used to characterize the inter-flow interference. First consider the effective path $P_i(n_c, m)$, when a cluster size n_c and modulation order m are used. The set of nodes in $P_i(n_c, m)$ is a subset of those in P_i since VMISO hops can skip over intermediate SISO nodes. Given a neighbor list, which consists of the number of links overheard by each of the neighbors, a source node of a VMISO link can determine how many links, it has to share the channel with. i.e. to

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Variables:
1   $f$: Flow-id, $P_j$: $j$th shortest path, $N$: Maximum cluster size
2   $n_c$:cluster size, $n'_c$: current best cluster size,
3   $m$: modulation order, $MAX_M$:Current Maximum metric
4   $SNR_{TH}(m)$: SNR Threshold of $m$,$l$: Number of paths
5   $MAXP$: Current highest metric path-id, $M$: Highest
        modulation order, SNR(n): $SNR$ of node $n$
6   $m'$: Current best modulation order,
7   $M(P_j, n_c, m)$: Metric of path $P_j$ with cluster size $n_c$
        and modulation order $m$,$D$: VMISO link data rate
8   $I(n_c, n)$:Interference value for node $n$ and $n_c$ neighbours,
9   $P_j(n_c, m)$: Subset of $P_j$ connected with links using
10  rate $m$ and cluster size $n_c$, $T(n_c)$- $n_c * 1$ STBC rate
11  $F(P_j, n_c, m)$: Bottleneck interference of path $P_j$
        with cluster size $n_c$ and modulation order $m$

Compute-path-info ($f$)
    INPUT: Source,Destination pair of flow $f$
    OUTPUT: $l$ Paths $P_j$ and I($n_c$,n) $\forall n \in P_j$, $n_c \leq N$
12  For $j = 1$ to $l$
13      $P_j$ = Compute-SISO-shortest-path($f$)
14      For each $n \in P_j$
15          For each $n_c \leq N$
16              $I(n_c, n)$ =Interference-load($n$,$n_c$)

Compute-metric($P_j$,$n_c$,$m$)
    INPUT:$P_j$,$n_c$,$m$,$S$
    OUTPUT:$M(P_j, n_c, m)$
17  $F(P_j, n_c, m) = max(I[n_c, n])\forall n \in P_j(n_c, m)$
18  If $n_c >= degree(n)\forall n \in P_j(n_c, m)$ and $SNR(n) > SNR_{TH}(m)$
19      $B = max(F(P_j, n_c, m), min(\frac{h(P_j)*S}{R(n_c,m)}, \frac{2*R_i(n_c)}{R(n_c,m)}))$
20      If $n_c > 1$
21          $D = \frac{T(n_c)*2^{m-1}}{T(n_c)*2^{m-1}+1}$
        Else
22          $D = 1$
23      return ($\frac{1}{B*D}$)
    Else
24      return(0)

Execution Sequence
25  For every unassigned flow $f$
26      Compute-path-info ($f$)
27      For each path $P_j$, $j = 1$ to $l$
28          $MAX_M = 0$, $n'_c = 1$, $m' = 1$
29          For each $n_c = 1$ to $N$
30              For each $m = 1$ to $M$
31                  $M(P_j, n_c, m)$ = Compute-metric($P_j$,$n_c$,$m$)
32                  If $M(P_j, n_c, m) > MAX_M$
33                      $M(P_j, n_c, m) = MAX_M$, $n'_c = n_c$
34                      $m' = m$, $MAXP = j$
35      $P(f) = P_{MAXP}$
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Fig. 3. Algorithm for joint Routing, Cluster size and Strategy assignment

form a VMISO link of n_c neighbors the maximum of the interference activity overheard by any of its n_c neighbors would be the bottleneck which leads to sharing among links in the contention region. Since each flow can have multiple VMISO hops, the bottleneck contention for each hop can be obtained as the maximum of these values across the VMISO link sources (i.e. nodes in $P_i(n_c, m)$).

$$F(P_i, n_c, m) = \max_{n \in P_i(n_c,m)} I(n_c, n) \tag{9}$$

where $I(n_c, n)$ is the maximum interference perceived by any of the n_c neighbors of node n.

Combining expressions 7, 8 and 9, the final throughput metric can be given as

$$M(P_i, n_c, m) = \max_{P_i,n_c,m} \frac{D(n_c, m)}{\max F(P_i, n_c, m), S_I(P_i, n_c, m)} \tag{10}$$

2) Constraints: With this we have the additional constraints that the links be bi-directional, the cluster size n_c for this path, is feasible at the VMISO end-points in the path and the SINR requirements are satisfied at the receiver. Thus the algorithm computes the values of P_i, n_c and m which maximize the metric subject to these constraints.

3) Algorithm: The details of the algorithm are presented in the pseudo code shown in Figure 3. The algorithm first determines the SISO shortest path information (line 26) along with the interference measure for each node in the path (lines 12-16). This is followed by identifying the bottleneck interference (line 17) for a given cluster size and modulation. Then, the feasibility of the VMISO link is checked to ensure that there is an end-to-end path for this n_c and m followed by determining the effective link rate of the VMISO links on the path (lines 20-22) and the path metric (lines 23-24). Then the expected path metric is computed for each of the available paths for different values of n_c and m and the 3-tuple values of P_j , n_c and m with the highest metric is chosen as the solution (lines 31-35).

From Figure 3, one can observe that the algorithm takes into account the considerations identified in §V-A. Specifically, self-interference for VMISO links is captured in line 19, whereas the interference across flows is captured in line 17. The impact of the local transmission is also incorporated into the metric computation and the rate of the STBC code for different values of cluster size is also considered (lines 20-22).

4) Complexity and Correctness: While a brute force solution would involve $n_c * f * m$ route computations for f flows, the proposed solution just requires f route computations, thereby significantly reducing the complexity of routing. Observe that the determination for cluster size, strategy combination is performed for the entire design space by computing the expected path metric using the available SISO path information. A critical feature of flow level assignment is that the bottleneck interference i.e. the maximum number of intersecting flows in any contention domain of the network decides the impact of inter-flow interference on the throughput of the flows. While adapting parameters such as n_c and m can be performed at a link-level in lieu of a flow-level, this introduces a higher possibility of link asymmetry and increases the complexity of routing significantly. Thus, the algorithm assigns the best flow-level cooperative routes while keeping the complexity within bounds.

VI. DISTRIBUTED REALIZATION

A. *Diversity Routing protocol*

In this section, we present the distributed diversity routing protocol called Proteus. We focus only on the route discovery step of the routing protocol and use conventional route maintenance procedures for maintaining routes and reacting to route failures. Other components such as forwarding are similar to popular on-demand protocols such as the Dynamic Source Routing protocol (DSR) [12], except that the source route packet also includes the cluster sizes and strategies to be used in addition to the IDs of intermediate nodes. This is needed since a given node which is part of multiple flows, can use different cluster sizes to support each of the flows.

1) Route Request: The first step in the route discovery phase is the transmission of the Route Request (RREQ) by the source. As in conventional routing protocols, nodes stamp their IDs on the RREQ packet. In addition each node j stamp the following 4-tuple (S_j, I_j, NL_j, F_j) where S_j is the received signal strength from the previous hop, I_j is the ambient interference level (the fraction of time, the channel is busy), NL_j, the neighbor list consisting of the number of links (unique source addresses) that each neighboring node has overheard and F_j, the number of flows already served by this node. The interference information is obtained by nodes monitoring the fraction of time that the channel is busy (the received signal crosses the carrier sense threshold). This is used to estimate the load on the channel. Similarly, the neighbor list consists of the number of active links overheard by each neighbor obtained when neighbors periodically broadcast HELLO messages conveying their IDs and the ambient interference information. The nodes also hear pilot tones to track the number of VMISO links in vicinity. Thus, the Route Request propagation proceeds using SISO transmissions as in popular source routing protocols, with modifications to provide information to the source that helps its decision making.

2) Route Response: When the destination receives the route request, it transmits the Route Response (RREP) after adding the information about its vicinity. Intermediate nodes forward the packet as usual, except that when any of their statistics has changed, they update it on the route response packet. When the source receives the route response (RREP), it uses the statistics available on the packet to compute the metric described in the algorithm in Figure 3. The source collects l paths received within a timeout duration (where l is a predetermined constant such as 4). The source computes the path metric for each path for different values of n_c, m and selects the value that provides the best metric. The algorithm in Figure 3 requires estimates for the following. (1) Approximate Interference powers for every node on the path (2) Number of flows already served by each node on the path (3) Node degree of each node on the path (3) Number of SISO hops in the path. The SISO hop length is also obtained as in conventional routing protocols, while the other information is available in the RREP. The number of flows already served by the node is directly read from the route response packet.

3) Route failures and Maintenance: We use default route maintenance mechanisms due to their simplicity. Thus, on a route failure a route recomputation is initiated and a new route is found.

B. *MAC layer support*

1) VMISO communications: For a VMISO transmission to be successful, the receiver needs three key pieces of information, namely the cluster size used for the transmission, the strategy (modulation) and knowledge of channel coefficients. The best cluster size and modulation for a given flow (identified at the end of the routing process described in §VI-A) are conveyed to the receiver of each VMISO link along with channel estimation between the transmitters and the receiver as described below.

Selection of transmitters: The first stage of every VMISO transmission is the local transmission of data from a source to its neighbors. The source node determines a subset of its neighbours for cooperation based on the results of the SISO path computation. Nodes that receive the transmission successfully, after identifying their IDs on the packet, transmit the pilot tone at an appropriate time, given by the order of nodes on the packet. If all nodes receive the local packet successfully, they transmit the pilot tones one after another in time. When the local transmission is not successful at any of the desired nodes, the desired number of pilot tones is not heard by the source and destination. Consequently, the VMISO transmission is suspended by the nodes when they do not overhear the correct number of pilot tones. The source then performs a random backoff before trying again. In this way, the unreliability of the local transmission is addressed.

Pilot tone stage: On hearing a single pilot tone, the receiver waits for a preset duration of time to receive pilot tones from the nodes of the VMISO cluster. Since the channel estimation duration required is very small ($< 50\mu s$ [13]) compared to the data durations, we allow a waiting time that is long enough to hear from β nodes (we use $\beta = 8$ in our solution). As in related work [4], we assume that the pilot tones are detectable over a range longer than the VMISO transmission range. This is accomplished using lower order modulations that have a long range. Further discussion on the overhead, collisions and failures of pilot tones is available in [1].

VMISO transmission: Once the pilot tones are successful, the (simultaneous) VMISO transmission begins with a preamble transmitted at the basic rate using the appropriate space time code, indicating the rate for the payload of the packet, so that the receiver can know the modulation to be used for decoding. With this information and that obtained in the previous stage, the receiver decides the number of transmitters and the appropriate space time code to be used. For each value of n_c , we use a fixed best rate space time code available and so this mapping is unique.

2) Other support: The MAC must support medium access with asymmetric links (e.g [14]) and the estimation of interference to be exposed to the routing layer.

VII. PERFORMANCE EVALUATION

A. Evaluation platform

The NS2 simulator (ns-2.32) was used. Rayleigh fading was used through the CMU extensions over a path loss model with an exponent of four. All nodes use a single channel of operation at 2.4GHz. Further a cumulative SINR based decoding procedure was developed. The diversity gains at different SINRs for different number of cooperative transmitters was used with a table lookup. Further, the SINR threshold for the basic rate (uncoded BPSK) was set to 25dB with a rate of 2Mbps.

Physical layer modeling: We do not perform bit-level simulations but provide the required packet level abstractions to get reasonably accurate results without significantly increasing the simulation time. When n_c nodes transmit simultaneously, the received powers of the n_c nodes are added along with their path loss and fading effects. Specifically the receiver computes $Pt * \sum_{i=1}^{n_c} {\alpha_i}^2 * d_i^{-4}$ and compares it with a specific threshold $SINR_T(n_c, m)$. The SINR threshold for each n_c and modulation m are obtained from [8] based on the current receive SINR. We consider BPSK, QPSK, 16-QAM and 64-QAM as the modulation set.

Network parameters: We use a 2500m by 2500m grid and deploy 200 nodes randomly in this region by default. The SISO transmission range is 250m for the basic rate. We setup random flows within the network using Constant Bit Rate traffic and User Datagram Protocol as the underlying transport protocol. We increase the sending rate to the maximum that the network can support. The default routing uses DSR. For the MAC, we use an idealized version of 802.11 which accommodates the presence of VMISO links using an approach similar to [4]. This MAC also handles the effects of differences in cluster sizes among nodes by allocating the channel fairly to different nodes. The local transmission rate of each VMISO link is the same as the corresponding SISO rate. The aggregate end-to-end throughput of all the flows is the main metric. When cluster size is varied, the number of nodes in the network is set so that the average node degree is greater than the maximum cluster size. We use the random way-point mobility model with the setdest utility in NS2. The mobility is varied between 0 m/s to 25 m/s with a pausetime of 20s. For each data point, we average over 10 seeds with a simulation time of 100s per seed.

We compare Proteus with SISO (conventional routing) and the state of the art VMISO-Range [4].

B. Results

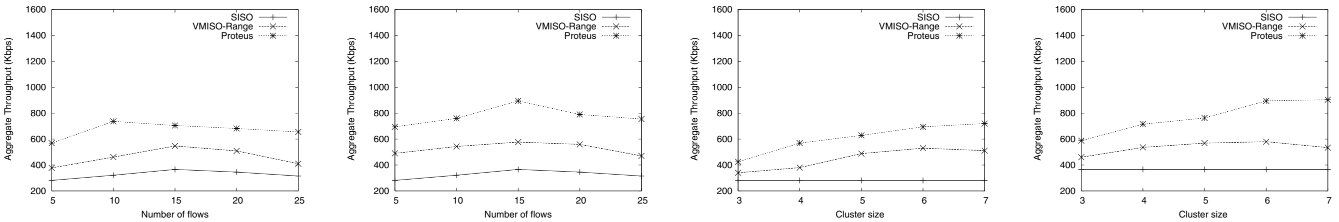
1) Impact of Number of nodes: Figures 4(a) and 4(b) depict the impact of varying number of flows when the number of nodes deployed in the network is 150 and 200 respectively. From both figures, one can observe that the throughput increases upto a certain number of flows when the available spatial reuse in the network is fully utilized and beyond that it decreases. However, the throughput of Proteus is always much better than SISO. The magnitude of the benefit is upto 2.1X for 150 nodes and 2.5X for 200 nodes. With 150 nodes, the average node degree being small, limits the cluster sizes that can be used. One can also observe that the throughput of using only range for routing although better than SISO (by about 1.3X and 1.6X), is still lesser than that of Proteus.

2) Impact of Cluster Size: The impact of varying cluster size is indicated in Figures 4(c) and 4(d) for 5 and 15 flows. One can observe that with increasing cluster size, the throughput of VMISO-range increases upto a certain point beyond which it decreases. This is because, for any given flow pattern, indiscriminate increase of cluster size beyond a value, just contributes to increased interference without any range benefits. On the other hand, we observe that the throughput of Proteus does not decrease with increasing cluster size, since the best strategy that maximizes overall throughput is chosen and the increased gains from cluster size are utilized as much as the network allows to improve rate and/or range.

3) Impact of Grid Size: We study the effect of grid size using a 'small' network, where the grid size is 1500m * 1500m. Since, the available spatial reuse itself is small the penalty of increased interference ranges due to VMISO transmission is lesser. Hence we observe an increase in throughput even with VMISO range. However, as the cluster size is increased, the benefits of VMISO range saturate because, the maximum range extension has been obtained. However, with Proteus, we observe that the throughput scales well with increasing cluster size since cooperation gains are also used for improving the rate. Thus, the throughput improves over SISO by a factor of 3X and less than 2X over VMISO range. The results for a larger grid size have already been discussed (Figures 4(c) and 4(b)).

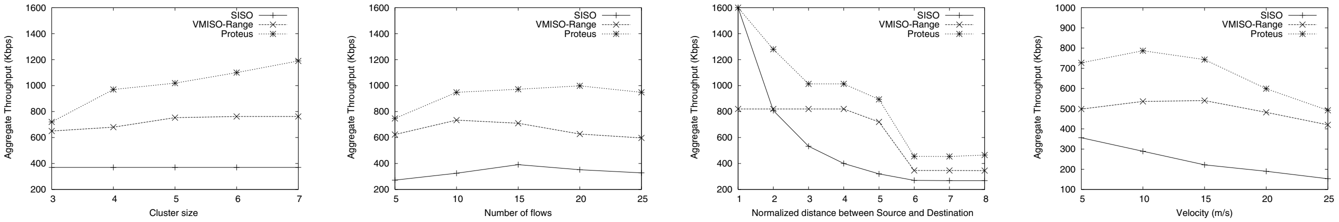
4) Impact of Mobility: Figure 5(d) presents the aggregate throughput as a function of node mobility when the velocity of nodes is changed form 5 m/s to 25 m/s. It is clear that high mobility degrades performance for SISO. On the other hand, VMISO-Range is able to prevent route failures since nodes stay connected for longer durations due to the longer ranges. But, interestingly for the mobility considered here, Proteus has benefits over both SISO and VMISO. Only, when the velocity of the nodes is around 25 m/s Proteus has a slight degradation in its benefits due to its aim of achieving highest rate routes. Hence, the impact of mobility is significant only when the velocity is high. This is due to the longer range links (compared to SISO) available even when using a higher rate.

5) Distance between Source and Destination: The throughput of the flow when the source-destination distance is varied is presented in Figure 5(c) where the x-axis represents distance normalized to SISO transmission range. It is clear from the figure that the strategy that gives the best throughput depends also on the distance. Specifically, the SISO throughput falls with increasing distance because of the number of hops within an interference region. VMISO-Range gives benefits when the number of hops is greater than 2. However, the best benefits are obtained with Proteus, when the source and destination are separated between 2 and 9 SISO hops. Thus, the results indicate that Proteus is likely to yield significant benefits for practical values of SISO hop lengths.



(a) Throughput with 150 nodes (b) Throughput with 200 nodes (c) Throughput with 5 flows (d) Throughput with 15 flows

Fig. 4. Throughput vs Cluster size



(a) Throughput vs cluster size with small grid size (b) Throughput vs flows with small grid size (c) Throughput with S-D distance (d) Throughput with mobility

Fig. 5. Throughput with grid size and mobility

VIII. RELATED WORK

The works most relevant to the present work are [2], [4], [11], [15] which consider the use of cooperative transmit diversity for routing. [2] studies the problem of choosing the modulation such that the cost of distribution to relays is much less than the benefit of cooperation in a 3-node network. [4] discusses a multilayer protocol for exploiting transmit diversity in adhoc networks using VMISO routes constructed on SISO paths and an inter cluster MAC protocol similar to IEEE 802.11. Similarly, [11] presents a forwarding protocol that uses transmit diversity to improve the reliability of Acknowledgment packets. Both these works focus on forwarding and not routing. In [15], the authors formulate the multi-source routing problem with cooperative communication and highlight the need for cooperative communication aware routing but do not consider varying the strategy (rate, range) or its relation with cluster size. Cooperative transmit diversity has also been considered in the context of broadcasting [5] and in other lower layer formulations such as [3]. Additionally, works on physical arrays [16], [6] have a fixed array size and different trade-offs than virtual arrays, whereas other forms of cooperative routing [17] do not consider concurrent transmitters.

IX. CONCLUSION

In this paper, we have described the design and evaluation of a routing protocol that leverages the presence of VMISO links in the network. We have highlighted the need for joint adaptation of cluster size and strategy of operation and studied the factors of VMISO links that affect network performance. We have proposed a routing algorithm that improves network throughput by leveraging VMISO links effectively, providing upto 300% improvement for reasonable node densities.

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