

Multi-layer Cooperative Transmission Protocol with VMISO and Power Control in Ad Hoc Networks

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Abstract—We present a multi-layer protocol based on power control and virtual Multi-Input Single-Output (VMISO). Specifically, we discuss the influence of rate, cluster size, and transmission range of the VMISO link on the whole performance improvements, where the key physical layer property that we focus on is an enlarged transmission range due to cooperative diversity. Further, the new protocol, termed the Joint Multi-layer Cooperative Transmission Protocol (JMCTP) including the VMISO routing protocol and the novel MAC protocol, proposes the distributed approach of using VMISO links with a fixed cluster size, a given rate, and a certain transmission range, where we leverage the translation of physical layer advantages into higher layer better performances. Moreover, power control is applied to the MAC and routing layer, which increases the robustness to mobility and interference-induced link failures. Finally, we evaluate JMCTP with a flat Rayleigh fading channel model that accurately captures the nature of VMISO transmissions. As compared to using only SISO links and other VMISO links, our work achieves a great increase in the end-to-end throughput and a sharp decline in the end-to-end delay.

Keywords—Cooperative transmission, Diversity gain, Virtual Multi-input Single-output (VMISO), Power Control

I. INTRODUCTION

Cooperative diversity [1]-[3] facilitates space-time communication by using virtual antenna arrays coupled with appropriate space-time codes to improve signal quality, thus significantly enhancing the performance of wireless networks. Specifically, a node with single antenna can utilize other nodes nearby as relays to form virtual antenna arrays to attain diversity gain. Further, based on the number of neighbours cooperating at the transmitting and receiving ends of a link, a virtual MISO (VMISO), virtual SIMO (VSIMO), or, virtual MIMO (VMIMO) link can be built. Additionally, VMISO requires the lowest efforts of cooperation at the transmitter while the other two virtual links need great amount of decoding information at the receiver [10].

Depending on a VMISO link, multiple cooperating nodes simultaneously transmit encoded versions of the same signal so as to get a better decoding performance at the receiver

compared to the traditional Single Input Single Output (SISO) system. That is, the diversity gain directly contributes to a smaller Signal-to-Noise Ratio (SNR) requirement, which in turn can be translated into a large transmission range or a high data rate under certain conditions, thereby improving communication performance in the wireless channel.

Most research in this area is to optimize physical layer performance such as [4]-[7], without considering in much detail how cooperation interacts with higher layers. However, it is increasingly important to investigate cooperative transmission on the higher layers and improve the whole network performance. A novel cross-layer approach is discussed in [8], where VMISO links are built from the source to the destination and vice versa. While bidirectional VMISO links bring better performances, link complexity is worth thinking. In [9], cooperative transmit diversity (also VMISO) is investigated in the context of broadcasting with a novel distributed network-wide broadcasting protocol. In [10], a diversity routing protocol is presented for multi-hop wireless networks with cooperative transmissions, which considers how the physical layer VMISO advantages translate into network level performance improvements by the integrative analysis of rate, cluster size, and transmission range.

In this paper, we propose a cross-layer protocol named the Joint Multi-layer Cooperative Transmission Protocol (JMCTP) including the VMISO routing and novel MAC protocol, where our work mainly focuses on the increased transmission range to improve MAC and routing layer functions due to cooperative diversity. Further, we improve the JMCTP to adapt to mobile ad hoc networks (MANETs) with modified MAC and routing protocol by using VMISO and power control. The advantages of JMCTP are as follows: 1) the protocol translates the physical layer VMISO benefits into higher layer better performances; 2) the design investigates the influence of rate, cluster size, and transmission range of the VMISO link on the whole performance improvements; 3) our protocol increases the robustness to mobility and interference-induced link failures by using power control; 4) our work achieves a great increase in the throughput and a sharp decline in the delay compared to using only SISO links and other VMISO links.

II. SYSTEM MODEL

As shown in Figure 1, we consider the scenario where one source node A transmits messages to the final destination J in a wireless ad hoc network with other nodes randomly deployed within a specified region. Each node is equipped with an omni-directional antenna, which helps to communicate and cooperate with each other. In this paper, we assume that each node knows the information of 1st hop neighbours. For the flexible implementation of our protocol, we further assume that each node can choose its transmitting power level.

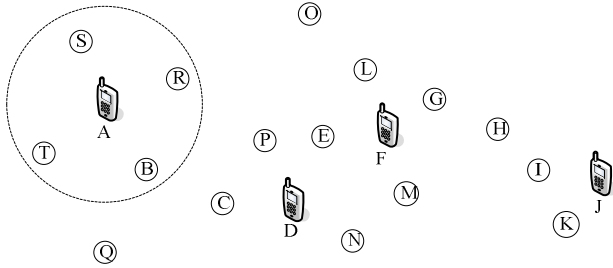


Figure 1. A scenario of the cooperative transmission in ad hoc network.

Specifically, message transmission is implemented via VMISO links. Details about VMISO and SISO links will be discussed in the following sections. Here, we just illuminate the foundation of a VMISO link. As presented in Figure 2, the source A transmits message to the destination D with B, R, S and T acting as cooperative nodes, thus a VMISO link is built. We can observe that VMISO increases transmission range and reduces SISO hops from A to D. VMISO enlarges transmission range by nodes cooperation while SISO can change transmission range by adjusting transmission power. Both will be used in our protocol.

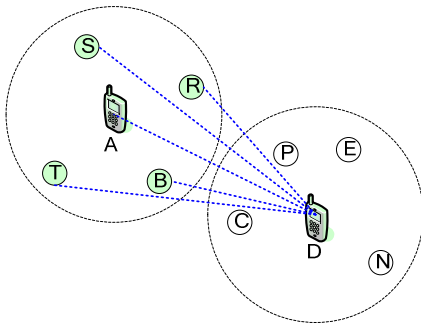


Figure 2. Cooperative transmission via a VMISO link.

A. SISO Transmission

1) **Transmission Power:** According to [15], in wireless networks, the transmit power at node i is proportional to $d(i,j)^\alpha$, and can be expressed as:

$$P_i = SNR_{TH} \times N_0 \times C \times d(i,j)^\alpha \quad (1)$$

Where SNR_{TH} denotes the SNR threshold for correct reception, N_0 refers to the power spectral density of white noise, $d(i,j)$ is the distance between node i and node j , α is the path loss exponent for free space propagation, and C is a constant that includes all other propagation effects such as antenna gains and carrier wavelength.

2) **Transmission Power vs. Transmission Range:** We assume that the node can receive the message correctly only if the SNR of receiving signal is above SNR_{TH} . According to (1), the relation between transmission range and transmit power is given in Table 1, which will be used in our modified MAC and routing protocol.

Table 1. Transmission Range vs. Transmission Power

Transmission range $d(i,j)$	Transmission power P_i
d	P
$2d$	$2^\alpha P$
$3d$	$3^\alpha P$
$4d$	$4^\alpha P$

B. VMISO Transmission

1) **VMISO Advantages:** When space-time encoded symbols are transmitted by spatially separated senders, the receiver with knowledge of the channel state information (CSI) can recover the symbols with much lesser bit error rate (BER) than otherwise, so transmit diversity with a VMISO link brings about a smaller SNR requirement. As for a target BER of 10^{-3} , the E_b/N_0 required for a SISO link is 25dB [11]-[13], whereas with a VMISO link, the E_b/N_0 is 10dB. Thus, for a target BER, the reduced SNR requirement because of cooperative diversity 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 [10].

2) **Enlarged Transmission Range:** For a specific cluster size N and modulation rate, the transmission range is uniquely determined by the transmit power of each node. As discussed in Section 2 of [8], the impact of the transmit Power on range and interference divides into two possibilities: (a) each of the N cooperating nodes may transmit with the SISO power P and (b) each may transmit with power P/N . In the former case, an increase of transmission range is almost four times of that with SISO due to increased power and the diversity gain, whereas an increase of interference range is less than two times of that with SISO due to increased power. Thus, the transmission range is significantly enhanced with only a slight increase in the interference range. In the latter case, diversity gain contributes to increased transmission range; however, the interference range is almost unchanged thanks to total transmit power equal to SISO power P .

3) **VMISO Feasibility:** Many works have recently observed the feasibility of VMISO. Specifically, Reference [8] demonstrates that in most cases the relative delay between signals from the cooperating transmitters is fairly small (less than 0.6 μ s) compared with the symbol duration in 802.11

standard and in all cases the physical layer approaches are able to handle lack of synchronization. Also, Reference [8] observes that in more than 85%-90% of the cases, the relative power difference between any two nodes is at most 5dB. Reference [14] indicates that the diversity gain is only dependent on the number of cooperating transmitters and not on the physical location of these transmitters as long as they are all within the SISO transmission range. Consequently, cooperative transmissions are feasible in practice.

III. DISTRIBUTED APPROACH

In this section, we introduce the JMCTP of the VMISO routing and novel MAC protocol, and the modified MAC and routing protocol to investigate how VMISO advantages are translated into higher layer better performances. Specifically, the modified protocol increases the robustness to mobility and interference-induced link failures by using power control, especially adapting to MANET. Moreover, in our novel MAC protocol, the forward communication consists of VMISO link realizing efficient transmission of large amount of data; however, the reverse communication adopts SISO links directly due to small amount of simple signal transmission, not building the reverse VMISO link. Further, our routing protocol facilitates MAC layer design with flexible implementation and lower complexity by means of VMISO and SISO links based on former Dynamic Source Routing protocol (DSR).

A. VMISO Routing Protocol

1) Primary Path: As described in Figure 3, the primary path is A, B, C, D, E, F, G, H, I, J. We select DSR to compute the primary path. Suppose that the nodes on the path have a chosen path identifier connected with the path. Additionally, from its routing table, each node knows its relative position on the path or the distance of SISO hops from the source of the path.

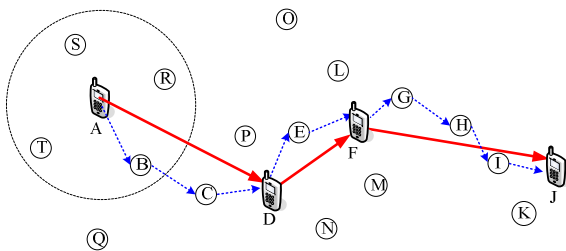


Figure 3. VMISO links are shown with solid arrows; SISO links are depicted by dotted arrows.

2) Diversity Routing: As shown in Figure 3, the new path comprised of the VMISO links is A, D, F and J. Similar to [8], the selection of the relay node is realized via VMISO anycast of the M-RTS message to the nodes on the primary path, and only is the M-RTS message anycast during the first packet transmission. As discussed in section □, VMISO increases transmission range four times as SISO does when

the diversity gain is used for range extension (with five cooperating transmitters). It means that a VMISO link can run across 4 SISO hops under certain conditions. In view of this, only one in four consecutive nodes may act as the relay node from the source of the anycast in our routing protocol (the relay node must have at least four neighbours within one SISO hop). Specifically, in a VMISO link, the maximum value of SISO hops equals 4, the minimum value is 1, and any value of SISO hops may be j (where $1 \leq j \leq 4$). Further, in order to avoid multiple responses to an M-RTS message, each candidate relay node uses a back-off timer, whose time-out is set to $(4-j) \times SIFS$ seconds. Once the next relay node is identified, it performs a similar anycast to identify the next relay until the final destination is reached.

B. Novel MAC Protocol

1) Finding Collaborating Nodes: As presented in Figure 4, the sender first multicasts a local RTS to select collaborating nodes and the chosen collaborating nodes then send pilot tones, respectively and sequentially (readers are referred to [8] for details). The source can not only hear the successful pilot tones but also can hear an unexpected tone. When detecting failure, it backs off. In other words, the forward VMISO transmissions are allowed only if a fixed number of collaborating nodes is available. In our design, the number is fixed at 4 and, thus, the total number of cooperating transmitters is 5, which ensures the same sensing range of all VMISO links.

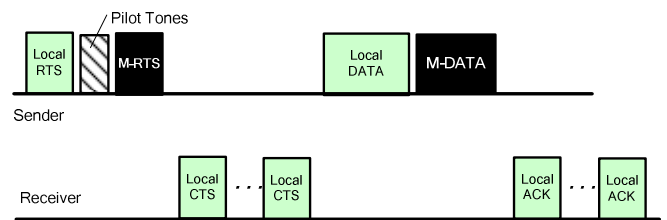


Figure 4. The sequence of packet transmissions on a VMISO link.

2) Forward VMISO and Reverse SISO: After the reliable transmission of the pilot tones, the collaborating nodes would jointly transmit an M-RTS message. As discussed in the VMISO routing protocol, we first select a relay node on the primary path as the receiver via VMISO anycast of the M-RTS message before the sender intends to perform the first packet transmission. When the relay node (or the receiver) is available, the forward VMISO link is founded. In response to the M-RTS, the receiver transmits the Local CTS message via reverse SISO links to the source. The Local CTS message would be sensed by the other competing candidate relay nodes and they would abort their scheduled Local CTS transmissions. Moreover, the hop count experienced by the Local CTS is j (where $1 \leq j \leq 4$) in accordance with the SISO hops of the relay node from the sender. Additionally, there is a standard time-out prior to the transmission of Local CTS and we suppose that the corresponding SISO links remain unchanged during the transmission of Local CTS. The same to Local ACK.

3) **Data Transmission and ACK:** After successful M-RTS and Local CTS, data transmission is performed by forward VMISO link and Local ACK message is transmitted by reverse SISO links. Whether the pilot tones are transmitted or not depends on the varying speed of the channel. When the channel is slow fading, data can be directly transmitted via established forward virtual MISO link without inserting pilot tones before M-DATA transmission. In a nutshell, M-RTS and M-DATA are transmitted by a VMISO link, leaving Local CTS and Local ACK for SISO transmissions different from the bidirectional MAC with VMISO in [8].

C. Modified MAC and Routing Protocol

1) **Modified MAC Protocol:** In MANET, due to the mobility of nodes and the interference induced links failures, the receiver transmits single Local CTS message directly to the sender with increased power, instead of going through several SISO links on the primary path, as shown in Figure 5. The power may be $P, 2^\alpha P, 3^\alpha P, 4^\alpha P$, respectively, according to the position of the receiver. Furthermore, Local CTS and Local ACK are short in comparison with the broadcast message so that the energy used to transmit them is negligible.

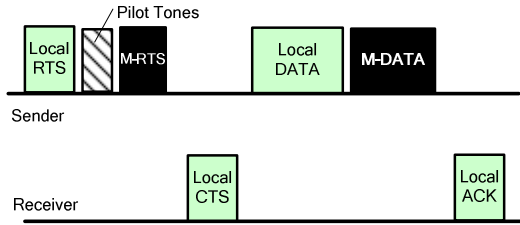


Figure 5. The sequence of packet transmissions with VMISO and power control.

2) **Modified Routing Protocol:** As assumed in section □, each node has an optional set of power and in most cases it only uses power P . However, when higher mobility and frequent link failures occur, candidate relay nodes will resort to the increased power. As shown in Figure 6, taking node 3 as an example, if node 3 becomes the relay node, it will transmit Local CTS and Local ACK with the power of $3^\alpha P$ (where $\alpha=2$) after a successful M-RTS and M-DATA, respectively.

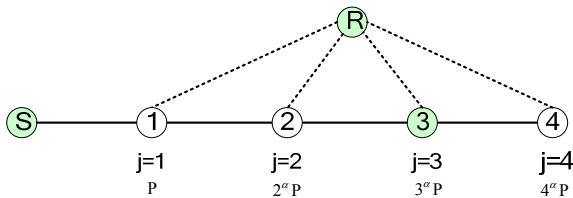


Figure 6. The selection of relay node with VMISO and power control.

3) **Robustness to Mobility and Link Failures:** VMISO anycast and power control allow for dynamic route recovery if any of the VMISO links fail to work. When link failure occurs, due to mobility and interference effects, the sender

would first resort to a VMISO anycast to find an alternative relay node after a protocol-specified number of unicast retries (four attempts). Interestingly, we do not rebuild the primary path, but only discover a new relay node irrespective of some of the nodes on the primary path maybe moving out of range. This process sharply decreases the number of new route discovery broadcasts compared to traditional on-demand routing schemes. Therefore, the use of VMISO anycast and power control significantly reduces the dependence of nodes upon the primary path and also provides an inherent robustness to mobility and interfere-induced link failures.

IV. PERFORMANCE ANALYSES

In this section, we evaluate the performances of JMCTP with a flat Rayleigh fading channel model that accurately captures the nature of VMISO transmissions. Especially, we set network parameters and do extensive analyses in terms of throughput and delay.

A. Simulation Settings

1) **Channel Model:** Flat Rayleigh fading is used with a path loss exponent of 4 (where $\alpha=2$ in the modified protocol). Suppose that all nodes work at 2.4-GHz band and the channel keeps unchanged during the packet transmission. Further, the SNR_{TH} is set to 25dB with a fixed data rate of 2Mbps, and the diversity gain D is set to 15 dB with five cooperating nodes. Then the preset threshold SNR now equals $(SNR_{TH} - D)$.

2) **Network Parameters:** Specifically, we consider a grid of 9 units by 9 units, each of which is 250m in length and breadth corresponding to the SISO transmission range for the basic rate. We deploy 200 nodes randomly in this area. Further, we use a CBR traffic source with a packet size of 512 bytes. The random waypoint model is used and the velocity is chosen randomly between 1 and 19 m/s with a pause time of 20s. For the MAC, we exploit 802.11 because it can support VMISO links by using a proper approach. The default routing uses DSR. For each VMISO link, the local transmission rate is equal to the corresponding SISO rate. Additionally, the end-to-end delay and throughput are the key metrics in our simulation.

3) **Time-out settings and Comparison:** According to [8], the time for pilot tone transmissions is totally set to $32\mu s$. When an anycast is invoked, the time-out preset is $4 \times SIFS$ seconds to account for all of the possible back-offs before an anycast response. Further, compared to the time-out in [8], for example, after the M-RTS is transmitted, the time-out for completely receiving the M-CTS is the value of the standard time-out for a Local CTS plus 1) the transmission time for a local CTS, 2) the time taken for the pilot tone transmissions, and 3) the transmission time for a M-CTS. Compared with our novel MAC protocol in section □, the value of the time-out for entirely receiving the Local CTS is j times of the sum of the standard time-out and the transmission time for the Local CTS. However, compared with our modified MAC protocol, the value of the time-out is sharply reduced with only the standard time-out plus the transmission time for a Local CTS.

B. Results

1) Simple Chain Topology Experiments: As discussed above, VMISO increases transmission range four times as SISO does. Thus, node S in Figure 7 can directly transmit packets to the destination at a basic rate of 2Mbps. There exist two transmissions: VMISO and SISO denoted by solid and dotted arrows respectively. As for VMISO transmission, our work is different from [8]. In [8], bidirectional VMISO links will be built before transmission while in our work just forward VMISO link is needed with reverse SISO transmission. Based on a 512-byte payload with a 20-byte RTS packet, a 16-byte CTS packet, and a 16-byte ACK packet, the end-to-end throughput is given as follows:

Only SISO transmission

$$\frac{512}{512+20+16+16} \times 2 \times \frac{1}{4} = 0.45 \text{ Mbps} \quad (2)$$

VMISO transmission in our work

$$\frac{512}{2 \times 512 + 2 \times 20 + 16 \times 4 \times 2} \times 2 = 0.86 \text{ Mbps} \quad (3)$$

VMISO transmission in [8]

$$\frac{512}{2 \times 512 + 2 \times 20 + 2 \times 16 + 2 \times 16} \times 2 = 0.9 \text{ Mbps} \quad (4)$$

VMISO transmission in our modified protocol

$$\frac{512}{2 \times 512 + 2 \times 20 + 16 + 16} \times 2 = 0.93 \text{ Mbps} \quad (5)$$

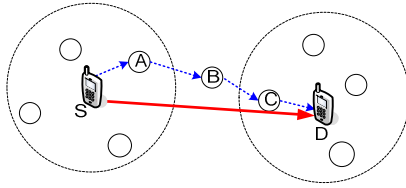


Figure 7. A simple chain with and without cooperation.

Thus, with VMISO links, S can transmit data at a rate which is twice of that possible with SISO, and our protocol can theoretically be on a par with or superior to bidirectional VMISO transmission in [8].

2) Node Density vs. Throughput: By analysis, when the average node degree is less than 5, the performance of our protocol reduces to that of SISO. However, as the node density increases, the throughput increases significantly for more nodes take part in the formation of VMISO links. Nevertheless, when the node degree arrives at a certain density threshold, the throughput does not increase any more because of the required number of neighbours available.

3) Comparison with other VMISO/SISO Transmissions: With appropriate node density, VMISO links are fully built, and our protocol can be on a par with bidirectional MAC in [8] when there is a proper or small quantity of data transmission. However, when a great amount of data

transmission, our protocol can be secondary to bidirectional MAC because of the trade-off between the complexity of forward VMISO link and the flexibility of the reverse SISO links. Further, as the node density reduces, our protocol is gradually superior to bidirectional MAC due to no need of building the reverse VMISO link. Especially in MANET, our modified protocol has more advantages over bidirectional MAC in [8] due to the presence of power control. Also, our protocol has more advantages over that with only SISO links because of enlarged transmission range with VMISO links. Therefore, throughput and delay are significantly improved.

V. CONCLUSIONS

In the existing literatures on cooperative diversity, there are few works translating the physical layer benefits into higher layer performance improvements. In this paper, JMCTP which includes the VMISO Routing Protocol and the Novel MAC Protocol is proposed by leveraging the presence of VMISO links in the MAC and routing layer. Further, the modified MAC and routing protocol increases the robustness to mobility and interference-induced link failures. There theoretical analyses show our work achieves a great increase in the end-to-end throughput and a sharp decline in the end-to-end delay.

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