

Diversity Routing for Multi-hop Wireless Networks with Cooperative Transmissions

Sriram Lakshmanan and Raghupathy Sivakumar
Georgia Institute of Technology
Atlanta, GA, USA
{sriram,siva}@ece.gatech.edu
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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 cooperating 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

One of the dominant impairments of a wireless channel is fading, random fluctuations in signal level along the space and time dimensions. This space and time dependent signal fluctuation, also called diversity, can be exploited by the use of multiple transmissions/receptions distributed across time or space with appropriate encoding to enhance and stabilize the signal level at the receiver. The multiple and ideally independent views of the signal are called diversity branches and ensure that the link reliability or error rate performance at the receiver is improved since the probability of all of them being in a fade at the same time reduces sharply with the number of views. Specifically, for a given Signal to Noise Ratio (SNR), the error probability in an uncoded Rayleigh fading channel without diversity is proportional to SNR^{-1} whereas with k diversity branches, the error probability falls as SNR^{-k} [1]. 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. The separation required for the channels to be independent is of the order of $\frac{\lambda}{2}$ where λ is the wavelength of the carrier signal used. Depending on whether the communication system uses multiple transmit antennas with a single receive antenna, or a single transmit antenna with multiple receive antennas, or multiple transmit antennas with multiple

receive antennas, the system is respectively called a Multiple Input Single Output (MISO), or a Single Input Multiple Output (SIMO), or a Multiple Input Multiple Output (MIMO) system. This is contrast to a traditional Single Input Single Output (SISO) system. 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 power¹. In such systems, the cooperation gain directly leads to a smaller 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, simula-

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

tions 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. Section III provides the background on VMISO links while Section IV motivates the need for adaptive consideration of strategy and cluster size. Section V discusses the algorithm design, while Section VI describes the realization of the routing protocol. Section VII presents the performance evaluation. Sections IX-X discuss related work, issues and conclusions.

II. SCOPE AND CONTRIBUTIONS

While cooperative transmissions can be used to realize VMISO or VMIMO communications, the focus of this paper is on VMISO communication. First, although VMISO allows improved data rates, the coordination overhead and complexity of channel state information and 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 distances². 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

The wireless channel is impaired by random fluctuations in signal level across space, time and frequency dimensions known as fading. This space and time dependent signal fluctuation (also called diversity) can be exploited by the use of multiple transmissions/receptions distributed across time or space with appropriate encoding to enhance and stabilize the signal level at the receiver. Such a paradigm is called space-time communication in which appropriately encoded symbols are transmitted/received at different points in space and time. The multiple (ideally independent) views (also called diversity branches) of the signal ensure that the link reliability or error rate performance at the receiver is improved since the probability of all of them being in a fade at the same time reduces sharply with the number of views. Specifically, for a given Signal to Noise Ratio (SNR), the error probability in an uncoded Rayleigh fading channel without diversity is proportional to SNR^{-1} whereas with N diversity branches, the error probability falls as SNR^{-N} .

Benefits: When spatially separated transmitters transmit encoded symbols across space and time, . In a SISO link, a single transmitter sends l symbols in lT_s whereas on a V-MISO link, there are n_c transmitters that transmit l complex symbols $\pm s_i, \pm s_i^*$ over kT_s seconds. Here, s_i^* is the complex conjugate of symbol s_i and $l \leq k$. This approach can provide large diversity gains, when the symbols are transmitted with a certain structure, namely the STBC.³ 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. The bandwidth utilization of an STBC is determined by its rate $R = \frac{l}{k}$. It is not possible to achieve full rate and full diversity with STBCs for all n_c and there is a rate penalty. For instance for $n_c = 2$, $R = 1$ but for $n_c = 3, 4$, the best code has $R = 3/4$. We factor this effect in our work by considering the best rate codes available for each n_c [1]. 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 BER of 10^{-3} , the E_b/N_o required for uncoded BPSK modulation is 25 dB [7] whereas with a V-MISO link, the required E_b/N_o is 10 dB (whereas 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

³STBCs are characterized by a $k * n_c$ matrix that specifies the structure as per which the symbols are transmitted by n_c antennas in each symbol duration T_s , where rows correspond to the time slot and columns correspond to the antenna element on which the symbol is transmitted.

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

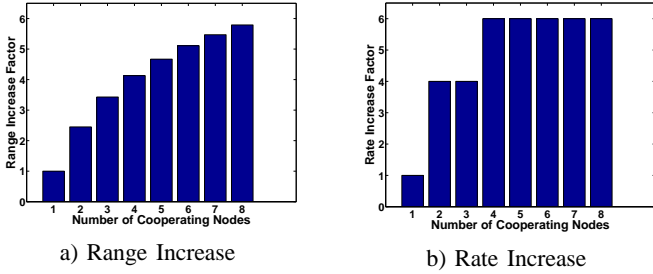


Fig. 1. Rate and Range improvements of a VMISO transmission

lesser than without diversity.⁴ For a specific target BER P_b , the reduced SNR requirement, can be translated into a longer transmission range for the same modulation rate or higher transmission rates by the use of higher order modulations for the same range or an intermediate rate, range pair. Consider BPSK modulation with diversity order n_c and a required bit error rate 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

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

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 transmission rates. 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) [1] is also considered. We consider the highest code rate for each n_c in this work). The values in the figure represent the *maximum* range or rate that can be obtained independently. Hence it is not possible to obtain the maximum rate and range simultaneously since the overall diversity gain is fixed for a fixed number of transmitters. However, several combinations of rate and range can be obtained depending on the way the diversity gain is used.

Since the cooperating transmitters are not co-located, the signals could be received at the receiver with different delays 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 [8],[9].

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

⁴In 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.

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 [10] with WLAN devices. All these works illustrate that cooperative transmissions are emerging close to practice. Although the basic scheme is shown to be feasible there are a few additional issues for implementation which we have identified and discussed in Section VIII.

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* (SINR) 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.

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 neighbour 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 neighbours. This is followed by the simultaneous transmission of encoded versions of the same message by the cooperating neighbours 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)Analysis: Let f be the number of flows each with an average hop length of h hops. If R is the (SISO) transmission range and R_i the corresponding interference range, the spatial reuse (number of simultaneously active links) in the network can be at most

$$SR = \frac{A}{\pi * R_i^2}$$

The total number of links that need to be scheduled to support the demand for all the f flows, is approximately $f * h$. In a manner similar to that in [11], the network throughput is then bounded as

$$T_{SISO} <= \frac{A}{\pi * R_i^2 * f * h} \quad (2)$$

We consider a VMISO transmission model where a local transmission is performed at rate D_L before each VMISO transmission. We represent the network throughput as T with

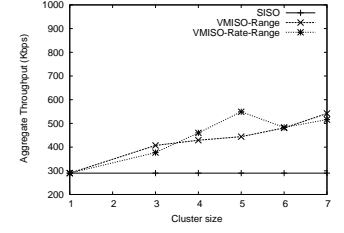
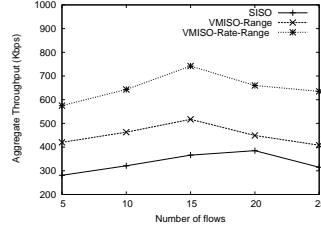
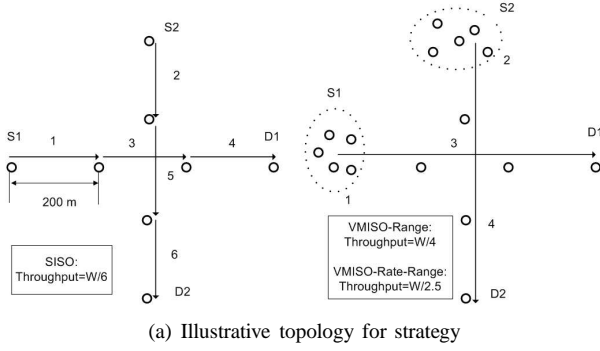


Fig. 3. VMISO benefits in arbitrary and random topologies

n_c : Cluster size
 n : Number of nodes in the network
 A : Area of the network
 d : Average (SISO) node degree
 NT : Network throughput
 P_b : Bit Error Rate
 m : Modulation index
 $R_f(n_c, m)$: Range extension factor for n_c and m
 f : Number of fbws
 h : Average hop length of a fbw
 D_L : Data rate of local transmission
 $D(n_c)$: Data rate when using cluster size n_c for rate increase,
 α : Path loss exponent,
 $SNR_T(m)$: SNR Threshold for modulation m ,
 R : SISO transmission range
 R_i : SISO Interference range

Fig. 2. Definition of variables

appropriate subscripts. We use n_c to represent the cluster size and consider only $n_c \leq d$. The default values of $P_b = 10^{-3}$ and BPSK modulation are used when quantifying benefits. The definition of variables used in this work is given in Figure 2. Thus, T_{SISO} represents 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. 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.

Using an analysis on the lines of [11], we obtain the order of benefits as:

i) Range Optimization:

When the cooperation gains are used for increasing range (RANGE strategy), the average hop length h is reduced by the factor $R_f(n_c)$. The increase in interference range is by the factor $n_c^{\frac{2}{\alpha}}$. Since each VMISO transmission is preceded by a

local transmission, the network throughput bound normalized to SISO can be given as

$$\frac{T_{RANGE}}{T_{SISO}} \leq \frac{R_f(n_c)}{1 + n_c^{\frac{2}{\alpha}}} \quad (3)$$

For our default values and the fact that the range extension is almost linear in n_c , the expression can be reduced to

$$\frac{T_{RANGE}}{T_{SISO}} = O(n_c^{\frac{1}{\alpha}}) \quad (4)$$

This indicates that a factor of $(\log(N))^{\frac{1}{2}}$ improvement in throughput is achievable with range in terms of the number of nodes in the network N .

ii)Rate Optimization:

Since there is no change in the average hop length with rate, and the local transmission is an additional overhead, the throughput with rate can (RATE strategy) be bounded as

$$\frac{T_{RATE}}{T_{SISO}} \leq \frac{\frac{1}{D(1)}}{\frac{1}{D(n_c)} + \frac{1}{D_L}} \quad (5)$$

$$\frac{T_{RATE}}{T_{SISO}} = O(1) \quad (6)$$

where $D(n_c)$ represents the maximum rate using the cooperation gain due to n_c nodes. This factor is less than one, when $D_L = D(1)$.

Thus using the cooperation gains of VMISO links purely for achieving higher data rates on the link does not improve the order of network throughput unlike in MISO or MIMO networks.

iii) Joint Range and Rate Optimization:

We develop a generic model for a VMISO throughput when using cluster size n_c and a link data rate. 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 under consideration. Also, we recall that

higher link rates are achieved using higher order modulations which can belong to different classes such as M-PSK or M-QAM. In general, identifying the rate improvements is non-trivial when different classes of modulations are used since the relation between error rate and SNR varies with different modulations. However, for several modulations of the same class such as BPSK, QPSK, etc. a single expression indexed by the order m can capture the error performance relation. Hence, we use a single class of digital modulations for the analysis. We use m to index the order of a class of modulations. 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 [7]. In general, identifying the rate improvements is non-trivial when different classes of modulations are used. Hence, we use a single class of digital modulations to still identify the key insights. 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 $m = 1$. 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 rate of the VMISO transmissions is now m times the SISO transmission rate, for a PSK constellation and higher (around 2^m) for QAM constellations. The corresponding change in the communication range depends on the SINR thresholds $SNR_T(m)$ and can be given as

$$R_f(n_c, m) = R_f(n_c, 1) * \left(\frac{SNR_T(1)}{SNR_T(m)} \right)^{\frac{1}{\alpha}} \quad (7)$$

which leads to

$$\frac{NT_{HYBRID}(n_c, m)}{NT_{SISO}} \leq \frac{m * R_f(n_c, 0) * \left(\frac{SNR_T(0)}{SNR_T(m)} \right)^{\frac{1}{\alpha}}}{m + n_c \frac{2}{\alpha}} \quad (8)$$

Simplifying further with the range extension being close to linear and $SNR_T(m) = 4^{m-1}$ for $m \geq 2$ (6dB per extra bit per symbol in [7]), the network throughput in this case (T_{HYBRID}) is related to the communication range, the cluster size n_c and modulation order m as

$$\frac{T_{HYBRID}(n_c, m)}{T_{SISO}} = \frac{R_f(n_c, m)}{1 + \frac{n_c \frac{2}{\alpha}}{m}} \quad (9)$$

We recall the final expression relating the order of throughput improvement to the modulation order m and the cluster size n_c as Simplifying further with the range extension being close to linear and $SNR_T(m) = 4^{m-1}$ for $m \geq 2$ (6dB per extra bit per symbol in [7]), we have

$$\frac{T_{HYBRID}(n_c, m)}{T_{SISO}} = O\left(\frac{m * n_c}{2^{\frac{m}{2}} * (m + n_c^{\frac{1}{2}})}\right) \quad (10)$$

Equation 10 (valid for $n_c \geq 2$) describes the dependence of network throughput on the cluster size and strategy using VMISO communication ⁵.

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

$$\frac{T_{RANGE}}{T_{SISO}} = O(\sqrt{n_c}), \text{ whereas } \frac{T_{RATE}}{T_{SISO}} = O\left(\frac{n_c}{m_{max}^2}\right)$$

Several critical observations follow from Equation 10. The main insights are:

- 1) Using adaptive rate and range yields almost a 2.2X improvement compared to SISO (for $n_c < 8$).
- 2) The benefits are higher when optimizing the rate and range than with the range alone.
- 3) The benefits are higher when the target BER P_b is lower (10^{-5} for instance).
- 4) The benefits are higher when the local transmission can be accomplished at a higher rate.
- 5) The results are a lower bound to the performance benefits achievable when the cluster size or strategy is varied at a finer granularity than on a network level.

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.

A. Illustrative examples

Figure 3(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). ⁶ Thus we observe that the

⁵Additionally, the effect of the code rate of the space time code can be obtained by replacing m in the equation with $m * CR(n_c)$. This leads to a modest decrease in VMISO benefits over SISO, but preserves rate-range benefits over range.

⁶In the above, when the bandwidth utilization of the space time code is also considered the achieved throughput change from $\frac{W}{6}$ with SISO to $\frac{W}{3.33}$ using range alone, to $\frac{W}{2.67}$ using rate and range.

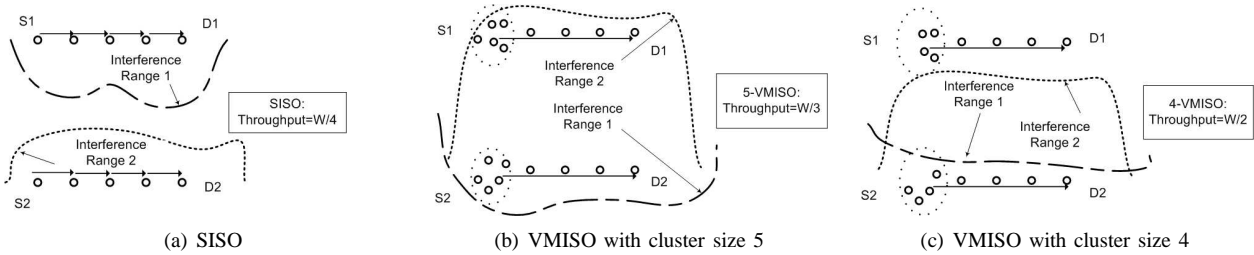


Fig. 4. Illustration for impact of cluster size

benefits over SISO increase from (1.5X) with maximum range to (2.4X) with adaptive rate-range. Next, we highlight the impact of cluster size through Figure IV where two flows are depicted. With SISO routing, each flow achieves a throughput of $\frac{W}{4}$. Consider the range strategy with a cluster size of 4 (Figure 4(c)), where three neighbors transmit along with the source node. Now, the total power at the receiver with a path loss exponent of 4 increases to $\sum_{i=1}^4 \frac{P}{d_i^4}$. Since the distance to the receiver is much higher than the distance between the transmitters, the increase in received power is approximately 4 times the average power with a single node transmission. This in turn translates to a $4^{\frac{1}{4}} = 1.41$ times increase in interference range compared to SISO. Consider that the flows are separated by 1.45 times the SISO interference range. Since the nodes are out of interference range, the throughput of each flow is now increased to $\frac{W}{2}$. However, when a cluster size of 5 is used (Figure 4(b)), the increase in interference range is approximately $5^{\frac{1}{4}} = 1.5^7$. This causes non-interfering nodes to become interfering leading to a throughput of $\frac{W}{3}$. Thus, we observe that the cluster size used affects throughput significantly and using all available neighbors for cooperation can degrade throughput (1.5X) compared to an intelligent choice of cluster size (2X).

B. 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 section 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 3(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,

⁷A more accurate calculation based on the SINR and different distances for a specific topology changes the absolute value of the distances but the effect of cooperation on interference still causes the observations to hold for each specific topology

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 3(c) shows that the optimal cluster size is not the same for all strategies and is not always the maximum cluster size.

C. 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.

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.

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 straightforward approach to using rate and range is to switch between the two strategies. However, as already seen in Section 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 section 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.

Additionally, the cluster size of a VMISO link must be less than the node degree in the vicinity of the source node and the SINR must be satisfied at the receiving end-point for the VMISO link to be feasible.

3) *Joint or Sequential - Ordering of decisions:* Given the sub-optimality of using rate or range optimization in isolation (described in Section IV), the next question to explore is whether the rate and range optimization must be performed in a joint manner or sequentially (i.e maximize either the rate or range and use the excess diversity gains for the other strategy). We show that such a sequential maximization approach is not sufficient to achieve benefits and highlight the need for joint maximization over achievable rate-range pairs using an illustrative topology in Figure 5.

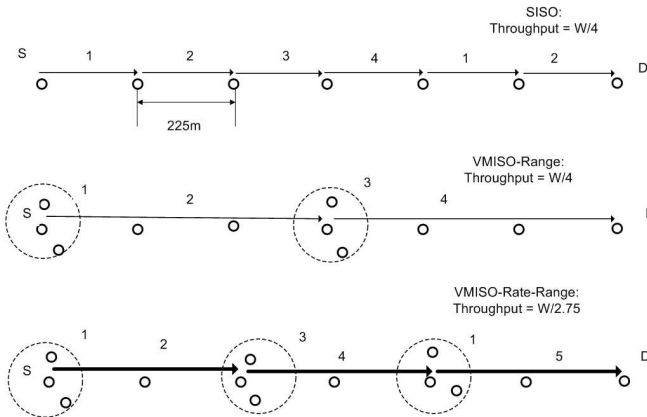


Fig. 5. Illustration for sub-optimality of simple rate adaptation with range

The figure represents a single flow with 6 hops. The slot schedule is also depicted on the links along with the throughput. For the flow shown, using SISO, with a transmission range of 250m, causes one in four hops to be inhibited with carrier sense protocols. A cluster size of 3 is available is available for cooperation. With this cluster size, the ranges for the basic rate, twice the rate and 4 times the basic rate are 3.43X, 2.88X, 1.88X respectively (using equation 7), with X the SISO range being 250m. Thus, SISO achieves a throughput of

$\frac{W}{4}$ and VMISO with maximum range achieves a throughput of $\frac{W}{4}$. This is because using the maximum possible range gives only 2.5dB of extra SNR over the threshold SNR for the basic rate. This is insufficient to increase the rate. On the other hand, for the VMISO-rate-range case, the VMISO link rates are 4 times higher than the SISO rate. Consequently, the number of VMISO hops is increased compared to VMISO range. Nevertheless, the overall throughput is now improved to $\frac{W}{2.75}$ since each of the slots 3,4,5 use 4 times the SISO data rate. The darker shading of links represents a higher rate. One can clearly see that simple rate adaptation with long-range links yields much lesser benefits than an intelligent choice of rate and range. Similarly simple range adaptation with high rate links, increases the number of hops without an increase in the throughput due to the overhead of local coordination.

B. Solution Description

When routes are computed in a network, the paths, the nodes and the links are of fundamental importance because they form the routes. Since the nature of the links is changed fundamentally when VMISO transmissions are used, the routing must be performed in a manner which takes into consideration, the nature of VMISO links. Hence the problem of utilizing VMISO links in a network can be formulated as a routing problem. Additionally, in our solution decision making is performed on a flow-level. Since we are interested in a distributed realization for the routing solution, we believe that it is justifiable choice given the reduction in complexity compared to link level decisions.

The proposed solution consists of two main components, namely the path metric and the path computation algorithm.

1) **Path Metric:** As discussed in the preceding paragraphs, the performance improvement is jointly decided by the strategy and cluster size. Thus a path metric which includes the considerations discussed above and that correctly quantifies the quality of a path, is needed. We describe the design of the path metric, by analyzing the fundamental relation between throughput, hop-length, cluster size and strategy. First consider a single flow. The metric for the end-to-end throughput of this flow for a path P_i , when using a cluster size n_c , a modulation order m , a basic rate W , a space time code of rate $CR(n_c)$ and packet size PS can be given as

$$M(P_i, n_c, m) = \frac{1}{\min(\frac{nhop(P_i)*S}{R(n_c, m)}, \frac{2*R_i(n_c)}{R(n_c, m)})} * \frac{CR(n_c)*2^{m-1}}{CR(n_c)*2^{m-1}+L(n_c)} * \frac{W}{PS}$$

Here $L(n_c)$ is an indicator variable that indicates whether a local broadcast is performed. $L(1) = 0$ and $L(n_c) = 1 \forall n_c > 1$. We have used the idea that the successive nodes on the SISO path are highly-likely separated by a distance S . Since W and PS are the same throughout the network, we will ignore them henceforth. Also, we use N to be the maximum cluster size whereas n_c represents the usable cluster size $n_c \leq N$.

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 MAX_P : Current highest metric path-id, $SNR(n)$: SNR of node n
- 6 m' : Current best modulation order, M : Highest modulation order
- 7 $M(P_j, n_c, m)$: Metric of path P_j with cluster size n_c and modulation order m ,
- 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 rate m and cluster size n_c

Compute-metric(P_j, n_c, m)

- INPUT: P_j, n_c, m, S
OUTPUT: $M(P_j, n_c, m)$
- 11 $F(P_j, n_c, m) = \max(I(n_c, n)) \forall n \in P_j(n_c, m)$
 - 12 If $n_c \geq \text{degree}(n) \forall n \in P_j(n_c, m)$ and $SNR(n) > SNR_{TH}(m)$
 - 13 $a1 = \max(F(P_j, n_c, m), \min(\frac{\text{nhop}(P_j) * S}{R(n_c, m)}, \frac{2 * R_i(n_c)}{R(n_c, m)}))$
 - 14 If $n_c > 1$
 - 15 $a2 = \frac{CR(n_c) * 2^{m-1}}{CR(n_c) * 2^{m-1} + 1}$
 - 16 Else
 - 17 $a2 = 1$
 - 18 return ($\frac{1}{a1 * a2}$)
 - Else
 - 18 return(0)

Compute-path-info (f)

- INPUT: Source, Destination pair of flow f
OUTPUT: l Paths P_j and $I(n_c, n) \forall n \in P_j, n_c \leq N$
- 19 For $j = 1$ to l
 - 20 $P_j = \text{Compute-SISO-shortest-path}(f)$
 - 21 For each $n \in P_j$
 - 22 For each $n_c \leq N$
 - 23 $I(n_c, n) = \text{Interference-load}(n, n_c)$

Execution Sequence

- 24 For every unassigned flow f
- 25 Compute-path-info (f)
- 26 For each path $P_j, j = 1$ to l
- 27 $MAX_M = 0, n'_c = 1, m' = 1$
- 28 For each $n_c = 1$ to N
- 29 For each $m = 1$ to M
- 30 $M(P_j, n_c, m) = \text{Compute-metric}(P_j, n_c, m)$
- 31 If $M(P_j, n_c, m) > MAX_M$
- 32 $M(P_j, n_c, m) = MAX_M, n'_c = n_c$
- 33 $m' = m, MAX_P = j$
- 34 $P(f) = P_{MAX_P}$

Fig. 6. Algorithm for Routing, Cluster size and Strategy assignment

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. Hence the values of (n'_c, m') of (n_c, m) that maximize $M(P_i, n_c, m)$ subject to the constraints is the best pair of cluster size and rate.

When multiple flows are considered, the interference and contention between links of the flow under consideration and links of other flows must be included. 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 . It is the nodes in this set to which the constraints of node degree, interference from other flows ;etc will apply. 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 form a VMISO link of n_c neighbors the maximum of the number of overheard links for its n_c neighbors would be the bottleneck and this link has to share the channel with the other links. Given this information, the bottleneck contention for this path can be obtained as the maximum of these values across all the nodes on $P_i(n_c, m)$. Since this is a function of n_c and m , one can determine the values n'_c and m' which have the minimum bottleneck contention.

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

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

Combining both expressions, the final throughput metric can be given as

$$M(P_i, k, m) = \frac{1}{\max(F(P_i, n_c, m), \min(\frac{\text{nhop}(P_i) * S}{R(n_c, m)}, \frac{2 * R_i(n_c)}{R(n_c, m)}))} * \frac{CR(n_c) * 2^{m-1}}{CR(n_c) * 2^{m-1} + L(n_c)}$$

Computing the values of P_i , n_c and m which maximize the metric, the best throughput performance is achieved.

2) **Algorithm:** The details of the algorithm are presented in the pseudo code shown in Figure 6. The algorithm first determines the SISO shortest path information along with the interference measure of each path as the maximum among the nodes in the path.(lines 16-21). The checking of feasibility is also performed here. Then it computes the path metric for each path for different values of n_c and m . The path, value of n_c and value of m with the highest metric is chosen as the solution (lines 25-32).

From Figure 6, one can observe how the algorithm takes into account the considerations identified in section V-A. Specifically, the functional relationship of the cluster size is included in the path metric along with the modulation order m which represents the strategy (lines 13 -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. The feasibility of a cluster size for a flow and the satisfiability of the SNR condition for the rate are both performed (line 12).

With multiple flows, the flow patterns determine the bottleneck interference experienced by each flow. Consequently, the determination for cluster size, strategy combination is performed for all the possibilities, since the dependence of network throughput on the strategy and cluster size cannot be isolated.

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. 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 6. 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 6 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.

However, the interference must be estimated. The source needs the number of other links that would be within carrier sense range of this node, to determine the contention level. While it is straightforward to identify the number of one-hop neighbors, computing the number of VMISO transmitters is non-trivial. Here the pilot tones are useful. The pilot tones being detectable over a larger range, allow more nodes to infer the presence of VMISO transmitters. The number of such distinct VMISO transmitters is identifiable from the address on the pilot tones. In this way, each node, constructs the interference profile. i.e the power pattern over time and maintains an average power estimate.

3) *Route failures and Maintenance*: While it is possible to design route maintenance approaches tailored to VMISO links, we use the default mechanisms for route failure detection and route recomputation. Thus, on a route failure a route recomputation is initiated and a new route is found.

In summary, the routing protocol is designed to exploit VMISO links in a distributed manner with MAC layer support described next.

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. We describe how they are obtained below.

Local transmission stage: The first stage of every VMISO transmission is the local transmission of data from a source to its neighbours. 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. The overhead of pilot tones is small since they are only few symbols in length [13]. Pilot tone collisions from the same cluster are avoided since the order of transmission of pilot tones is already decided and present in the local transmission packet. While pilot tones from different clusters can collide, the probability is very low, since the pilot tones would be

sensed by the carrier sense mechanism.

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 also support medium access with asymmetric links (e.g [14]) and must also support 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 modelling: 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 [7] based on the current receive SINR. We consider BPSK, QPSK, 16-QAM and 64-QAM as the modulation set. The signals from the different transmitters could arrive with slight relative time displacements. However, the composite VMISO signal obtained thus, is similar to a signal with multipath components. However, as observed in [10], the multipath effect does not affect the packet loss provided the delay spread is small or one of the signals is stronger than the others. Hence we include multipath induced Rayleigh fading to account for the nature of the VMISO channel.

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 CBR as the traffic generating application with UDP 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 VMISO link is the same as the corresponding SISO rate. The aggregate end-to-end throughput of all the flows is the main throughput metric. When cluster size used by nodes 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 simulate the effect of node mobility using the random waypoint model with the setdest utility in NS2. The mobility is varied between 0 m/s to 25 m/s. The usual pausetime used is for 20s. For each data point, we average the value over 10 seeds with a simulation time of 100s per seed.

B. Results

1) *Impact of Number of nodes:* Figures 7(a) and 7(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. The end-to-end throughput of SISO is not very high primarily due to the multi-hop burden of the flows which limits the number of links active within an interference range. Consequently, with increasing number of flows, the throughput reduces for all the mechanisms considered. 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 7(c) and 7(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. Similarly, when the

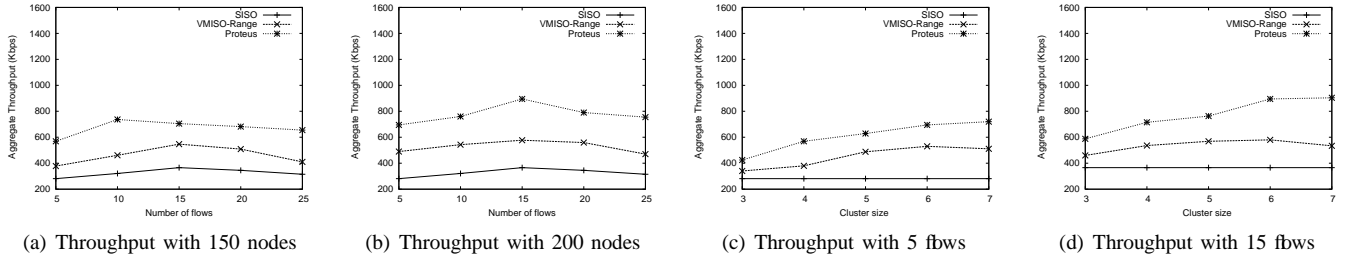


Fig. 7. Throughput vs Cluster size

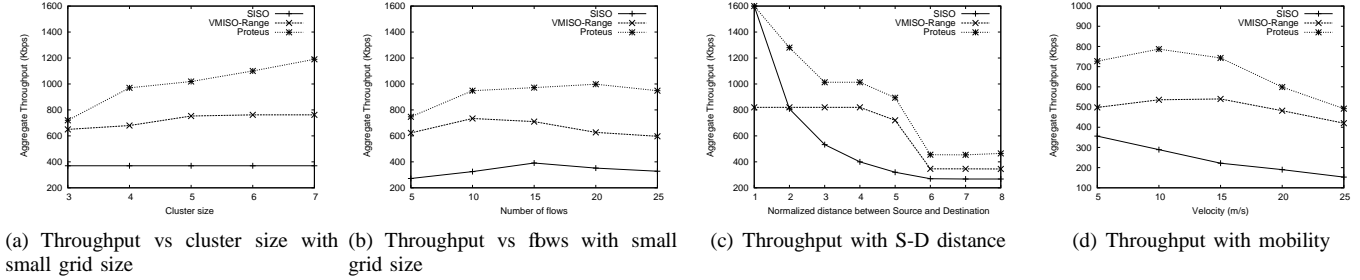


Fig. 8. Throughput with grid size and mobility

grid size is higher, the relative magnitudes of VMISO-range and the integrated algorithm is also reduced. The trends for the variation with number of flows is shown in Figure 8(b), which also indicate the higher throughputs with the proposed approach. The results for a larger grid size have already been discussed (Figures 7(c) and 7(b)).

4) *Impact of Mobility:* Figure 8(d) presents the aggregate throughput as a function of node mobility when the velocity of nodes is changed from 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 8(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.

VIII. DISCUSSION

Impact of Power Control: In the model considered in this paper, the nodes that cooperate do not adjust their power. This is motivated by related literature which discusses practical difficulties in achieving fine grained power control in wireless networks. However, the developed optimization framework and the algorithm can be used even when the nodes perform power control. In this case, the factor by which the nodes reduce the transmit power will determine the nature of the cooperation gains. When all the nodes reduce the transmit power equally so that the total power is equal to that transmitted in the SISO case, the interference range increases very slightly while providing an improved communication range. The improvement in communication range is much lesser than the improvement obtained with all nodes transmitting at the fixed (maximum) power. This factor can be incorporated into the routing protocol when determining the improvements with different cluster sizes and the strategies.

Practical Feasibility: Although the feasibility of a basic cooperative transmit diversity scheme was established in [10], we present additional practical challenges to be overcome to make Cooperative transmission routing feasible. First, the transmitting nodes must be able to perform Space-Time coding. Space time coding has the advantage that the signals transmitted by the different nodes are just different in sign (\pm) or related as complex conjugates (s, s'). Since digital modulators already embed these functionalities, with slight modifications in the symbols transmitted space time signalling can be achieved. The second important challenge is synchronization. The oscillators on the different nodes are separated in frequency and phase. These offsets affect the signal received at the receiver and must be overcome in order to realize cooperation gains. Third, since cooperative transmission involves more than one transmitter, the dynamic range of the signal is increased. This

poses stricter requirements on the Automatic Gain Control circuitry at the receivers. This must also be accounted for. *Granularity of cluster size assignment:* In this work, we have used assignments at a flow level. It is possible to perform a more fine-grained selection of cluster size and obtain more benefits.

Granularity of strategy choice: For the strategy choice too, we have stipulated that a single strategy be used, so that benefits can be obtained while keeping the problem tractable. As we have observed the optimal strategy choice cannot be based on a single global statistic, but needs a more careful consideration of flow patterns. In that case, the exact position of a VMISO link on the path would also affect the throughput.

Handling Link asymmetry: In this work, we have avoided the link asymmetry problem by the use of an idealized Medium Access Control scheme. Although there exist MAC protocols to handle link asymmetry [14], designing a Medium Access Control protocol to accommodate VMISO transmissions with different cluster sizes is an interesting problem for future work.

Coded Modulation: Forward Error Correction is typically performed to handle the impairments of the channel such as fading. Fundamentally, diversity gain alters the slope of the error rate curve vs SNR whereas the use of error control codes provides a horizontal shift of the curves. Further, the coding gain is typically constant at a high enough SNR unlike the diversity gain [1]. Hence we have considered uncoded and space time coded systems (with diversity gains). When Forward error correction is used, the diversity gains change depending on the coding gain. More investigation is needed to understand the benefits when space-time codes are used in conjunction with forward-error correction codes.

Receiver of VMISO link Another feature of VMISO links, is the choice of the receiver for the VMISO link. For a given range, there are multiple nodes that could serve as potential 'end-points' of the VMISO link. The choice of the node is important because the interference and contention existing across a destination cluster could be vastly different. Hence for a given range, choosing a node within a destination cluster, that has lesser cumulative interference could allow improved performance.

IX. RELATED WORK

The works most relevant to the present work are [4], [2], [10], [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 [10] presents a forwarding protocol that uses transmit diversity to improve the reliability of Acknowledgement 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 diversity gains and tradeoffs than virtual arrays making them different from the problem considered in the present work.

X. CONCLUSION

In this paper, we have described the design and evaluation of a routing protocol that leverages the presence of V-MISO 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 practically reasonable node densities.

REFERENCES

- [1] A. Paulraj, R. Nabar, and D. Gore, "Introduction to space-time wireless communications," *Cambridge University Press*, May 2003.
- [2] S. Barbarosa and G. Scutari, "Distributed space-time coding for multihop networks," in *IEEE ICC*, 2004.
- [3] J. N. Laneman and G. W. Wornell, "Distributed space-time coded protocols for exploiting cooperative diversity in wireless networks," *IEEE Transactions on Information Theory*, pp. 2415–2525, 2003.
- [4] G. Jakllari and et al, "A cross layer framework for exploiting virtual miso links in mobile ad hoc networks," *IEEE Transactions on Mobile Computing*, 2007.
- [5] —, "Cooperative diversity in wireless networks: efficient protocols and outage behaviour," *IEEE Journal On Selected Areas in Communication*, 2007.
- [6] K. Sundaresan and R. Sivakumar, "Routing in ad-hoc networks with mimo links," in *IEEE ICNP*, 2005.
- [7] J. Proakis and M. Salehi, *Digital Communications*. McGraw-Hill Science/Engineering/Math, 2007.
- [8] G. Barriac, R. Mudumbai, and U. Madhow, "Distributed beamforming for information transfer in sensor networks," in *IEEE IPSN*, 2004.
- [9] D. R. B. III, G. B. Prince, and J. A. McNeill, "A method for carrier frequency and phase synchronization of two autonomous cooperative transmitters," in *IEEE SPAWC*, 2005.
- [10] M. Kurth and et al, "Cooperative opportunistic routing using transmit diversity in wireless mesh networks," in *IEEE INFOCOM*, 2008.
- [11] P. Gupta and P. R. Kumar, "The capacity of wireless networks," *IEEE Transactions on information theory*, vol. 46, no. 2, pp. 388–404, Mar. 2000.
- [12] D. Johnson, D. Maltz, and J. Broch, *DSR : The Dynamic Source Routing Protocol for Multihop Wireless Ad Hoc Networks*. Addison-Wesley, 2001, ch. 5, pp. 139–172.
- [13] B. Daneshrad and B. Hochwald, "How much training is needed in multiple antenna wireless links?" *IEEE Transactions on Information Theory*, pp. 951–963, 2003.
- [14] G. Wang and et al, "A mac layer protocol for wireless networks with asymmetric links," *Elsevier Adhoc Networks Journal*, pp. 424–440, 2008.
- [15] J. Zhang and Q. Zhang, "Cooperative routing in multi-source multi-destination multi-hop wireless networks," in *IEEE INFOCOM*, 2008, pp. 2369–2377.
- [16] E. Gelal, G. Jakllari, and S. Krishnamurthy, "Exploiting diversity gain in mimo equipped ad hoc networks," in *Asilomar Conference on Signals, Systems and Computers*, 2006.