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# ENERGY-EFFICIENCY ANALYSIS AND OPTIMIZATION FOR VIRTUAL-MIMO SYSTEMS

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ABSTRACT:

In this paper, we studied the performance of bit error rate(BER) for a virtual multiple-input multiple-output (MIMO) based communications architecture. As a case, wireless sensor networks with clusters were considered. Then an optimal transmitting power(TP) scheme for cooperative sensor nodes was presented. Specifically, by minimizing BER of the Nt×1 virtual MIMO system, we derived the closed-form of the optimal TP for each cooperating node in one cluster. Through simulations, we compared this strategy with an equal TP assignment method. Its performance enhancement was verified by extensive simulations under different scenes. At the aim to energy efficient, a thorough explanation of optimally choosing number of cooperating nodes was also delivered by the aid of mathematical analysis as well as simulation verifications.

Keywords: energy efficiency, virtual MIMO, wireless sensor networks (WSNs)

## 1. INTRODUCTION

Wireless sensor networks (WSNs) have being research hotspots recently as they use cheap and low-power sensors to perform surveillance tasks. For example, environmental monitoring, military surveillance, animal tracking, and home applications. However, sensor nodes are usually battery operated and their operational life time should be maximized, hence energy consumption is a crucial issue in real WSN applications [1]. Since multiple-input-multiple-output (MIMO) can dramatically increase the channel capacity while also reduce transmission energy consumption in fading channels, schemes named virtual MIMO have been proposed for WSN to improve the system performance [2][6]. Similar to MIMO, in such a strategy, when a node has information to send, it cooperates with adjacent nodes tied by single-antenna to transmit its information to a certain destination, which forms a virtual antenna array. So the adjacent nodes who participate in cooperating act as the relay channels for the source node [2][3][4][6].

In [2], S. Cui analyzed the total energy consumption per bit of multi-antenna nodes. The represents that single input-single-output (SISO) systems use more energy than MIMO as the communication scheme. And X. Li [6] proposed no a virtual MIMO scheme using two transmitting sensors and space-time block code (STBC) to provide transmission diversity in WSN with neither antenna-array or transmission synchronization. Studies above have shown that cooperation among sensor nodes can lead to significant capacity increases. However, in these literatures , they both assumed that each node has the same channel fading conditions and equal transmitting power(TP). In fact, it may be reasonable to assume that the channel gains from each cooperating node to the destination are different, as senor nodes are always placed randomly in a complex environment. So setting the optimal transmitting power for each cooperating node in one cluster is necessary to maximize the system performance. In this paper, the optimality is determined in terms of minimizing the bit-error–rate (BER) of the system. As a case, an Nt×1 virtual MIMO network topology is considered. And the closed-form solutions of optimal TP are provided.

To make the virtual MIMO network energy efficient, methods for choosing number of cooperating nodes is also delivered. The rest of the paper is organized as follows. In Section II, related work about virtual MIMO is given. In Section III, we present the system model and provide exact BER expressions under a Nakagami fading narrowband channel with parameter m , and we compute the optimal TP for each cooperating node. In Section IV, performance improvement of the proposed scheme is compared to traditional strategies through simulations, and the effect of the number of the cooperating nodes on the EPUB (Energy-per-useful-bit) is analyzed by the aid of mathematical analysis and simulation verifications. Finally, in Section V, we conclude the whole paper.

## 2. Related Work

The origin of cooperative communication can be traced back to the work of Cover and El Gamal [3] , which presents numerical results for the relaying scenario of Gaussian channels setup. And in [4], authors set up the first information theoretic approach to cooperative for multi-hop transmission. As real MIMO techniques require complex transceiver circuitry and large amount of signal processing which lead to increased power consumption at the circuit level, it is not a viable technology for energy-limited wireless sensor networks. However, it is showed in recent papers that implementing MIMO techniques in wireless sensor networks via cooperative communication techniques is possible instead of physically having multiple antennas at the sensor nodes. And such scheme is named by virtual MIMO [2]. In [2], Cui studied such distributed MIMO techniques and analyzed the total energy consumption per bit of SISO and MIMO, and then showed the feasibility of virtual MIMO in WSNs. They observed that virtual MIMO scheme can offer considerable energy savings in cooperative wireless sensor networks even after allowing for additional circuit power, communication and training overheads. S. Jagannathan et al [8] investigated the effect of time synchronization errors on the performance of the cooperative MIMO systems, and concluded that the cooperative MIMO scheme has a good tolerance of up to 10% clock jitter. Based on the energy model proposed in [2], Yuan [9] presented an optimal cross-layer design of virtual MIMO for WSNs to ensure quality of service (QoS). J. N. Laneman did the research work on the system capacity analysis of the virtual MIMO scheme in [10]. As to the optimization of virtual MIMO, [11], [17] and [18] present power allocation optimization methods in the case of a single node transmitting at any time.

In [19] [20], with perfect channel knowledge at the transmitter under fixed nodes with no fading, they showed the investigation on the minimum energy consumption with the constraint that cooperating nodes are along the optimal non-cooperative route. And [21] proposes a minimum power cooperative routing algorithm in which, at any time, either a direct transmission or a single relay-aided transmission can occur. In [22] the choice of the number of cooperating transmitters and the cooperation strategy are investigated to exploit the diversity gain for an increase in either the range or the rate of the links or both. In [23], authors propose optimal co-operator selection policies for arbitrary topologies with links affected by path loss and multipath fading.

However, how to optimally choosing TP for each cooperating node in virtual MIMO under different channel gains has not been addressed in the previous literatures. The analysis of this paper extends the work in the previous literatures as it applies to general multi-hop WSN under different channel gains.

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## 3. SYSTEM MODEL

We consider a transmitter node with $Nt$ antennas and a destination node with a single antenna, as shown in Fig. 3.1. There are $Nr - 1$ single-antenna relays in the proximity of the destination. We refer to the destination and relays as the receiver group, which together with the transmitter form a virtual-MIMO system [3]. We assume that the nodes within the receiver group are close, but the distance between the transmitter and the receiver group is large. For the sake of demonstrating the performance of EE with more tractable mathematical expressions, we consider $Nt = Nr = 2$ in this paper. There are two orthogonal communication channels, i.e., the data channel between the transmitter and the receiver group, and the cooperation channel between the receivers.

### 2.1. Channel Model

In Fig. 3.1, $\boldsymbol{x} = [x1, x2]^T$ denotes the transmitted signals, and $[yr, yd]^T$ denotes the corresponding received signals at the relay and the destination. Without loss of generality, the data channels are represented by $hi = (ci/\sqrt{Ktd\zeta})$ $(i \in [1, . . . ,3])$, where $ci$ is a circularly symmetric complex Gaussian random variable with unit variance and zero mean. As the relay is close to the destination, we assume that they are equally distanced from the transmitter, which is denoted by $d$. Scalar $\zeta$ is the path loss exponent, and $Kt$ is a constant indicating the physical characteristics of the channel and the power amplifier [15]. That is, the data channels are modeled as Rayleigh fading with $E[|hi|2] = 1/(Ktd\zeta)$. In matrix form, the received signal vector is

$$\begin{bmatrix} y_r \\ y_d \end{bmatrix} = \boldsymbol{H}\boldsymbol{x} + \boldsymbol{n}; \qquad \boldsymbol{H} = \begin{bmatrix} h_1 & h_2 \\ h_3 & h_4 \end{bmatrix} \tag{3.1}$$

where the data channel matrix $\boldsymbol{H} \in C^{Nr\times Nt}$ is complex Gaussian distributed. $\boldsymbol{n} = [n1, n2]^T$ is the noise vector with components $n1, n2 \sim CN(0, N0)$. We assume that perfect CSI is available at the receiver side only. Let $W$ denote the bandwidth of the data channel. In addition, suppose that the two antennas at the transmitter use the same average transmit power $P$st, i.e., $E[|x1|^2] = E[|x2|^2] = P$st. Here, we consider equal power allocation among the transmit antennas as it is an optimal power allocation when no CSI is available at the transmitter side [16]. At the receiver group side, there is a short-range cooperation channel between the relay and the destination, which is modeled as an additive white Gaussian noise channel. The relative power gain of the cooperation channel to the power gain of data channels is represented by $G$. As the receivers are closer in our system model, the case of interest is when $G$ is high. $Wr$ and $P$rt denote the bandwidth of the cooperation channel and the transmit power of the relay, respectively.

### 2.2 Realistic Energy Consumption

In a practical setting, to quantify the total energy consumption of the entire system, both the transmit energy and circuit energy consumed at the transmitter and the relay need to be considered. For instance in [8] and [17], the total supply energy at a base station includes the energy consumed for the power amplifier, radio-frequency circuitry, baseband unit, and direct current (dc) and alternating-current (ac) converters. In general, the total supply power and the transmit power at a base station is nearly linear, and consequently, a linear power model has been defined in [8] and adopted in this paper. Therefore, at the transmitter, the total power for $Nt$ antennas is given by $Nt(\xi sP\text{st} + P\text{sc})$, where $P$sc is the load-independent circuit power at the minimum nearly zero output power, and $\xi s$ is the scaling factor of the load-dependent power. For the relay, using a similar linear power model, we have the total supply power $(\xi rP\text{rt} + P\text{rc})$, where $P$rc denotes the load-independent circuit power at the relay. Note that the scaling over signal load (i.e., the values of $\xi s$ and $\xi r$) largely depends on the

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type of the station. Reference [8] presents the model parameters for various transmitter types in a 3rd Generation Partnership Project Long Term Evolution (3GPP LTE) network, and [18, Table I] presents the parameters for the relay model, which could be adopted in our system.

We assume that the transmitter and the relay are subject to separate power constraints: $0 < P_{st} \leq P_{max,s}$ and $0 < P_{rt} \leq P_{max,r}$. For the relay, we define $\gamma = P_{rt}/P_{st}$ to be the power allocation ratio between the relay and the transmitter. Compared with a total power constraint, this assumption of separate power constraints is more practical for wireless networks because the transmitter and relay are usually geographically separated and are supported by separate power supplies [19]. With the knowledge of $P_{st}$, the relay will decide its own transmit power (via choosing a value of $\gamma$). Finally, the total power of the entire system is

$$\begin{aligned} P_{tot} &= N_t(\xi_s P_{st} + P_{sc}) + \xi_r P_{rt} + P_{rc} \\ &= (N_t\xi_s + \gamma\xi_r)P_{st} + N_t P_{sc} + P_{rc} \\ &0 < P_{st} \leq P_{max,s}, \quad 0 < \gamma \leq P_{max,r}/P_{st}. \end{aligned} \tag{3.2}$$

## 2.3 Impact of Relay Protocol

Relay protocols are usually classified into three categories, namely, DF, AF, and CF, which require different signal processing techniques at the relay. However, these techniques have similar complexity. Since the power consumed in the baseband unit is mainly defined by complexity, the power difference of the three protocols (caused by different signal processing techniques) is quite small compared with other parts of the circuit power (such as that for the radio-frequency circuitry) and can be neglected. We thus consider that the circuit power at the relay $P_{rc}$ remains the same for the three relay protocols. In addition, the relay is assumed to be closer to the destination in this paper; compared with DF, the CF protocol provides superior capacity performance [5], [20]. Therefore, given the same $P_{rt}$, DF and CF have the same total power consumption, but CF is more spectrally efficient. According to the definition of EE, CF has better EE than DF.

In addition, the AF protocol is a special case of CF, in which case the relay simply scales and forwards the analog signal waveform that is received from the transmitter without any particular processing [21]. AF requires equal bandwidth allocation for the data and cooperation channels as the amplified analog signal needs to occupy an unchanged bandwidth. However, for CF, the signal at the relay is quantized and can be re-encoded so that the bandwidth of the cooperation channel can be changed and optimized, as will be shown in Section IV-B. Therefore, for any given channel conditions, CF performs better than or equal to AF in terms of their EE performance. Thus, in this paper, we assume that the relay sends its observation to the destination implementing CF cooperation, where a standard source coding technique [5] is used by the relay.

## 3. EMA ALGORITHMS

We find EMA algorithm that maximizes the lower bound of EE in (1) and it is realized by minimizing PC per sub-band n defined as

$$PC_n \triangleq cP_{tx,n} + L_n P_{fix} \tag{2}$$

We derive the minimum PC of (2) that achieves R for any user in a TDMA or SDMA mode to determine the MA for each sub-band.

### (A) PC of TDMA

We first derive the PC of TDMA with OFDMA. To allow the target rate R of user u through the sub-band with Bandwidth Ω and variance the power control factor pu is lower bounded as

$$p_u \geq \sigma^2\left(2^{\frac{R}{\Omega}}-1\right)g_u^{-1}\ \forall u \epsilon U \quad (3)$$

Therefore, the minimum transmit power for achieving R is derived for the TDMA user u as derived for the TDMA user u as

$$P_{tx,n}^{TDMA} = g_u \min\{p_u\} = \sigma^2\left(2^{\frac{R}{\Omega}}-1\right) \quad (4)$$

Since K users are supported through K time slots, the PC in (2) is derived for the TDMA as follows:

$$PC_n^{TDMA} = c\sum_{u \epsilon U_n} P_{tx,u}^{TDMA} + KP_{fix} = cK\sigma^2\left(2^{\frac{R}{\Omega}}-1\right) + KP_{fix} \quad (5)$$

## (B) PC of SDMA

Next, the PC of SDMA with OFDMA is derived. Since the SDMA can be implemented with Ln time slots (1 ≤ Ln ≤ T), each sub-band supports the K users with less time slots in fair comparison with TDMA. To allow the target rate R of user u ∈Un with Ln SDMA slots through the bandwidth Ω, the minimum required transmit power on each sub-band is derived for one SDMA time slot as follows:

$$PC_{tx,n}^{SDMA} = \min\left\{\sum_{m \epsilon M}\|w_{mn}^r\sqrt{Q_n}\|^2\right\} = \sigma^2\left(2^{\frac{R}{L_n\Omega}}-1\right)\|W_n\|_F^2 \quad (6)$$

where‖.‖F is the Fresenius norm of a matrix and Wn is the pseudo-inverse of the channel matrix. Since Ln SDMA time slots are used, the PC in (2) is derived for the SDMA as (1 ≤ Ln ≤ T)

$$PC_n^{SDMA} = cL_n PC_{tx,n}^{SDMA} + L_n P_{fix} = cL_n\sigma^2\left(2^{\frac{R}{L_n\Omega}}-1\right)\|W_n\|_F^2 + L_n P_{fix} \quad (7)$$

## (C) EMA Algorithm for each sub-band:

To find the optimal MA for each sub-band n, we need to compare in (5) and in (7), which requires time complexity. For large N, as the complexity is more, we find the optimal number of SDMA slots for each sub-band n, denoted. This can be obtained by assuming a floating value instead of Ln in (7). Now we get a differentiable function over as

$$f(l_n) = cl_n\sigma^2\left(2^{\frac{R}{l_n\Omega}}-1\right)\|W_n\|_F^2 + l_n P_{fix} \quad (8)$$

Now make the first derivative of with respect to be zero to find the minimum value of .Thus,

$$l_n^* = \frac{R\ln 2}{\Omega\left(W\left(\frac{1}{\exp(1)}\frac{P_{fix}}{c\sigma^2\|W_n\|_F^2}-1\right)+1\right)} \quad (9)$$

Where exp(·) is an exponential function and W(·) ≥ −1denotes the upper branch of Lambert W function, which is given as z = W(z) . Finally we obtain the optimal SDMA slot length from (9) that is the nearest integer to and satisfies 1 ≤ $L_n^o$ ≤ T. After finding, we compare and to determine MA on sub-band n. Here, the complexity is reduced as only a pair of comparison is needed for each sub-band. Now, the EMA algorithm is designed by comparing and as follows:

After finding, we compare and to determine MA on sub-band n. Here, the complexity is

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reduced to Õ(N) as only a pair of comparison is needed for each sub-band.

$$EMA_n = \begin{cases} SDMA, if \; ||W_n||_F^2 \leq \xi_n \\ TDMA, otherwise \end{cases}$$

$$\text{where } \xi_n = \frac{(T - L_n^o) P_{fix}}{c L_n^o \sigma^2 \left( 2^{\frac{R}{L_n^o \Omega}} - 1 \right)} + \frac{\kappa \left( 2^{\frac{R}{\Omega}} - 1 \right)}{L_n^o \left( 2^{\frac{R}{L_n^o \Omega}} - 1 \right)} \quad (10)$$

To guarantee EE improvement, we further compare the EE of a pure TDMA with EE of the EMA algorithm for each sub-band, and then determine the MA technique that achieves the higher EE.

### (D) EMA Algorithm for the whole sub-band

In this algorithm, we consider an EMA algorithm that selects either pure TDMA or SDMA for the whole sub-band. This further reduces the complexity. The total PC of SDMA for all sub-bands is defined from (8) as

$$f(\{L_n\}) = c \sum_{n \in N} L_n \sigma^2 \left( 2^{\frac{R}{L_n \Omega}} - 1 \right) ||W_n||_F^2 \max\{L_n\} P_{fix} \quad (11)$$

The optimal Ln's that minimize (12) are identical to one another Method. This allows one-dimensional line search from 1 to T to find L* optimally, which requires Õ(T) time complexity.

### E. Normalized EMA algorithm:

The general communication system is depicted as

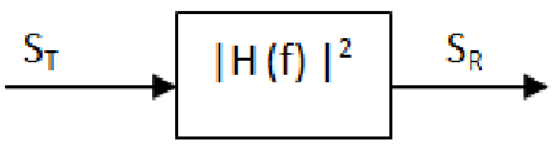


Figure 1: Block diagram of simple communication system

Based on the transmit power ST and receive power SR, the channel power gain is defined as SR /ST. For a non-ISI channel, using a flat transmit power spectrum, the channel power gain is defined as

$$\frac{S_R}{S_T} = \int_{-\infty}^{\infty} |H(f)|^2 \, df \quad (12)$$

This is usually normalized to unity. One should be aware that the channel gain can be greater than unity in frequency ranges near the peak of the frequency response. When dealing with real channels, it is common to normalize the frequency response so that the maximum value is unity. Thus, we shall also normalize the power frequency to unity. This ensures that the minimum Eb/N0 is always -1.6 dB. That is, we shall normalize the frequency response such that the - 3 dB bandwidth is 1 Hz. We shall call this as peak bandwidth normalization. For an m-tap channel with unit energy normalization |H(f)|2, the frequency response with peak bandwidth normalization is given as

$$|G(f)|^2 = \frac{1}{M} \left| H\left(\frac{f}{n}\right) \right|^2 \quad (13)$$

Where M is the maximum value of |H(f)|2 and n is the scaling factor which makes the -3 dB bandwidth of |G(f)|2 equal to 1. Normalization by the maximum value ensures the channel maximum power gain is unity. Thus, no particular channel has a gain over another channel in the frequency ranges where the transmit power is concentrated.

## 4. NUMERICAL RESULTS

### Proposed Results Work:

We assume that the channel is AWGN with zero mean and unit variance. For the transmit antenna correlation, we apply a correlation matrix with a correlation factor 0.3. A noise variance is defined such that each received antenna achieves 20 dB SNR. The overall bandwidth is 10 MHz. We set the overhead PC parameter as c = 5.26

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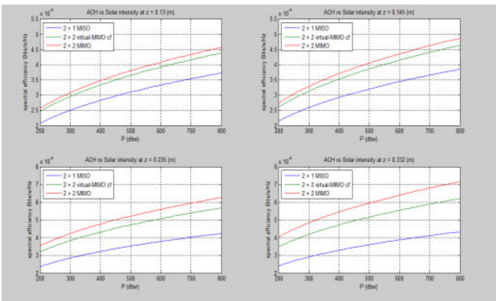

FIGURE 1: Simulation results and upper bounds of the ergodic capacity for Nt × Nr MIMO and virtual-MIMO systems.

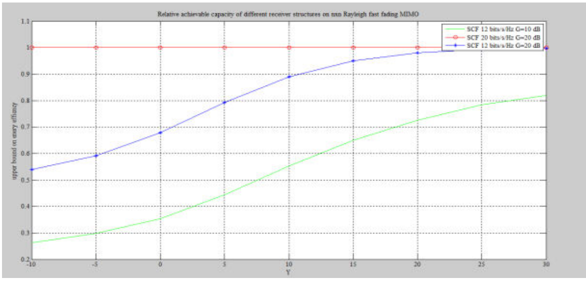

Fig. 2. Effects of varying the values of γ on the EE performance of the virtual MIMO system with CF by setting SCF = 10, 12 bits/s/Hz and G = 10, 20 Db under bandwidth Scenario I.

## Extension work:

**Energy Efficient Multiple Access Scheme for Multi- User System with Improved Gain**

To improve the energy efficiency (EE) of multi-user multiple-input multiple-output (MIMO) orthogonal frequency-division multiple access (OFDMA) system, an Energy-efficient multiple access (EMA) scheme is proposed. It improves EE by selecting either time-division multiple access (TDMA) or space-division multiple access (SDMA) based on the no. of users or power consumption. Here, we introduced normalization process for power in OFDM system to improve the power gain. Numerical results verify that the EE and power gain can be significantly improved through the proposed EMA scheme.

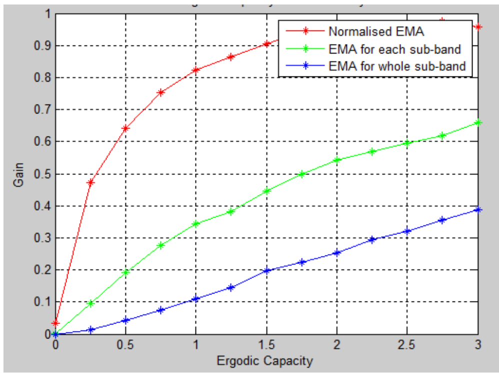


Figure 3: Comparison of gains of different MA methods for M = T = 30, N = 40, and U = 700.

We assume that the channel is AWGN with zero mean and unit variance. For the transmit antenna correlation, we apply a correlation matrix with a correlation factor 0.3. A noise variance is defined such that each received antenna achieves 20 dB SNR. The overall bandwidth is 10 MHz. We set the overhead PC parameter as c = 5.26.

In Fig. 2, to compare the proposed EMA algorithms with the optimal EMA strategy, we evaluate the EEs for a small-size system with M = T = 2 and N = 4. As mentioned previously, EMA algorithm for the whole sub-band reduce the complexity of optimal strategy from Õ(TN) to Õ(N) and Õ(1). Based on the results of the small-size system, we surmise that the proposed EMA algorithms work properly for a large-size system without significant performance loss compared to the optimal EMA.

In Fig.3 and 4, we show the EE of a larger-size system with M = 30, T = 30, N = 40, and U = 700. Fig.3 shows EEs over Pfix with R = 1 Mbps and it shows that SDMA is preferable if the TPI term is dominant. Fig.4 shows that the gain is improved to unity after normalization process.

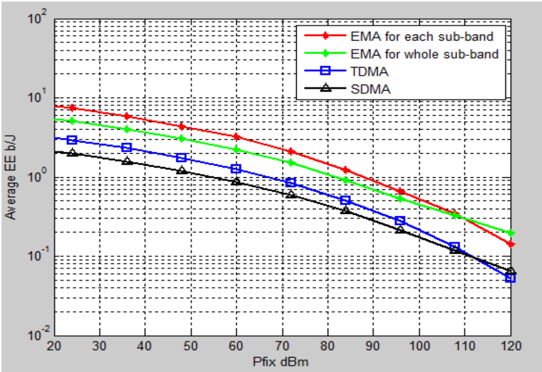


Figure 4: Comparison of the average EE of different MA methods for M = T = 30, N = 40, and U = 700.

## 5. CONCLUSION

In this paper, we have proposed energy efficiency (EE)- aware multiple access (EMA) scheme. Based on the required power consumption to achieve the fixed feasible target rates, the EMA chooses either a time-division multiple access or spatial-division multiple access (SDMA) for each sub-band. For the EE-aware SDMA, optimal number of SDMA slots has been derived. It has been shown that the SDMA is most likely selected if i)the target rate is high, ii) the transmit-power-independent power consumption is high, or iii) the channel quality is good. Simple EMA algorithms have been devised and their impact on EE and gain improvement has been verified by simulation. The results have provided valuable insight to extend EE-aware system with the consideration of i) the uncertainty of channel state information and ii) power consumption of uplink communications.

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