Multi-Hop Cooperative MIMO Transmission in Wireless Sensor Networks

M. Baskar, T. Rajendran, K. Ravishankar, D. Rajeswari

Abstract: ***This article presents a multihop spatial multiplexing cooperative MIMO (SM-CMIMO) transmission scheme. The SM-CMIMO scheme employs a novel configuration on MIMO system which works in a cooperative manner, to achieve a least energy consuming path, with reduced rate of bit error and higher data rate. In this approach, list of relay nodes located in equal distance at any route towards destination selected. The source selects a set of relay nodes and cooperative nodes to frame a cooperative MIMO System. The cooperative nodes are selected using NSA (Node Selection Algorithm) with no channel state, bit error rate and data rate constraints. Each hop is evaluated for suitable replacement with V-MIMO configurations. To reduce the depletion of energy at MIMO cooperative network, at the middle of these hops, relay nodes are selected and evaluated for possible replacement of long-hop with two smaller MIMO transmission hops. We show that proposed SM-CMIMO transmission offers significant energy efficiency improvement compared with SISO transmission. The performance of the system degrades indirectly with the channel correlation.***

Index Terms—Cooperative Multiple Input Multiple Output (MIMO), Energy, Fading, Bit Error Rate (BER), Wireless Sensor Network (WSN).

I. INTRODUCTION

The increased usage of wireless technology has increased the requirement of multiple input and multiple output (MIMO) systems to support the growing data rate requirements. The authors of [1] have shown the ability of MIMO technique to increase the energy efficiency over SISO systems. The MIMO communication system comes with multiple transmitter and receivers with multiple antennas. They have dedicated properties like antenna angle and height. The performance of the MIMO antenna depends on the angle of radio and the height where it is located. This supports the higher data rate and the link capacity also gets increased due to the huge number of antennas. The gain has been increased by the number of antennas and all of them can be used to transmit the signals at the same time. However, it becomes impractical to deploy MIMO technology to WSN nodes of small physical size, since small-sized nodes can be fitted with only one antenna. In WSNs the nodes are often powered by batteries of low capacity and limited lifetime. Also, replacement or recharging of these nodes is often impractical or difficult for certain cases. However, authors have shown that, more than one nodes with single antenna can be joined to form a virtual multi-antenna node (cooperative MIMO)[2]. In large-scale wireless adhoc /sensor networks, with low signal amplification capability sensor nodes; where both source and destination are not located within the range of other. The communication between them will be by means of multihop transmission. However, the lifetime of the network can be improved by increasing the energy efficiency. As mentioned in [3,4], few of the applications of the WSNs being used are: environment, health monitoring and infrastructure facilities. In [5], the authors presented a comparative study on the energy utilization produced by different designs of MIMO antenna systems like of virtual single input multiple output(V-SIMO), virtual multiple-input-single-output (V-MISO), and virtual multiple-input-multi-output (V-MISO), V-MIMO for single hop transmission. Recent research work has shown that, to enhance energy efficiency over SISO systems, cooperative MISO are implemented in wireless multihop adhoc networks by exploiting the spatial diversity [5,6]. To improve the energy efficiency a tradeoff algorithm virtual multiple input multiple output system is presented in [7]. Similarly in [8], energy based cooperative system named V-MISO has been presented. In [9], the same has been configured with multihop nodes and in [10], a cluster based MIMO system has been presented which cluster the MIMO antennas according to the energy parameter.. In [11], the author studied the radio reusability of V-MIMO system and an adaptive system is presented in [12]. In [13] a multi-hop V-MIMO communications using distributed space–time coding was investigated. In [14] a V-MIMO network that offers high end-to-end connectivity for multihop transmission, by constructing a minimum energy consuming route is proposed. In [15], to enhance energy efficiency in an adhoc network, the authors have discussed of employing cooperative MISO transmission for which the distance on hop and the number of cooperating nodes are optimized. In [6], Vertical-Bell Laboratories Layered Space-Time (VBLAST) technique has been utilized towards the overhead reduction incur on cooperative transmission exploited the multiplexing gain of VMIMO. In [16], the author defines a low rate DDoS attack detection algorithm which combines four different models. Each model works based on the traces of previous access. This needs huge amount of data to be transferred between the controlling devices to the source which manipulate the data to identify the low rate attack. Similarly in [17], the presence of network threat is detected in a region based approach, which uses the traces generated at

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specific region towards mitigation. This paper present a energy efficient SM-CMIMO algorithm to support node selection and multi hop transmission is presented. The remaining sections of this paper are organized as follows; Network system description and V-MIMO operations for multihop transmission are given in section II. Section III presents the energy consumption of the SM-CMIMO multi-hop scheme. The configuration and node selection algorithms are presented in section IV. The analysis results are presented in section V and conclusion has been presented in section VI. In Fig.1, a WSN with multihop transmission is presented where a node has dedicated antenna. Between the ***S*** and ***D***, inter-hop relay nodes are available to ensure transmission towards destination. In order to reduce the energy depletion, the MIMO node has been used which reduce the energy and improve the data rate. The transmission process using all V-MIMO configurations is explained in the following paragraph. In the first hop, the source node ***S*** splits the data packets into N (N is number of cooperative nodes for the hop) equal size smaller data packets and distributes these data packets to the cooperative nodes selected. The communication between a node and its neighboring nodes is referred to as local transmission stage. It is assumed that in IEEE 802.11, the synchronization is performed by beaconing. In next stage, referred to as long haul transmission stage, the ***S*** and its cooperative nodes CNs simultaneously transmit the data to the inter hop relay node ***R***1. The transmission scheme in the first hop is referred to as V-MISO transmission. In the second hop, ***R***1 sequentially distributes the data to the next inter-hop relay node ***R***2 and its CNs, which is a long haul communication. The N-1 CNs of ***R***2 quantizes their received signal samples (n_r bits per sample) and transmits these bits to its ***R***2 using M-QAM by TDMA. The transmission scheme in the second hop is referred to as V-SIMO transmission. Similar to the first hop, in the third hop, ***R***2 distributes packets to its CNs, sequentially. Then ***R***2 with its CNs simultaneously transmit the data to the destination node ***D*** and its CNs. The CNs(for all the hops, CNs are selected using NSA) of the ***D***, which transmit the bits to D using M-QAM by TDMA. The transmission scheme in this last hop is referred to as V-MIMO transmission.

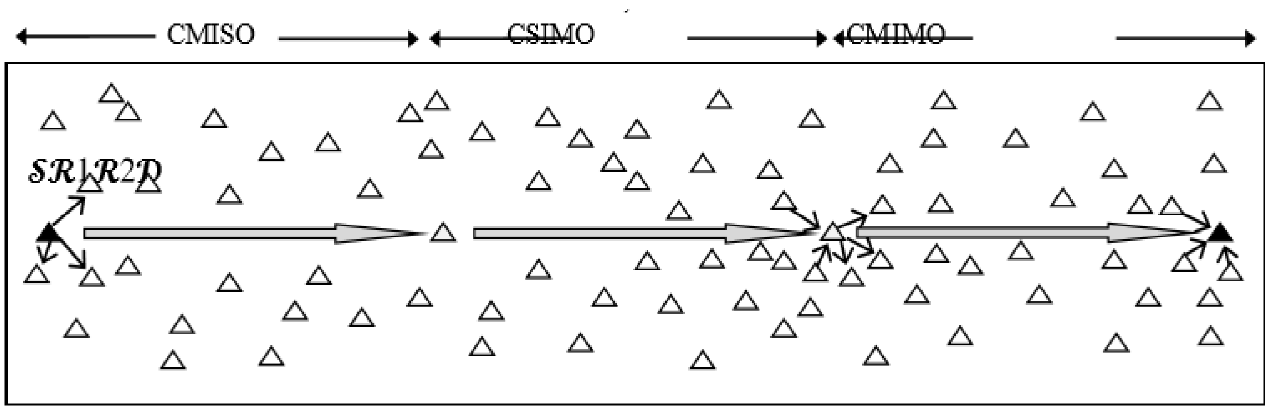

Fig.1 Multihop Cooperative MIMO Transmission

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II. ENERGY CONSUMPTION MODEL

It is assumed that, the wireless channels between the neighbors of any node is independent and distributed in identical way where the fading is α_1^2 and path loss exponent equal to 4.Whereas, the channel between a node with its cooperative nodes inter-hop node is assumed to experience a combination of frequency-flat Rayleigh fading with parameter α_2^2, shadowing, and the exponent of loss is 4. It is also assumed that, the wireless channel is changing gradually and it will be a constant one in specific time. We consider, only the correlation effect, caused by shadowing, for simplicity. We present the energy consumption of SM-CMIMO based scheme as follows:

For a single hop transmission, the energy consumption per bit, E_{SH} is the average energy consumption at transmitting-end local communication, E_{TS}, plus average energy consumption at receiving-end local communication, E_{RS} plus aver- age energy consumption for long-haul communication, E_{LH}

$$E_{SH} = E_{TS} + E_{RS} + E_{LH} \quad (1)$$

We assume that the $\mathcal{S}$has data packet of L bits to be transmitted to cooperative node i, and a fixed M-QAM with coherent modulation/demodulation for the local communication. The average energy consumption at transmitting-end local communication, E_{TS} is given by

$$E_{TS} = N_T L E_i^T \quad (2)$$

The receiving-end has N_{R-1} CNs nearby $\mathcal{R}$which allows virtual antenna array. These CNs transmit the received bits to R using M-QAM using TMDA. The average energy consumption at receiving-end local communication, E_{RS} is given by

$$E_{RS} = N_{R-1}\ E_j^R n_r\ \frac{L}{b} \quad (3)$$

where constellation size, $b = \log_2 M^L$(4). The $\mathcal{S}$ and its CNs, sends data towards R simultaneously. Let us denote let M^L and M^l denotes the QAM constellation sizes used for local and long-haul communications, respectively. E_b^L as the average total energy per bit for long-haul communication. The average energy consumption for long-haul communication, E_{LH} is given by

$$E_{LH} = E_b^L N_T L E_i^T \quad (5)$$

As is shown in [4], [19] ,for linear dependence of power amplifiers power consumption on the transmit power P_O^L, The total power consumption of the power amplifiers is given as

$$P_A^L = N_T\,(1 + \alpha^L) P_O^L \quad (6)$$

where $\alpha^L = \frac{\xi^L}{\eta} - 1$ and η is the RF power amplifier drain efficiency,$\xi^L$is peak-to-average ratio (PAR) that depends on the modulation type and the constellation size.

For the M-QAM systems that is assumed, then

$$\xi^L = 3\frac{M^L - 2\sqrt{M^L} + 1}{M^L - 1} \text{ [20]} \quad (7)$$

As in [22], the transmit power can be computed in terms of the specified data rate and BER

$$P_O^L = G d_L^{\alpha} \bar{E}_b^L R_b^L \quad (8)$$

where R_b^L is the bit rate and α is the path loss exponent of each node during the long-haul communication?

The constant $G = \frac{(4\pi)^2 M_l N_f}{G_T G_R \lambda^2}$ (9) where M_L is the link margin that compensates for interference , background noise or the hardware process variations, G_T and G_R are the value of gain obtained by both transmitter and receivers. For the wireless communication channels, the path loss exponent α may lie in the range 2 to 5, with α = 2 representing free space propagation loss. Since a fading channel is assumed for the long-haul communications, for a given BER requirement, E_b^L can be found by inverting the average bit error probability $\bar{P}_b \approx \bar{P}_{js}\left(\frac{1}{b} + \frac{1}{N_T \log_2 M}\right)$ (10) where $\bar{P}_{js}$ is average probability of joint symbol. The total consumption of power can be measured as follows: $P_c^L \approx N_T(P_{DAC} + P_{mix} + P_{filt} + P_{sync}) + N_R(P_{sync} + P_{LNA} + P_{mix} + P_{IFA} + P_{filr} + P_{ADC})$ (11)

where $P_{DAC}, P_{filt}, P_{sync}$, $P_{LNA}, P_{mix}, P_{IFA}, P_{filr}$, and P_{ADC} represent the D/A power consumption produced and values of active filters, amplifiers and so on..

Table 1: System Parameters

B = 10KHz	L_i = 20Kbits
fc = 2.4GHz	P_{DAC} = 15.4mW
η =0.35	P_{ADC} = 6.7mW
N_f = 10dB	P_{sync} = 50mW
N_o = -171dBm/Hz	P_{IFA} = 3mW
G_tG_r= 5dBi	P_{LNA} = 20mW
M_L = 40dB	P_{filt}= P_{filr} = 2.5mW

The ratio of total energy incur at fixed rate system has been measured using (6) and (8):

$$E^L = \frac{3G(M^L + 1 - 2\sqrt{M^L})}{\eta\,(M^L - 1)} d_L^{\alpha} \bar{E}_b^L + \frac{P_c^L}{R_s N_T\ b} \quad (12)$$

where$b = \log_2 M^L$ and for simulation symbols per sec, R_s= B bauds is assumed.

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For local communication, E_i^T , E_i^R can be computed using (12) by substituting for M^L , $d_L^{\propto}$, $\bar{E}_b^L$ the corresponding M^l , $d_l^{\propto}$, $\bar{E}_b^l$ and P_c^l $\approx(P_{DAC}+P_{mix}+P_{filt}+P_{sync})+(P_{sync}+P_{LNA}+P_{mix}+P_{IFA}+P_{filr}+P_{ADC})$ (13)

But, if the channel is Rayleigh fading then

$$\bar{E}_b^l=\frac{2N_o(M^l-1)}{3\log_2 M^l}\left[\left(1-\frac{\bar{P}_b\log_2 M^l}{2\left(1-\sqrt{M^l}\right)}\right)^{-2}-1\right]^{-1} \quad (14)$$

III. SM-CMIMO PROTOCOL

The proposed SM-CMIMO multi-hop transmission scheme works as follows. Initially, the $\mathcal{S}$ gathers location information of the WSN nodes. Between the $\mathcal{S}$ to D, the $\mathcal{S}$ tries to create a Cooperative MIMO network. As shown in [27], with the maximum transmitter power 10mW and receiver sensitivity -85dBm the maximum transmission distance of a WSN node is just greater than 102m. We consider the long hop distance D_L =100m so that there is no network connectivity issue. Between the transmission path from$\mathcal{S}$to $\mathcal{D}$, for every D_L distance, relay nodes are selected. In order to check for the possibility of reducing the energy consumption of the Cooperative MIMO network, the energy consumption of each long-hop is evaluated for different configurations. Any node will be substituted with MIMO only when it has higher energy consumption or SISO configuration which is now better configuration. To further check the possibility of reducing the energy consumption of the Cooperative MIMO network, at the middle of these hop, again relay nodes are selected so that the length of long hop is the sum of two equal smaller-hops; the hop distance of smaller-hop being D_L/ 2. These smaller-hops are also evaluated for the possible substitutes with suitable cooperative MIMO configuration, if it is worth. If there is a reduction in the energy consumption for any hop, that hop is substituted with MIMO (V-MISO or V-SIMO) or SISO configuration All substitutes with suitable configurations must satisfy the BER, data rate, and network connectivity requirements. Finally, to substitute long hops with the two smaller-hops, the sum of energy consumptions of two smaller-hops should be less than the energy consumptions of long hop. For the evaluation of energy consumption of each hop, the selection of CNs is performed byNSA algorithm.

A. SM-CMIMO Algorithm

The Pseudo Code of SM-CMIMO algorithm given below:
Step 1. Source node $\mathcal{S}$gatherslocation information of nodes.
Step 2. Between $\mathcal{S}$ and $\mathcal{D}$, interhop relay nodes are selected at every$D_L$distance.
Step 3. Compute the number of CNs for which energy consumption is minimum using (1)and run NSA algorithm to select the CNs within $D_l$distance of the $\mathcal{S}$, relay node and destination node.
Step 4.Compute energy consumption of each inter-hop with V-MIMO, V-MISO, V-SIMO or SISO transmission modes using (1).
Step 5. Select the less energy consuming transmission mode for the hops, among the four transmission modes.
Step 6.For each hop, perform the following procedure for possible energy consumption reduction.
Step 6.1. Select the relay node at the middle of large transmission hop.
Step 6.2.Repeat step 3to 5. for each small hops.
Step 6.3. If energy consumption of large trans- mission hop is more than sum of energy consumption of two smaller transmissions hops
Then
Step 6.4. Substitute large transmission hop with smaller transmission hops.
Else
Step 6.5.Retain large transmission hop.
The computation burden is not much significant for number of CNs greater than five.

B. NSA Algorithm

The channel correlation is always harmful to multiplexing MIMO systems, due to the fact that existence of high correlation increases dependence among input data streams' channel responses. This introduces poor data stream. So the selection of the cooperative nodes should be such that, correlation is minimal among each node. In this paper, a correlation model is presented to reduce the distance between the points. Equivalent to this we can choose cooperating nodes where the distance is maximum between any two nodes should be greater or equal to minimum distance D_{min}. For the minimum energy consumption, the minimum number of cooperative nodes for V-MIMO is computed using (1). The D_{min} can be $\lambda \geq D_{min} < D_l$.
The NSA algorithm works as follows:
Algorithm:
Step 1.**Neighbor node selection** -For each node within D_l distance of a node, if battery life, B_l of a node ≥ B_{lth}, (B_{lth} threshold battery life) then a node is selected as neighbor node.
Step 2.**Minimum number of CNs computation**- For the minimum energy consumption, the minimum number of cooperative nodes for V-MIMO is computed as follows:
Step 2.1 Compute energy consumption for different number of CNs using (1).
Step 2.2 Perform comparisons and select the number of CNs as minimum number of CNs for which the energy consumption is minimum.
Step 3.**Cooperative node selection** - among the nodes selected from step 1, CNs are selected as follows:
Step 3.1. We assume that, the number of nodes selected for cooperation(including source node), j = 1.Then for node i, if the distance between the node i and node j, $d_{ij}=\left[\left(x_i-x_{j+1}\right)^2+\left(y_i-y_{j+1}\right)^2\right]^{\frac{1}{2}} \geq D_{min}$, then compute the total distances ,

$$d_S=\sum_{i=1}^{j}\left[\left(x_i-x_{j+1}\right)^2+\left(y_i-y_{j+1}\right)^2\right]^{\frac{1}{2}}$$

Step 3.2.For next node,i = i+1. Repeat step 3.1 for remaining nodes. Select the node with maxi- mum total distance as CN.
Step 3.3.Number of CNs selected, j = j+1.
Step 3.4.Repeat steps 3.1 to 3.4 for selecting remaining CNs.

IV. PROCEDURE TO ESTABLISH AN SM-CMIMO TRANSMISSION

This section details the procedure to establish SM-CMIMO transmission.

Step 1.All the nodes broadcast a message periodically to the neighbor nodes which are located within the transmission range or distance, D_l. Neighbor nodes, upon receiving the request, send reply message along with its identification number (ID), list of M node addresses and CSI information so as to participate in the cooperation. Based on nodes battery life conditions, nodes are selected as neighbor nodes.

Step 2. Then source node, relay nodes and destination node can run NSA algorithm to select CNs.

Step 3. The $\mathcal{S}$ informs these CNs of their role in the SM-CMIMO transmission through a multicast or unicast message.

Step 4. It forms a TDMA schedule and broadcasts to selected CNs and then, stream has been distributed to each CN.

Step 5.Then, long-haul any one of V-MIMO versions transmission begins.

Step 6. Above steps 4&5 are followed for all hop transmissions.

V. RESULT

In the simulations, the placement of nodes in WSN is random with a uniform probability distribution of density ρ,

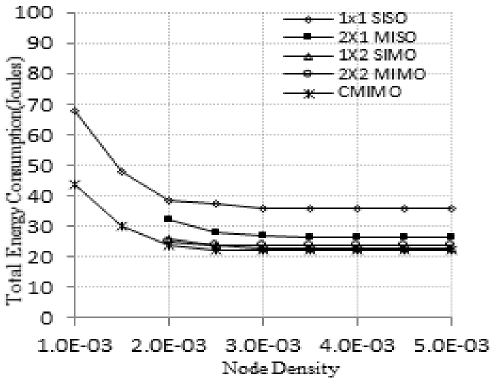

Fig. 2. Total energy consumption of MIMO schemes with Two CNs

local transmission distance D_l = 10m,*Dsd* = 500 m, *Dmin* = 0.5m and$B_{lth,}$ 20%. The simulation parameter values used are shown in Table I. The average total energy consumption performs a comparison of different multihop schemes are shown in fig.2. Given the same BER and end-to-end throughput constraints, for ρ = 0.002 (relatively medium node density), the SM-CMIMO transmission scheme attains a significant average energy efficiency enhancement of 37.3%, 7.7%, 25%, or 4 % when compared with either SISO, V-SIMO, V-MISO, or V-MIMO configurations, respectively. For the relatively high node density, ρ = 0.003, SM-CMIMO offers an average energy efficiency improvement of 38.9%,18.5%, 3.5%, or 6.8% when compared with SISO, V-SIMO, V-MISO, or V-MIMO configurations, respectively. For the lower node density, ρ = 0.001, an energy efficiency of 25.67% is attainable when compared with the SISO configuration.

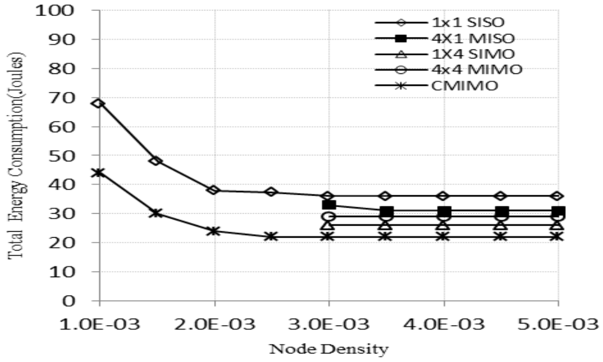

Fig.3. Total energy consumption of MIMO schemes with four CNs

The average total energy consumption performs- ance of multihop schemes of four MIMO is compared with proposed SM-CMIMO scheme as shown in fig.3. For ρ = 0.005(relatively high node density), the SM-CMIMO scheme offers a significant aver-age energy saving of 38.9%, 15.4%, 29%, or 24 % when compared with either SISO, V-SIMO, V-MISO, or V-MIMO configurations, respectively. For the lower node density,ρ = 0.001, the average energy saving gain of SM-CMIMO compared with SISO is 35.3%.For the medium node density,ρ = 0.003, the average energy saving is almost same as that of relatively high node sensitivity. In fig. 4., we show the performance of the system of the proposed SM-CMIMO scheme for two different channel correlation values. The performance of the system degrades as the channel correlation increases.

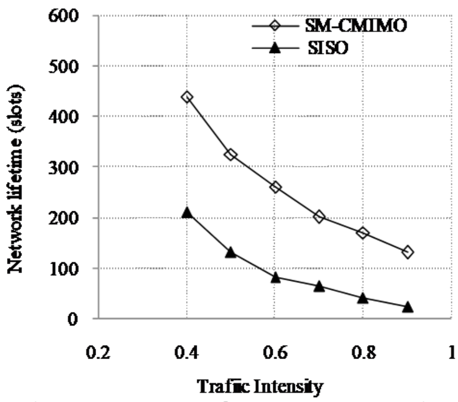

Fig 4. System performance comparison for different channel correlation parameters

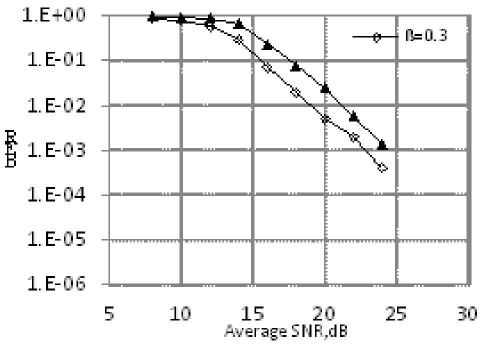

Fig.5 Network life time vs. Traffic intensity.

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Lastly, in fig.5, lifetime is the time when the first-node dies in a wireless network. We see that, as the cooperation overhead of SM-CMIMO transmission scheme are amortized by the higher number of data packets, the proposed SM-CMIMO protocol provides a significant improvement in network compared to SISO transmission scheme. Nonetheless as expected the network lifetime decreases with the traffic intensity.

VI. CONCLUSION

The proposed SM-CMIMO multi-hop transmission scheme improves energy saving than different MIMO designs at similar BER, node density and throughput conditions. However, the performance is indirectly proportional with channel correlation. It is also seen that, the network life time of SM-CMIMO transmission scheme noticeably improved than other designs.

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