Optimal Design of Virtual MIMO for WSN Performance Improvement

KAN Baoqiang[1] , Lei Zhao[2] , JH Fan[1] , JY Wang[3]

1. PLA University of Technology, Nanjing 210007, China
2. Laboratory of Sensor Networks and Institute of Computing Technology and Academy of Sciences Beijing 100080)
3. College of Missle, Air Force Engineering University, Xi'an 710052, China;

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 $N_t \times 1$ 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. He represents that single-input-single-output (SISO) systems use more energy than MIMO as the communication scheme. And X. Li [6] proposed a virtual MIMO 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 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 $N_t \times 1$ 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

Corresponding author (email: bqkan@163.com)

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 cooperator 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.

3. Model And Optimal Design

3.1 .Network model

We consider a cluster based wireless sensor network, where collected data is to be transmitted from a source to a destination by $N_t\times1$ virtual MIMO clusters. It is depicted in Fig.1. Considering the real wireless environment, we model the wireless link between any two nodes in the network as a Nakagami-*m* fading narrowband channel. And parameter *m* is for its routine mathematical manipulations and generality. The channel fades for different links are assumed to be statistically i.i.d. This is a reasonable assumption as the relays in scenes similar to Fig.1 are usually spatially well separated. The additive noise power at all receiving terminals is modeled as zero-mean complex Gaussian random variables with variance 1. To make it simple for medium access, the relays are assumed to transmit over orthogonal channels, thus no inter interference between relays is considered in the signal model, which is also assumed in [16][24].

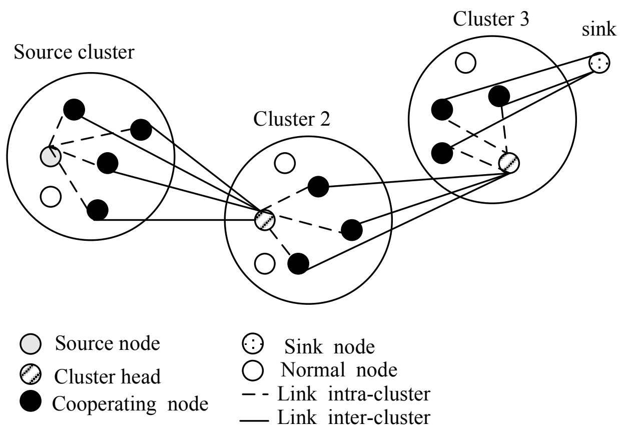


Fig.1 Cluster based virtual MIMO scheme for WSN[9]

To make the virtual MIMO 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.

As we assumed that the transmitted signal on the *i*th cooperating node, or equivalently virtual MIMO antenna, undergoes Nakagami-*m* fading with fading parameter m_i and average fading power $\overline{H}_i = \mathrm{E}(H_i)$, i=1,2,…,N_t , then we can get the instantaneous signal-to-noise ratio (SNR) per symbol of the *i*th diversity channel

$$\gamma_i = (H_i T_s p_i)/N_0 \quad (1)$$

where N_0 is the single-sided thermal noise spectral density, H_i is the fading power of the ith diversity path, p_i is the transmitting power of the ith cooperating node, and T_s is the symbol duration, assumed to be constant. Let $\bar{\gamma}_i$ be the average received SNR of the ith path , it can be given by

$$\bar{\gamma}_i = (\bar{H}_i T_s p_i)/N_0 = C_i p_i \quad . \quad (2)$$

Here, we consider a M-QAM transmission through the ith node which can be seen as an antenna. So its conditional BER (conditioned on the instantaneous *SNR*)can be expressed by $\Pr ob(\text{error} \mid \gamma) \approx \frac{4}{b}\left[1-\frac{1}{2^{\frac{b}{2}}}\right]Q(\sqrt{\frac{3b\gamma}{2^b-1}})$, in which b is the number of bits per symbol and $b=\log_2 M$, $Q(\cdot)$ is the Q-function defined as $Q(x) = (1/\sqrt{2\pi}\int_x^{\infty} e^{-\lambda^2/2}d\lambda)$. We assume that clock and carrier frequency information is available at the receiver, the BER can be well approximated by Chernoff bound [12][13]:

$\Pr ob(\text{error} \mid \gamma) \approx a_1 \exp(-a_2\gamma)$ for b>4, here a_1 and a_2 are constants.

As we know, for 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

$$p_\gamma(\gamma) = \left(\frac{m}{\bar{\gamma}}\right)^m \frac{\gamma^{m-1}}{\Gamma(m)} \exp\left(-m\frac{\gamma}{\bar{\gamma}}\right) \qquad \gamma \geq 0 \quad (3)$$

m is the Nakagami fading parameter (m>1/2), and $\Gamma(\cdot)$ is the gamma function[12].

So the average BER in the ith path can be given by

$$P_{ei} = \int_0^{\infty} \Pr ob(\text{error} \mid \gamma) p_{\gamma_i}(\gamma_i) d\gamma_i$$

$$= \int_0^{\infty} a_1 e^{-a_2\gamma_i} \left(\frac{m_i}{\bar{\gamma}_i}\right)^{m_i} \frac{\gamma_i^{m_i-1}}{\Gamma(m_i)} \exp\left(-m_i\frac{\gamma_i}{\bar{\gamma}_i}\right) \quad (4)$$

where $x = \gamma_i/\bar{\gamma}_i$.

By simple algebra of Eq.(4) ,we have

$$P_{ei} = a_1(1+\frac{a_2\bar{\gamma}_i}{m_i})^{-m_i} \quad (5)$$

Assuming the channel fading for different links to be statistically independent, then the average BER of N_t diversity channels would be the product of BERs for each path where we have from (5), that is

$$P_e = a_1\prod_{i=1}^{N_t}(1+\frac{a_2\bar{\gamma}_i}{m_i})^{-m_i} \quad (6)$$

3.2 Problem Formulation

To make the virtual MIMO energy efficient, the problem can be stated as maximizing the throughput under the total transmitting power 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 transmitting power for each node(just like one antenna).

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

The transmitting powers allocation vector Φ is trivially constrained to the nonnegative orthant, i.e. $\Phi > 0$, as transmitting powers are non-negative.

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

Combining the function in (6) with the set of constraints defined above yields the following transmitting power allocation optimization problem which aims to find the globally optimal allocation over the set of cluster heads.

$$\begin{cases} \Phi^* = \arg\min\limits_{\{\Phi\}} \ P_e \\ \text{subject to} : 1^T\Phi \leq P \\ \qquad \Phi \geq 0 \end{cases} \quad (7)$$

Theorem 1. The optimal transmitting power for the cooperative system given in $N_t\times 1$ virtual MIMO clusters is

$$p_{i\_optml} = m_i \max(0, \frac{P}{\sum_{n=1}^{N_t} m_n} + \frac{\sum_{n=1}^{N_t}(m_n/C_n)}{a_2\sum_{n=1}^{N_t} m_n} - \frac{1}{a_2 C_i}) \quad (8)$$

The proof is given in Appendix .

4.**Numerical Results**

In this section, we evaluate the performance improvement of the proposed scheme.

Fig. 2 shows the average BER performance of the virtual MIMO based on the total power using optimal TP scheme and equally common one, respectively. The comparison is for N_t = 3 cooperating nodes where ,for example, we set C_1:C_2:C_3=10:5:1. As it can be seen, the performance degradation of the equal TP scheme is more severe than that of optimal power allocation. That is to say , for a required BER performance, optimal TP scheme has less power consumption. For example, when using optimal transmitting power for each different cooperating node, at BER=10^{-3}, optimal scheme needs 36% less power. It also can be seen 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.

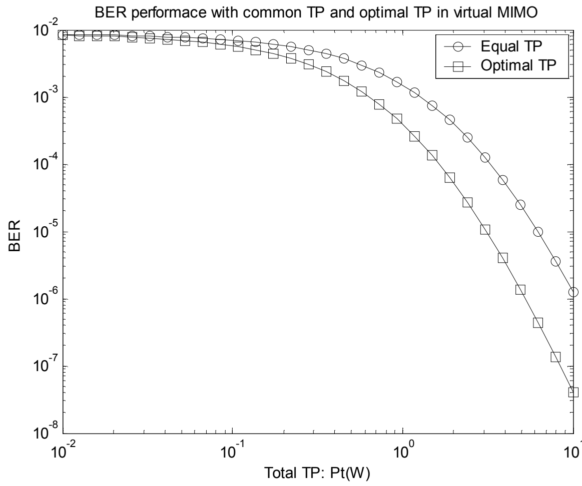


Fig.2 BER performance of optimal and equal TP

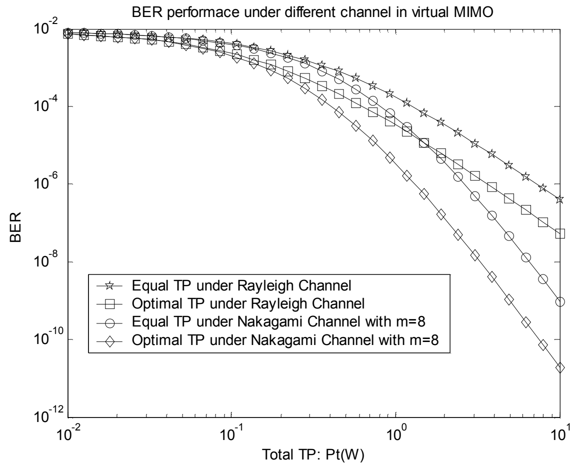


Figure 3 BER performance in different channel conditions

In the second experiment, we compared both equal and optimal power allocation strategies on different channel scenarios, for example, a Rayleigh fading channel (m=1) and a m=8 Nakagami one. The results are showed in Fig. 3 , where we can observe that the amount of performance improvement is greater in better channel conditions.

The third clear comparison could be made on the number of cooperating nodes, that is N_t. To this aim, we considered a Nakagami-m scenario with different N_t. The channel conditions are set to the same for all experiments and are equally distributed. As we can see from Fig. 4, the BER performance improvement is higher for larger number of cooperating nodes. But it should be noticed that the more the 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, where might be an issue.

By [15], the energy consumption per bit can be given by

$$E_{bit} = (P_{pa} + P_c)/R_b\,, \tag{9}$$

where P_{pa} is power consumption of the power amplifier (PA) and P_c is total values for DAC, the mixer ,the low-noise amplifier(LNA),the intermediate frequency amplifier(IFA), the active filters et al., we use the model introduced in [5]. From [15], $P_{pa} = (1+\alpha)P$, in which α is the efficiency of the power amplifier , then ,

$$P_c = N_t(P_{dac} + P_{mix} + P_{filt} + P_{syn}) + (P_{\ln a} + P_{mix} + P_{ifa} + P_{filr} + P_{adc}) \tag{10}$$

To make clear comparison , we use the energy-per-useful-bit (EPUB) metric, which was presented in [11]. By Eq.(6), the EPUB can be stated as follows:

$$EPUB = E_{bit}/(1-P_e) \tag{11}$$

By Eq.(6) and Eq.(9), we can get

$$\begin{aligned} EPUB &= E_{bit}\Big/\Big(1 - a_1\prod_{k=1}^{N_t}\big(1+\frac{a_2\overline{\gamma}_k}{m_k}\big)^{-m_k}\Big) \\ &= \Big(\frac{P}{\eta} + \mathrm{P_c}\Big)\Big/\Big(\mathrm{R_b}\Big(1 - a_1\prod_{k=1}^{N_t}\big(1+\frac{a_2\overline{\gamma}_k}{m_k}\big)^{-m_k}\Big)\Big) \\ &= \Big(\frac{P}{\eta} + \mathrm{P_c}(N_t)\Big)\Big/\big(\mathrm{R_b}(1 - P_e(N_t, P))\big) \end{aligned} \tag{12}$$

Taking the values in [5], we can describe the plot of EPUB versus total TP with different number of cooperating nodes in Fig.5. As we can see, when P_c dominates the power consumption, the more number of cooperating nodes leads to less energy efficient. However, when the total TP is high enough , the number of cooperating nodes make little effect on the EPUB.

Table 1 Values for node's physical layer[5]

f_c	2.5 GHz
P_{mix}	30.3mW
P_{filt}	2.5mW
P_{filr}	2.5 mW
P_{lna}	20mW
P_{syn}	50mW
R_b	1Mbps
P_{adc}	7mW
P_{dac}	15.4mW
η	0.3

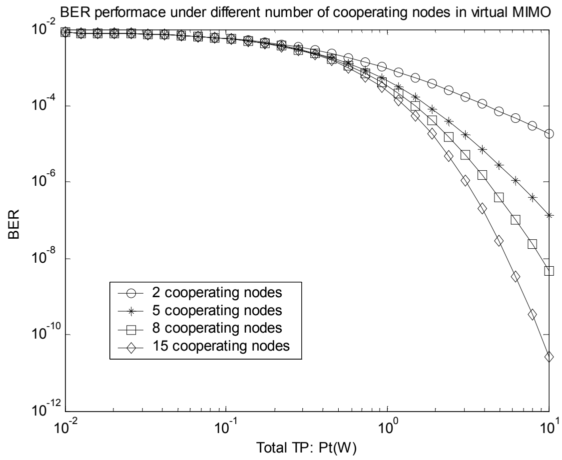


Figure 4 BER performance under different number of cooperating nodes

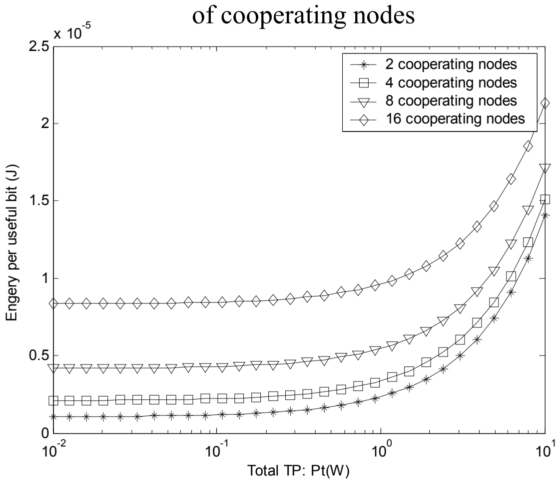


Figure 5 EPUB versus total TP with different number of cooperating nodes

5. Conclusion

In this paper, we have introduced a new optimal TP strategy for each cooperating node by evaluating BER performance of a cluster based virtual MIMO wireless sensor network. Closed-form expressions for (i) the average BER experienced by each diversity branch, (ii) the optimal TP for each cooperating node have been derived. The BER performance of a network with a equal TP scheme has been compared with that of a network with optimal TP one. It has been shown that the BER performance of a network with an optimal TP for each cooperating node strategy which intends to minimize BER of the system can achieve better than that of a network with equal common TP ones. This brings less power consumption for forward, so that a highly limited resource sensor network could achieve a longer life. As all the overhead in the scheme is mainly in software energy used to digital processing and the energy exchanged in the initial stages of transmission scenario, the proposed scheme even doesn't make any other additional overhead, but just few software calculations for the TP values when in initialization. Finally, the impact of the number of the cooperating nodes on the EPUB is analyzed by the aid of mathematical analysis as well as simulation verifications.

ACKNOWLEDGEMENT

This research was supported by National High-Tech Research and Development Plan of China (No. 2006AA01Z223).

Appendix

This appendix outlines the proof for Eq. (8) .

Since the total TP is fixed, the constraint in this case is $P=\sum_{i=1}^{N_t} p_i$ ($p_i \geq 0$), where P is the value of total TP. Equivalently, one can minimize the logarithm of the objective function, obtaining the following program:

$$\begin{cases} \text{minimize } \log(P_e)=\log(a_1)-\sum_{i=1}^{N_t} m_i \log(1+\frac{a_2 C_i}{m_i} p_i) \\ \text{subject to}: \qquad P=\sum_{i=1}^{N_t} p_i \\ \qquad\qquad\qquad\quad p_i \geq 0 \qquad \forall i \in I \end{cases} \tag{A.1}$$

The function can be written as

$$Z=\log(a_1)-\sum_{i=1}^{N_t} m_i \log(1+\frac{a_2 C_i}{m_i} p_i)+\xi \sum_{i=1}^{N_t} p_i \tag{A.2}$$

where ξ is the Lagrange multiplier. The partial derivative, with respect to p_i, of the Lagrangian yields:

$$\frac{\partial Z}{\partial p_i}=\xi-\frac{a_2 C_i}{1+\frac{a_2 C_i}{m_i} p} \tag{A.3}$$

Setting the partial derivative to 0 and solving for ξ , one gets

$$\xi=\frac{a_2 C_i}{1+\frac{a_2 C_i}{m_i} p} \tag{A.4}$$

The next step is to solve for p_i in terms of ξ and substitute it back in the constraint equation. Let $p_i(\xi)$ be the inverse of equation (A.4), it can be given by

$$p_{i\_optml}=m_i(1/\xi-1/a_2 C_i) \tag{A.5}$$

and substitute this value back into the constraint equation $P=\sum_{i=1}^{N_t} p_i$ ($p_i \geq 0$), obtaining:

$$1/\xi = \frac{P}{\sum_{n=1}^{N_t} m_n} + \frac{\sum_{n=1}^{N_t}(m_n / C_n)}{a_2 \sum_{n=1}^{N_t} m_n} \quad (A.6)$$

then by Eq.(A.6) and (A.5) , we can lead to Eq.(8).

REFERENCES

[1] F. Akyildiz, W. Su, Y. Sankarasubramaniam, E. Cayirci,. Wireless sensor networks: a survey. *Computer Networks*, 2002, Vol.38 ,pp. 393-422.

[2] S. Cui, A. J. Goldsmith, and A. Bahai, Energy-efficiency of MIMO and cooperative MIMO techniques in sensor networks, *IEEE J. Select. Areas. Commun.*, vol. 22, no. 6, pp. 1089–1098, Aug. 2003.

[3] T.M. Cover and A.A. El Gamal, Capacity theorems for the relay channel, I*EEE Trans. on Information Theory*, vol. 525, no. 5, pp. 572–584, Sep. 1979.

[4] G. Kramer, M. Gastpar, and P. Gupta, “Cooperative strategies and capacity theorems for relay networks,” *IEEE Trans. on Information Theory*, vol. 51, no. 9, pp. 3037–3063, Sep. 2005.

[5] S. Cui, A. J. Goldsmith, and A. Bahai, “Modulation optimization under energy constraints,” in *Proc. ICC’03*, AK, May 2003, pp. 2805–2811.

[6] X. Li, “Energy efficient wireless sensor networks with transmission diversity," *IEE Electronics Letters*, vol.39, pp.1753-1755, Nov. 2003.

[7] S. K. Jayaweera, “An energy-efficient virtual MIMO architecture based on V-BLAST processing for distributed wireless sensor networks,” in *2004 First Annual IEEE Communications Society Conference on Sensor and Ad Hoc Communications and Networks*,pp.299-308, Oct. 2004.

[8] S. K. Jayaweera, “Virtual MIMO-based Cooperative Communication for Energy-constrained Wireless Sensor Networks” *,IEEE Transactions on W*ireless communications, vo5.5, pp.984-989, May. 2008.

[9] Y. Yuan, Z. H. He, and M. Chen, “Virtual MIMO-based Cross-Layer Design for Wireless Sensor Networks” *,IEEE Transactions on Vehicular Technology*, vo55.3, pp.856-864, May. 2009.

[10] J. N. Laneman and G. W. Wornell, “Distributed space-time-coded protocols for exploiting cooperative diversity in wireless networks,” *IEEE Trans. Inf. Theory*, vol. 49, no. 10, pp. 2415–2425, Oct. 2008.

[11] M. Chen, S. Serbetli, and A. Yener, “Distributed power allocation strategies for parallel relay networks,” IEEE Trans. Wireless Commun., vol. 7, no. 2, pp. 552–561, Feb. 2008.

[12] A.J. Goldsmith and S.G. Chua, “Variable-Rate Variable-Power M-QAM for Fading Channels”, *IEEE Transactions on* communications., Vol. COM-45, pp. 1218–1230, 2007

[13] M S Alouini and A J Goldsmith, “Adaptive modulation over Nakagami fading channels ” , Wireless Personal Communications , Vol. 13, pp. 119–143, 2007.

[14] Ammer J., Rabacy J., “The Energy-per-Useful-Bit Metric for Evaluating and Optimizing Sensor Network Physical Layers”, SECON’08,vol..2, pp. 695-700.

[15] Kan B Q, Cai L, H.S Zhu, et al. Accurate energy model for WSN node and its optimal design. *Journal of Systems Engineering and Electronics* .Volume 19, Issue 3, June 2008, Pages 427-433.

[16] Ahmed K. Sadek, Weifeng Su, K. J. Ray Liu. Multinode Cooperative Communications in Wireless Networks*. IEEE Transactions On Signal Processings* .Volume 55, Issue 1, Jan 2007, Pages 341-356..

[17] J. Si, Z. Li, Z. Liu, and X. Lu, “Joint route and power allocation in cooperative-multihop networks,” in Proc. IEEE Int. Conf. Circuits and Systems for Commun., Shanghai, China, May 2008, pp. 114–118.

[18] Z. Yang and A. Høst-Madsen, “Routing and power allocation in asynchronous Gaussian multiple-relay channels,” EURASIP J. Wireless Commun. and Networking, vol. 2006, no. 2, pp. 1–11, Apr. 2006.

[19] F. Li, A. Lippman, and K. Wu, “Minimum energy cooperative path routing in wireless networks: an integer programming formulation,” in Proc. IEEE VTC Spring, Melbourne, Australia, 2006.

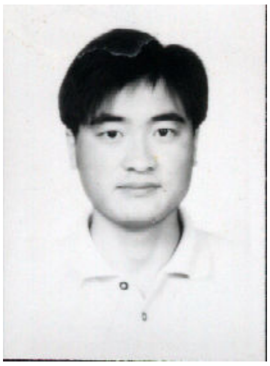
[20] A. E. Khandani, J. Abounadi, E. Modiano, and L. Zheng, “Cooperative routing in static wireless networks,” IEEE Trans. Commun., vol. 55, no. 11, pp. 2185–2192, Nov. 2007.

[21] A. S. Ibrahim, Z. Han, and K. J. Liu, “Distributed energy-efficient cooperative routing in wireless networks,” IEEE Trans. Wireless Commun.,vol. 7, no. 10, pp. 3930–3941, Oct. 2008.

[22] S. Lakshmanan and R. Sivakumar, “Diversity routing for multi-hop wireless networks with cooperative transmissions,” in Proc. IEEE SECON, Rome, Italy, 2009.

[23]Michele Rossi, Cristiano Tapparello, and Stefano Tomasin. On Optimal Cooperator Selection Policies for Multi-Hop Ad Hoc Networks. IEEE Transactions on wirless communications., Vol. 10(2), pp. 506–518, Feb. 2011.

[24]P.Varzakas, “Average Channel Capacity for Rayleigh Fading Spread Spectrum MIMO systems”, International Journal of Communication Systems, vol. 19, no.10, Dec.2006, pp. 1081-1087.



Kan Bao-qiang received his B.Sc. and M.Sc. degrees in electric engineering from the Air-Force engineering University, China, in 2002 and 2005, respectively, and the Ph.D. degree in computing from the same one, in 2008. Currently, he is a network researcher in Nanjing telecommunication technology institute ,China.

His research interest network and control systems, and wireless information theory.

E-mail: bqkan@163.com