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## Energy-efficient design of VMIMO for WSN applications

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**Abstract** Wireless sensor networks (WSNs) have been paid more attention in recent years. However, energy efficiency is still a troublesome issue in real WSN applications. In this paper, we studied the performance of a virtual multiple-input multiple-output (VMIMO)-based communications architecture for WSN applications. By analyzing the bit error rate (BER) of each cooperative branch, we presented the closed-form expressions for optimal transmitting power (TP) scheme in  $K \times 1$  VMIMO cluster-based system. Then, the impact of the number of cooperating nodes on energy efficiency with energy-per-useful-bit (EPUB) metric was studied. Performance enhancement of the strategy with optimal TP assignment was verified by extensive simulations under different scenes. A thorough explanation of optimally choosing the number of cooperating nodes was also delivered by the aid of simulation verifications.

**Keywords** energy efficiency, virtual multiple-input multiple-output (VMIMO), wireless sensor networks (WSNs)

### 1 Introduction

Wireless sensor networks (WSNs) have been paid more attention recently as they can perform surveillance tasks, such as environmental monitoring, military surveillance, animal tracking, etc. However, energy consumption is still a crucial issue in real WSN applications as sensor nodes are usually battery operated and their operational lifetime should be maximized [1].

In recent years, some efforts of researchers address this issue, as summarized in Ref. [1], various efficient strategies have been developed. Among them, a novel scheme named virtual multiple-input multiple-output (VMIMO) has been

proposed for WSN to improve the system performance. Similar to multiple-input multiple-output (MIMO), in such a strategy, a node that has information to send cooperates with adjacent nodes attached single-antenna to transmit its information to a certain destination or next hop cluster head, which forms a virtual antenna array. From the MIMO architecture view, adjacent nodes that participate in cooperating act just as the relay channels for the source node [2–5].

In Ref. [5], Cui et al. analyzed the total energy consumption per bit of multi-antenna nodes. They represented that single-input single-output (SISO) systems use more energy than MIMO systems as the communication scheme. Li et al. [6] proposed a VMIMO scheme using two transmitting sensors and space-time block code (STBC) to provide transmission diversity in WSN with neither antenna-array nor transmission synchronization.

Studies above have shown that cooperation among sensor nodes can lead to significant capacity increase. However, they both assumed that each cooperative node experienced the same channel fading conditions and selected the equal transmitting power (TP). In fact, the channel gains from each cooperating node to the destination may be different, as WSN nodes are always placed randomly in a harsh environment. So how to optimally set the TP for each cooperating node in one cluster is necessary to maximize the system performance. In this paper, we investigate the optimality in terms of minimizing the bit error rate (BER) performance of the system. As a case, a  $K \times 1$  VMIMO cluster-based network topology is considered. The closed-form solutions of the optimal TP are presented. To make the VMIMO network energy efficient with energy-per-useful-bit (EPUB) metric, methods for choosing number of cooperating nodes are also delivered.

The rest of the paper is organized as follows. In Section 2, related works about VMIMO for WSN applications are presented. In Section 3, we give the system model and deduce the exact BER expressions under a Nakagami fading narrowband channel with parameter  $m$ . Then, we compute the optimal TP for each cooperating node and analyze the impact of the number of cooperating nodes

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considering the EPUB metric. In Section 4, we give the simulation verifications. Finally, in Section 5, 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 [7], which presented numerical results for the relaying scenario of Gaussian channels setup. In Ref. [8], authors set up the first information theoretic approach to cooperative for multi-hop transmission.

Although MIMO techniques can greatly enhance the system performance, it is not a feasible way to directly apply them in real WSN applications, as MIMO techniques require complex transceiver circuitry and large amount of signal processing that may lead to burdensome power consumption for energy-limited WSNs. Thanks to works in recent years, it has been shown that MIMO techniques in WSNs via cooperative communication can be possible instead of physically being armed multiple antennas. Such scheme is named by VMIMO [5].

In Ref. [5], Cui et al. studied such distributed MIMO techniques and analyzed the total energy consumption per bit for SISO and MIMO, which validated the feasibility of VMIMO for WSNs. They observed that VMIMO scheme can greatly offer energy savings in cooperative WSNs even considering additional circuit power, communication, and training overheads.

Jagannathan et al. [9] 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 Ref. [5], Yuan et al. [10] presented an optimal cross-layer design of VMIMO for WSNs to ensure quality of service (QoS). Laneman and Wornell did the research work on the system capacity analysis of the VMIMO scheme in Ref. [11].

As to the optimization of VMIMO, Refs. [12–14] presented power allocation optimization methods in the case of a single node transmitting at any time. In Refs. [15] and [16], 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. Reference [17] proposed a minimum power cooperative routing algorithm, where at any time, either a direct transmission or a single relay-aided transmission can occur. In Ref. [18], the choice of the number of cooperating transmitters and the cooperation strategy were investigated to exploit the diversity gain for an increase in either the range or the rate of the links or both. In Ref. [19], authors proposed optimal cooperator selection policies for arbitrary topologies with links affected by path loss and multipath fading.

However, how to optimally choose TP for each cooperating node in VMIMO under different channel conditions has not been addressed in previous studies.

## 3 System model and optimization for energy efficiency

### 3.1 System model

We consider a  $K \times 1$  VMIMO cluster-based WSN depicted in Fig. 1. Sensed data to be transmitted are delivered to  $K$  relay nodes in one cluster; then, it is forwarded to the next hop cluster head by cooperation. To reflect the real wireless environment, we consider Nakagami- $m$  fading narrowband channel model for the wireless link between any two nodes. Here, the parameter  $m$  is for its routine mathematical manipulations and generality. We assume that the channel fades for different links are statistically i.i.d.. This is a reasonable assumption as the relays in scenes similar to Fig. 1 are usually spatially well separated. We model the additive noise power at each receiving terminals as

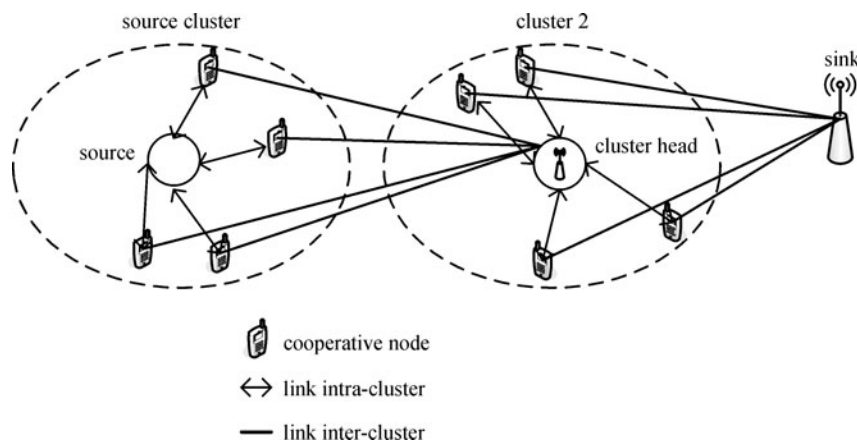


Fig. 1 Cluster-based VMIMO scheme for WSN

zero-mean complex Gaussian random variables with variance 1. To make medium access simple, we assume that cooperating nodes transmit over orthogonal channels; hence, inter-interference between relays could be omitted in the signal model, which is also assumed in Ref. [18].

To make the VMIMO-based system energy efficient, it is necessary to decrease the error probability, which means to reduce the retransmission times when nodes operating with low TP level. Here, we mainly focus on the average BER performance. For the receiving cluster head, the received signal from the  $k$ th cooperating node can be given by

$$\tilde{x}_k(t) = \alpha_k e^{j\theta_k} \tilde{s}_k(t) + \omega_k(t), 0 \leq t \leq T, k = 1, 2, \dots, K, \quad (1)$$

where  $\tilde{s}_k(t)$  is transmitted signal by the  $k$ th cooperating node,  $\alpha_k e^{j\theta_k}$  is the complex fading coefficient, and  $\omega_k(t)$  is additive Gaussian noise. Generally, the fading coefficient is constant in symbol duration  $T$ , then we can omit  $\theta_k$ . Equation (1) can be simplified to

$$\tilde{x}_k(t) = \alpha_k \tilde{s}_k(t) + \omega_k(t).$$

Then, we can get the average signal-to-noise ratio (SNR) per symbol of the  $k$ th diversity channel:

$$\begin{aligned} \bar{\gamma}_k &= (\overline{SNR})_k = \frac{E[|\alpha_k \tilde{s}_k(t)|^2]}{E[|\omega_k(t)|^2]} \\ &= \frac{E[|\tilde{s}_k(t)|^2]}{E[|\omega_k(t)|^2]} E[\alpha_k^2]. \end{aligned} \quad (2)$$

Supposing each cooperating link has the single-sided thermal noise spectral density  $N_0$ , we have

$$\bar{\gamma}_k = \frac{TE[|\tilde{s}_k(t)|^2]}{N_0} E[\alpha_k^2], k = 1, 2, \dots, K. \quad (3)$$

The instantaneous SNR is

$$\gamma_k = \frac{Tp_k}{N_0} \alpha_k^2, k = 1, 2, \dots, K. \quad (4)$$

As we know, for Nakagami multipath fading (NMF) channels, the probability distribution function (PDF) of the channel gain is an expression of gamma function. The received SNR is then gamma distributed according to the PDF, given by

$$\begin{aligned} f_{\Gamma_k}(\gamma_k) &= \left(\frac{m_k}{\bar{\gamma}_k}\right)^{m_k} \frac{\gamma_k^{m_k-1}}{\Gamma(m_k)} \exp\left(-\frac{m_k \gamma_k}{\bar{\gamma}_k}\right), \\ 0 &\leq \gamma_k, k = 1, 2, \dots, K, \end{aligned} \quad (5)$$

where  $m_k$  is the Nakagami fading parameter ( $m > 1/2$ ) for the  $k$ th link and  $\Gamma(\cdot)$  is the gamma function [20].

Here, we consider an  $M$ -QAM transmission through the  $k$ th node that can be seen as an antenna. Therefore, its conditional BER (conditioned on the instantaneous SNR) can be expressed by

$$\text{Prob}(\text{error}|\gamma) \approx \frac{4}{b} \left[1 - 2^{-\frac{b}{2}}\right] Q\left(\sqrt{\frac{3b\gamma}{2^b - 1}}\right), \quad (6)$$

where  $\gamma$  is instantaneous SNR,  $b$  is the number of bits per symbol and  $b = \log_2 M$ , and  $Q(\cdot)$  is the Q-function defined as

$$Q(x) = \frac{1}{2} \text{erfc}\left(\frac{x}{\sqrt{2}}\right).$$

We assume that carrier frequency information and clock synchronization are available at the receiving cluster head, and the BER can be well approximated by Chernoff bound  $\text{Prob}(\text{error}|\gamma) \approx a_1 \exp(-a_2 \gamma)$ . Here,  $a_1$  and  $a_2$  are constants that depend on modulation mode and  $b$ . From Ref. [20], we have  $a_1 = 0.2$ ,  $a_2 = 1.6/3$  for 16-QAM.

Combined with Eq. (6), we can get the average BER for the  $k$ th branch:

$$P_{ek} = \int_0^\infty \text{Prob}(\text{error}|\gamma_k) f_{\Gamma_k}(\gamma_k) d\gamma_k. \quad (7)$$

Based on the gamma function, Eq. (7) can be simplified to

$$P_{ek} = a_1 \left(1 + \frac{a_2 \bar{\gamma}_k}{m_k}\right)^{-m_k}, k = 1, 2, \dots, K. \quad (8)$$

Assuming the channel fading for different links to be statistically independent, we can find that the average BER of  $N_t$  diversity channels would be the product of BERs for each path where we have from Eq. (8), that is,

$$P_e = a_1 \prod_{k=1}^K \left(1 + \frac{a_2 \bar{\gamma}_k}{m_k}\right)^{-m_k}, k = 1, 2, \dots, K. \quad (9)$$

### 3.2 Problem formulation

To make the VMIMO-based system energy efficient, it is equivalent to be the problem of maximizing the throughput with the total TP constraint. As the throughput is determined by the BER performance, minimizing the average BER of the virtual MIMO system would be favorable and we use it to calculate the optimal TP for each node (just like one antenna).

Letting  $p_i$  denote the TP allocated to diversity path  $i$  by the cluster head, the problem of interest is thus for each cluster head to determine the optimal  $N_t \times 1$  TP allocation vector  $\Phi$ ,  $\Phi = \{p_1, p_2, \dots, p_i, \dots, p_{N_t}\}$ , subject to total power constraints.

The TP allocation vector  $\Phi$  is trivially constrained to the nonnegative value, i.e.,  $\Phi > 0$ , as TP are nonnegative.

Considering the total transmit power for a cluster is limited to a fixed  $P$ , the TP allocation vector is also constrained as  $\mathbf{1}^T \Phi \leq P$ . These constraints define the convex space of feasible allocation vectors  $\Phi$  characterizing TP allocation solutions for each cluster head.

Combining the function in Eq. (9) with the set of constraints defined above yields the following TP allocation optimization problem, which aims to find the globally optimal allocation over the set of cluster heads:

$$\begin{cases} \Phi^* = \arg \min_{\{\Phi\}} P_e, \\ \text{subject to } \mathbf{1}^T \Phi \leq P, \\ \Phi \geq 0. \end{cases} \quad (10)$$

**Theorem 1** The solution of optimization problem stated in Eq. (10) is unique.

*Proof.*

From Ref. [21], the objective function in Eq. (10) is a polynomial function that is a strict convex function. The constraint in Eq. (10) is a linear function of the power allocation parameters; thus, it is a convex function. Therefore, the solution of optimization problem stated in Eq. (10) is unique.  $\square$

**Theorem 2** When the total TP is constrained, the optimal TP for the  $K \times 1$  VMIMO cluster-based system, stated in Eq. (10), can be written as

$$P_{opt\_k} = m_k \left[ \frac{P}{\sum_{n=1}^K m_n} + \frac{\sum_{n=1}^K (m_n/C_n)}{a_2 \sum_{n=1}^K m_n} - \frac{1}{a_2 C_k} \right]_0^{P_{\max}}, \quad (11)$$

where  $[\bullet]_0^{P_{\max}} = \min(\max(\bullet, 0), P_{\max})$ ,  $C_k = \frac{T}{N_0} E[\alpha_k^2]$ .

*Proof.*

Equivalently, we can minimize the logarithm of the objective function by translate the optimization problem to be

$$\begin{cases} \text{minimize } \log P_e = \log a_1 - \sum_{k=1}^K m_k \log \left( 1 + \frac{a_2 C_k}{m_k} p_k \right), \\ \text{subject to } \sum_{k=1}^K p_k = P, \\ 0 \leq p_k \leq P_{\max}, \\ \forall k \in \{1, 2, 3, \dots, K\}. \end{cases} \quad (12)$$

The Lagrangian of the problem stated in Eq. (10) is

$$L = \log a_1 - \sum_{k=1}^K m_k \log \left( 1 + \frac{a_2 C_k}{m_k} p_k \right) + \zeta \sum_{k=1}^K p_k, \quad (13)$$

in which  $\zeta$  is the Lagrange multiplier.

The partial derivative with respect to  $p_k$  of the Lagrangian yields

$$\frac{\partial L}{\partial p_k} = \zeta - \frac{a_2 C_k}{1 + \frac{a_2 C_k}{m_k} p_k}. \quad (14)$$

Because the strong duality condition holds for convex optimization problems, by Karush-Kuhn-Tucker (KKT)

conditions, we have  $\frac{\partial L}{\partial p_k} = 0$  and

$$\zeta = \frac{a_2 C_k}{1 + \frac{a_2 C_k}{m_k} p_k}. \quad (15)$$

Therefore, we can get

$$P_{opt\_k} = m_k \left( \frac{1}{\zeta} - \frac{1}{a_2 C_k} \right). \quad (16)$$

By  $P = \sum_{k=1}^K p_k$ ,  $p_k \geq 0$ , we have

$$1/\zeta = \frac{P}{\sum_{n=1}^K m_n} + \frac{\sum_{n=1}^K (m_n/C_n)}{a_2 \sum_{n=1}^K m_n}. \quad (17)$$

Combining Eqs. (16) and (17), it can be verified that Eq. (11) holds true.  $\square$

### 3.3 Impact of $K$ on EPUB metric

By Ref. [22], the energy consumption per bit can be given by

$$E_{bit} = \frac{\sum_{k=1}^K P_{pa\_k} + P_c}{R_b}, \quad (18)$$

where  $R_b$  is data rate,  $P_{pa\_k}$  is power consumption of the power amplifier (PA), and  $P_{pa\_k} = p_k/\eta$ ,  $\eta$  is the efficiency of the PA, and  $P_c$  is total values for digital-to-analog converter (DAC), the mixer, the low-noise amplifier (LNA), the intermediate-frequency amplifier (IFA), the active filters, etc. From Ref. [15], we have

$$P_c = K(P_{dac} + P_{mix} + P_{filt} + P_{syn}) + (P_{lna} + P_{mix} + P_{ifa} + P_{filtr} + P_{adc}). \quad (19)$$

To make clear comparison, we use the EPUB metric, which was presented in Ref. [23]. By Eq. (18), the EPUB can be stated as follows:

$$EPUB = \frac{E_{bit}}{1 - P_e}. \quad (20)$$

By Eqs. (9) and (18), we can get

$$\begin{aligned} EPUB &= \frac{E_{bit}}{1 - a_1 \prod_{k=1}^K \left( \frac{1 + a_2 \bar{\gamma}_k}{m_k} \right)^{-m_k}} \\ &= \frac{\sum_{k=1}^K \frac{P_{opt\_k}}{\eta} + P_c}{R_b \left[ 1 - a_1 \prod_{k=1}^K \left( \frac{1 + a_2 \bar{\gamma}_k}{m_k} \right)^{-m_k} \right]} \\ &= \frac{\frac{P}{\eta} + K\alpha + \beta}{R_b (1 - P_e(p_{opt\_k}, K))}, \end{aligned} \quad (21)$$

where  $\alpha = P_{dac} + P_{mix} + P_{filt} + P_{syn}$ ,  $\beta = P_{lna} + P_{mix} + P_{ifa} + P_{filr} + P_{adc}$ , both can be seen as constant.

From Eq. (21), we can find that there is a tradeoff between the number of cooperating nodes and the EPUB metric. However, it is not an easy way to find the optimal solution with closed-form expression. In fact, it may be more feasible to set different integer values for Eq. (21) to determine the optimal solution. In the next section, we will give the more details.

## 4 Simulation results

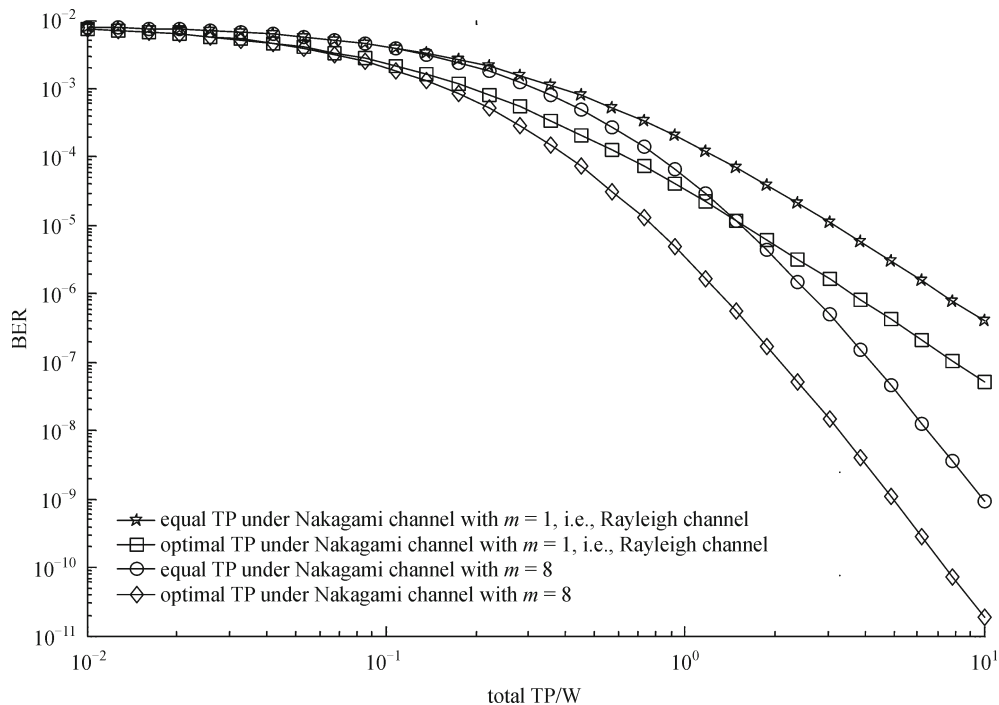
In this section, we evaluate the performance improvement of the proposed scheme. First, we only consider the transmit power consumption and set  $K=3$ ,  $C_1:C_2:C_3 = 10:5:1$ . We compared both equal and optimal power assignment strategies under different channel scenarios, for example, a Rayleigh fading channel ( $m=1$ ) and a Nakagami one ( $m=8$ ). The results are shown in Fig. 2, where we can observe that the amount of performance improvement is greater in better channel conditions and that, when the total power is low, the optimal strategy tends to assign most of power to the best branch, which improves the communication reliability between clusters.

Then, we make a clear comparison on the number of cooperating nodes, that is,  $K$ . To this aim, we also considered a Nakagami- $m$  scenario with different  $K$ . The channel conditions are set to the same for all experiments and are equally distributed. As we can see from Fig. 3, the

BER performance improvement is higher for larger number of cooperating nodes. However, it should be noticed that the more number of cooperating sensor nodes is, the bigger the cluster of them should be formed. This will require more number of nodes to maintain synchronization and more energy consumption on nodes' physical circuits, which might be an issue. Taking the values in Ref. [24], for example in Table 1, we can describe the plot of EPUB versus total TP with different number of cooperating nodes in Fig. 4. As we can see, when  $P_c$  dominates the power consumption, the more number of cooperating nodes leads to less energy efficiency. However, when the total TP is high enough, i.e.,  $P \gg 0$  dBm, the number of cooperating nodes makes little effect on the EPUB.

**Table 1** Values for node's physical layer

parameters	value
$f_c$	2.5 GHz
$P_{mix}$	30.3 mW
$P_{filt}$	2.5 mW
$P_{filr}$	2.5 mW
$P_{lna}$	20 mW
$P_{syn}$	50 mW
$R_b$	1 Mbps
$P_{adc}$	7 mW
$P_{dac}$	15.4 mW



**Fig. 2** BER performance evaluation for different channel conditions

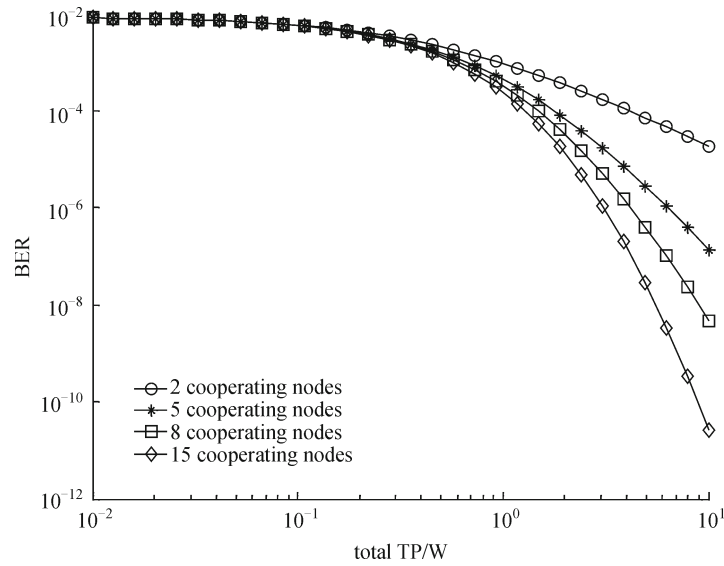


Fig. 3 BER performance with different number of cooperating nodes

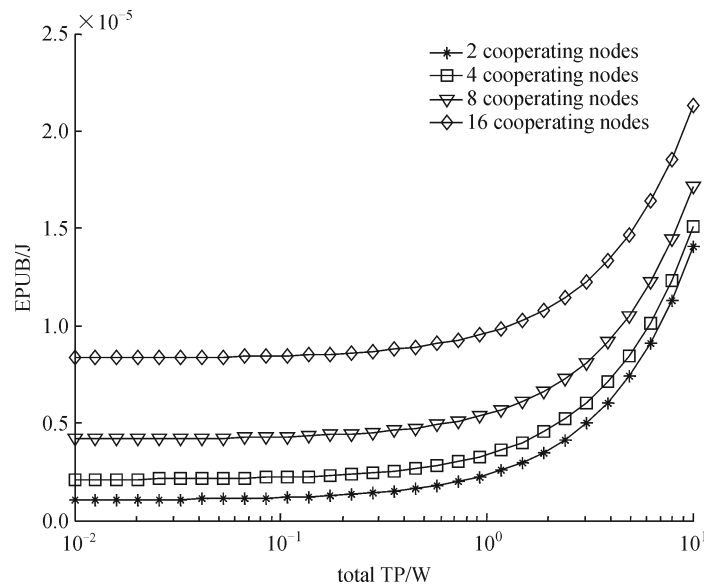


Fig. 4 EPUB versus total TP with different number of cooperating nodes

### 5 Conclusions

In this paper, we studied energy efficient strategies for VMIMO networks with WSN applications. We derived the closed-form solutions for the optimal transmit power among cooperating nodes by taking both the statistical BER under different channel conditions and the residual energy information into account. Simulations demonstrated that the proposed optimal power assignment strategies could considerably improve the energy efficiency compared to the equal transmit power scheme.

Furthermore, it is shown that, by selecting the optimal number of cooperative nodes, the EPUB increased compared to the static cooperation.

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